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Construction Projects Status Tracking: A Real-Time Data-Driven Framework for Delay Management and Analysis

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Summary

Construction delays remain one of the most critical challenges in project delivery, often resulting in cost overruns, schedule slippages, and weakened stakeholder confidence. Traditional delay management methods are largely reactive, relying on periodic reporting and fragmented communication across project teams. In contrast, the increasing availability of digital tools offers the opportunity to adopt more proactive, data-driven approaches. This study introduces a framework that centralises and analyses real-time project data from multiple stakeholders, including head contractors, subcontractors, consultants (via Building Information Modelling—BIM), and on-site teams. By integrating these diverse inputs into a unified Power BI dashboard, the framework enhances early delay detection, improves coordination, and supports timely decision-making. Earned Value (EV) metrics are embedded as key control points, providing early signals of deviations and potential risks.

Despite these advances, several research gaps remain. Existing systems are often costly and complex, highlighting the need for simple, inexpensive, and user-friendly solutions. Real-time data acquisition and centralisation are still underdeveloped, limiting the speed and reliability of insights. Current practice focuses heavily on retrospective reporting, with limited capability for real-time analytics or predictive forecasting. Stakeholder communication and coordination continue to be fragmented, while systematic early notification systems for emerging delays are rarely implemented. Finally, there is a need to harness historical and live data together to enable predictive delay analytics. Addressing these gaps would help shift construction delay management from reactive intervention towards proactive risk mitigation.

Guided by these gaps, the research is shaped around three central questions: (1) What causes delays in major construction projects, and how do these delays affect stakeholder collaboration? (2)

How are digital technologies currently being deployed to improve project performance in relation to delays and risks? (3) How can a new framework be designed and evaluated to strengthen early delay detection and enhance project outcomes? To answer these questions, five objectives are established. First, to identify and analyse the key project stakeholders and the principal causes of delay. Second, to review and assess the role of digital technologies in construction projects. Third, to develop a framework that integrates real-time data for enhanced monitoring, reporting, and early detection of delays. Finally, to evaluate this framework in practice, assessing its effectiveness in improving transparency, stakeholder coordination, and overall project performance.

In doing so, this research contributes to the advancement of digital construction management by embedding real-time analytics into live project environments. The proposed framework not only improves transparency and resource allocation but also lays the foundation for predictive delay management, thereby aligning construction practices with the broader ambitions of Industry 4.0.

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Glossary

AD	Actual Duration
API	Application Programming Interface
BIM	Building information modelling
CAD	Computer-Aided Design
CPI	Cost Performance Index
CPM	Critical Path Method
CR	Change request
CV	Cost Variance
DPI	Duration Performance Index technique
DSS	Decision support system
EVA	Earned Value Analysis
EVM	Earned Value Management
EVM	Earned Value Management
GIS	Geographic Information System
ICT	Information and Communication Technology
IFC	Issue For Construction (Design)
IoT	Internet of Things
IT	Information Technology
MBIE	Ministry of Business, Innovation and Employment
NZD	New Zealand Dollar
PV	Planned Value
RealCONs	Real-Time Construction Project Analysis Framework
RFI	Request For Information
RFID	Radio Frequency Identification
RFQ	Request For Quotation
SPI	Schedule Performance Index
SQL	Structured Query Language
SV	Schedule Variance

Chapter 1: INTRODUCTION

This opening chapter sets the foundation for the thesis by outlining the research problem, aims, objectives, and guiding questions. It introduces the methodological approach adopted in the study and explains the overall structure of the thesis. The central focus of the research is the development of a framework for real-time delay detection and management in construction projects, with particular attention to how digital technologies can support stakeholder coordination and performance monitoring.

The research is guided by three key questions: (1) What are the primary causes of delays in major construction projects, and how do they affect stakeholder collaboration? (2) How are digital technologies currently being used to improve project performance, particularly in relation to delays and risks? (3) How can a proposed framework be designed and evaluated to strengthen early delay detection and project outcomes? To address these questions, five objectives are established: identifying stakeholders, analysing the causes of delays, reviewing digital technologies, developing the proposed framework, and evaluating its effectiveness. A mixed-methods research design is employed, combining qualitative and quantitative approaches to generate both depth and breadth of insight. Real-time data analytics, visualisation through Power BI, and earned value (EV) performance metrics form the analytical backbone of the study. The empirical work is centred on case studies drawn from major and smart construction projects in New Zealand, providing a practical and contextually relevant testbed for the framework. Definitions of what constitute “major projects” and “smart projects” are provided in Section 1.8 to ensure conceptual clarity.

The remainder of this thesis is structured as follows. Following this introductory chapter, Chapter 2 presents the literature review, covering the concepts of delay, real-time digital technologies in construction management, and international best practices. Chapter 3 outlines the research methodology, including the rationale for the mixed-methods approach. Chapter 4 presents the case study findings, while Chapter 5 details the development and application of the proposed framework. Chapter 6 provides an evaluation of the framework and its implications for construction management practice. Finally, Chapter 7 concludes the thesis by summarising the contributions, highlighting limitations, and identifying directions for future research.

1.1 OVERVIEW

Understanding delays in major construction projects and identifying technological solutions for their management requires a clear grasp of both the underlying causes of delays and the tools available to address them. Delays remain one of the most common and disruptive challenges in large-scale projects, often resulting in cost inflation, schedule overruns, contractual disputes, and reputational damage (Amini, Rezvani, Tabassi, & Malek Sadati, 2023; Shanmugapriya & Subramanian, 2013). They arise from a wide range of sources, including poor planning, design errors, unforeseen site conditions, regulatory and contractual constraints, labour shortages, and external factors such as extreme weather (Demirkesen & Tezel, 2022; Doloi, Sawhney, Iyer, & Rentala, 2012; Durdyev & Hosseini, 2020). As projects grow in scale and complexity, the impacts of such delays become even more significant, making it essential to develop effective methods for their analysis, mitigation, and reduction (Abdallah et al., 2022; Memon, Rahman, & Azis, 2011; Varajão, Magalhães, Freitas, & Rocha, 2022; Williams, Vo, Samset, & Edkins, 2019). Traditional approaches such as the Critical Path Method (CPM), Earned Value Management (EVM), risk registers, and structured change management procedures have been widely applied to monitor and mitigate delays.

While these methods remain valuable, their reliance on periodic reporting and static data limits their effectiveness in fast-moving project environments. With increasing project complexity, there is a growing need for more dynamic and predictive solutions (Hammad et al., 2019; Pan & Zhang, 2023; Piras, Muzi, & Tiburcio, 2024).

Recent technological developments have transformed the landscape of delay management. Digital tools such as Building Information Modelling (BIM), artificial intelligence (AI), the Internet of Things (IoT), drones, and advanced data analytics provide powerful capabilities for predicting, monitoring, and reducing delays (Amini et al., 2023; Love, Lucas, Kelbert, & Bedrosian, 2018; Obakin, Afolami, & Akande, 2024). BIM enables the creation of detailed digital models that can be linked with real-time progress data, allowing early identification of clashes or changes likely to cause delays (Deacon & Van der Lingen, 2015; Ekanayake, Wong, Fini, & Smith, 2021; Petroutsatou, 2022), AI algorithms, informed by historical project data and external factors such as weather, can forecast potential disruptions. IoT devices and sensors capture site conditions and equipment usage in real time, while drones and laser scanners enhance site monitoring (Elshaer, 2013; Gemino, Horner Reich, & Serrador, 2021; Reiff & Schlegel, 2022). Together, these technologies improve accuracy, enhance predictive capability, and support better resource allocation (Hammad et al., 2019; Pan & Zhang, 2023; Piras et al., 2024). Despite their promise, significant challenges remain. High implementation costs, technical complexity, fragmented data systems, and concerns around data security continue to limit widespread adoption (Azhar, Carlton, Olsen, & Ahmad, 2011; Honnappa & Padala, 2022; Parsamehr, Perera, Dodanwala, Perera, & Ruparathna, 2023; Radman, Jelodar, Lovreglio, Ghazizadeh, & Wilkinson, 2022). Current studies also show that while real-time monitoring technologies are increasingly applied, they are often implemented in isolation rather than as part of an integrated, centralised framework. Many existing data fusion models lack the ability to unify progress tracking across disciplines, especially in complex multi-stakeholder environments (Hassan, Kowalska, & Ashraf, 2023; Keyvanfar, Shafaghat, & Awanghamat, 2021). IoT devices

provide real-time data on project progress, equipment usage, and site conditions, enabling stakeholders to take proactive measures (Jain et al., 2021; Rao et al., 2022).

The integration of technology into delay management presents both benefits and challenges. The benefits include improved accuracy and efficiency, enhanced predictive capabilities, and better resource allocation (Cheng & Ugrinovskii, 2016). However, challenges include high initial costs, technical complexity, and concerns about data security (Du, Zou, Shi, & Zhao, 2018). Despite these challenges, real-time data analytics, predictive technologies, and collaborative platforms have proven crucial in improving project timelines and reducing delays. For this purposes, cost overruns and schedule delays are prevalent in construction projects, leading to disputes and claims. Recent studies emphasize the importance of real-time tracking and timely progress reporting for smart construction management. Technologies like remote sensing, RFID tags, and 3D laser scanners have been used to acquire real-time data on construction sites (Moselhi, Bardareh, & Zhu, 2020; Rao et al., 2022). Moreover, current data fusion models lack a centralised progress tracking system, particularly in multidisciplinary projects (Fadhel et al., 2024).

These limitations highlight clear research gaps. First, there is a need for simple, cost-effective, and user-friendly systems that can be easily adopted by diverse stakeholders. Second, stronger mechanisms for real-time data acquisition and centralisation are required to avoid fragmentation. Third, existing systems focus more on retrospective analysis than on predictive analytics, leaving a gap in proactive delay forecasting. Fourth, real-time early-warning and notification systems are underdeveloped, limiting the ability of project teams to act before delays escalate. Finally, greater integration is needed to support collaboration and communication across contractors, subcontractors, consultants, and clients, especially in large multidisciplinary projects. Addressing these gaps would advance delay management from reactive monitoring to proactive, predictive control, offering a critical step forward for construction project management.

This study investigates the frequent causes and consequences of delays in major construction projects. Common factors include errors in planning and design, shortages of resources, regulatory hurdles, and external influences like adverse weather. The research evaluates current management strategies and identifies a critical gap in the early detection of such delays. To address this, a novel, real-time, and data-driven analytical framework named RealCONs is introduced. Specifically designed for the electrical and instrumentation trades, RealCONs is developed in alignment with **SMART** specifications: **S**imple, **M**easurable, **A**nalytical, and **R**eal-**T**ime. The framework leverages real-time data to provide proactive solutions, enabling early delay notifications and minimising project disruptions. As such, this doctoral research offers significant contributions through its innovative approach to real-time delay management:

1. **Seamless Integration with Existing Tools:** RealCONs integrates familiar tools used by construction project teams, such as Oracle Primavera (P6), MS Project, Oracle Aconex, BIM (Revit, Navisworks), QR codes, smartphones, and Power BI. This allows the framework to be adopted without requiring additional training or new skills, making it both efficient and cost-effective.
2. **Data Translation and Visualisation:** For this purpose, this doctoral research used Power BI. This platform is the core of the framework, connecting the tools through SQL Server, APIs, server-side scripting (PHP), Python, and SQL. RealCONs translates data from various sources—such as BIM, P6, SQL Server, and Aconex—into visual and analytical insights using Power BI, enhancing decision-making.
3. **Improved Communication and Delay Classification:** The framework enhances communication accuracy and flexibility by automating data exchange and recognizing responsible parties across different project sites (e.g., issues reported from site to consultant via head contractor). It also categorizes delays based on their nature, improving overall project communication and accountability.

4. **Real-Time Analysis with Earned Value Metrics:** RealCONs integrates earned value metrics, such as the Schedule Performance Index (SPI) and Cost Performance Index (CPI), to provide early identification of delay impacts on time and cost. This helps project managers forecast costs (particularly labour) with greater accuracy, reliability, and accessibility.

The key novelty of RealCONs is that it delivers early-stage delay notifications through a low-cost, process-based framework that integrates real-time data without imposing additional financial burdens. This results in high efficiency in time and cost savings for companies. To validate the effectiveness of the framework, both theoretical and experimental methodologies will be employed. Six months of data from smart construction projects in New Zealand were analysed to demonstrate the framework's ability to track progress and assess productivity.

1.2 BACKGROUND

Most of time delays in construction projects are a pervasive issue that can have significant financial, contractual, and reputational consequences (Akinsiku & Akinsulire, 2012; Milind Mehta, Chang, Oh, Kwon, & Kim, 2022). The scale and complexity of modern construction projects, especially major projects, increase the likelihood of delays, making them a critical area of study in project management and construction engineering (Bahamid, Doh, Khoiry, Kassem, & Al-Sharafi, 2022; Qazi, Quigley, Dickson, & Kirytopoulos, 2016). Understanding the causes of these delays and developing effective strategies for their mitigation has been a focal point of research in construction management over the past several decades. Research has consistently highlighted the multifaceted nature of delays in construction projects (Bahamid et al., 2022; Ingle & Mahesh, 2022; Williams, 2016). These delays often arise from a combination of technical, operational, and external factors that disrupt the planned schedule. Previous studies such as those by Assaf and Al-Hejji (2006) and Gómez-Cabrera, Gutierrez-Bucheli, and Muñoz (2024) identified common causes of delays,

including design changes, inadequate project planning, and resource shortages. More recent studies have expanded on these causes, highlighting the growing complexity of modern construction projects and the increased coordination required between multiple stakeholders, including contractors, subcontractors, consultants, and government agencies (Alkilani & Loosemore, 2024).

The consequences of these delays are substantial, leading to cost overruns, project disputes, and sometimes even the failure of projects (Alkilani & Loosemore, 2024). As per Osei-Asibey et al. (2024), delays in large-scale construction projects not only inflate budgets but also erode stakeholder confidence and damage the reputation of the firms involved. In major infrastructure projects, where timelines are often linked to political or public commitments, delays can have even more profound effects, leading to public dissatisfaction and legal disputes (Florichel, Abdallah, Hudon, Petit, & Brunet, 2023; Musenero, Baroudi, & Gunawan, 2023).

Traditionally, delay analysis and mitigation strategies in construction projects have relied on several well-established methodologies, such as the Critical Path Method (CPM) and Earned Value Management (EVM) (Akram, Habib, & Deveci, 2023; Ekanayake et al., 2021; Khan, Ali, Garai-Fodor, & Csiszárík-Kocsir, 2023). These methods provide project managers with tools to assess which tasks are critical to the project's completion and how any delays in these tasks may impact the overall timeline. According to Hegazy, Saad, and Mostafa (2020), CPM remains one of the most commonly used techniques for understanding the sequential relationships between activities and identifying critical tasks that must be managed to avoid project delays.

As projects become more complex, these traditional methods have proven to be insufficient on their own for managing the dynamic nature of modern construction environments. Projects now require more proactive delay mitigation techniques that not only react to delays but also predict them before they occur (Grzeszczyk, Sainati, & Unterhitzberger, 2024; Gurgun, Koc, & Kunkcu, 2024). The concept of risk registers and contingency planning, as noted by Padil, Bakhary, Abdulkareem,

Li, and Hao (2020), has gained traction as part of a broader strategy to anticipate potential sources of delay and mitigate their impact. These methods rely on historical project data and expert judgment to estimate risk, but they still face limitations in handling real-time project data and rapidly changing site conditions.

In recent years, technological advancements have introduced new tools for delay management, particularly in the areas of real-time data analytics and Building Information Modelling (BIM) (Lauria & Azzalin, 2024; Radman, Jelodar, Lovreglio, Ghazizadeh, et al., 2022). These technologies have revolutionized how project delays are detected, managed, and mitigated. BIM, for instance, offers a highly visual and collaborative approach to project planning and execution, allowing for greater foresight in identifying potential delays arising from design or coordination issues (Bryde, Broquetas, & Volm, 2013). By creating digital models of construction projects, BIM integrates information from all project stakeholders, enabling more precise planning and reducing the risk of delays due to miscommunication or design flaws (Cannavacciuolo, Ferraro, Ponsiglione, Primario, & Quinto, 2023; Darko, Chan, Yang, & Tetteh, 2020).

Moreover, IoT applications and real-time data analytics have opened up new avenues for tracking project progress. As noted by Li et al. (2018), IoT-enabled sensors installed on construction sites and equipment provide continuous streams of data on project performance metrics, such as worker productivity, equipment usage, and material availability (Radman, Babaeian Jelodar, Ghazizadeh, & Wilkinson, 2021a; Radman, Jelodar, Lovreglio, Ghazizadeh, et al., 2022). This real-time data, when analysed through machine learning algorithms and advanced analytics platforms, offers project managers the ability to predict potential delays more accurately and take pre-emptive action before they escalate (Karamthulla, Muthusubramanian, Tadimarri, & Tillu, 2024).

The adoption of real-time data in construction project management has marked a paradigm shift in how delays are managed. Real-time data allows for immediate updates on site conditions,

project progress, and material logistics, providing a dynamic view of project status (Dardouri et al., 2023; Yang, Li, Yu, & Zhong, 2024). This immediacy in data availability has the potential to significantly reduce delays by enabling project managers to quickly identify and respond to any deviations from the project schedule. The integration of real-time data through platforms like Power BI, combined with IoT and API-driven data collection methods, allows for centralized data analysis and sharing among all stakeholders, facilitating quicker decision-making and accountability (Adeniran, Efunniyi, Osundare, & Abhulimen, 2024; Banerjee, 2022).

The implementation of real-time data analytics has also enabled the application of predictive models, which leverage historical data to forecast potential delays. By utilising AI and machine learning algorithms, construction projects can now predict delays based on factors such as weather patterns, equipment usage, and workforce productivity (Datta, Islam, Sobuz, Ahmed, & Kar, 2024; Gondia, Siam, El-Dakhakhni, & Nassar, 2020). This predictive capability provides project managers with valuable insights into potential risks before they materialize, allowing for more proactive delay management strategies. While the application of technology in delay management offers significant advantages, such as enhanced efficiency, accuracy, and predictive capabilities, it also comes with its own set of challenges. The upfront cost of implementing technologies like BIM, IoT, and AI can be prohibitive, particularly for smaller projects or firms with limited resources (Hall, Durdyev, Koc, Ekmekcioglu, & Tupenaite, 2023). Additionally, the complexity of these technologies necessitates specialized training for personnel, which can introduce a learning curve and further increase costs (Abdelalim, Essawy, Alnaser, Shibeika, & Sherif, 2024).

Another major challenge is data security (Ahmad, Rasool, Javed, Baker, & Jalil, 2021). As construction projects increasingly rely on cloud-based platforms for real-time data sharing and analysis, they become vulnerable to cyber-attacks or data breaches (Sharma & Barua, 2023). Protecting sensitive project data is paramount, and failure to do so can lead to significant financial and legal repercussions. Despite these challenges, the benefits of utilising advanced technologies in

managing construction delays cannot be understated. As construction projects grow in size and complexity, the ability to leverage real-time data, predictive analytics, and collaborative platforms will continue to be essential for ensuring projects are delivered on time and within budget (Rahaman, Rozony, Mazumder, & Haque, 2024; Zhu, Hwang, Ngo, & Tan, 2022).

In major construction projects, early-stage delay notifications play a critical role in identifying and addressing potential disruptions to the project timeline (Gwynne, Purser, Boswell, & Sekizawa, 2012; Tinaburri, 2022). These notifications are issued during the projects' phases to alert stakeholders about occurred or even potential delays that could impact the overall schedule and cost (Nikander, 2002; Ye et al., 2023). Timely recognition of these delays allows for more efficient mitigation strategies, thus minimizing the risk of prolonged disruptions. However, detecting and notifying delays at early stages is challenging due to the complexity of construction processes, the dynamic environment, and the involvement of multiple stakeholders (Alvand, Mirhosseini, Ehsanifar, Zeighami, & Mohammadi, 2023; Sharma & Barua, 2023).

To manage this complexity, several data analysis methods are commonly used to predict and analyse delays. The four popular data analysis techniques include windows analysis method, time impact analysis method, impacted as-planned analysis method and as planned vs. as-built analysis method. While these methods are widely adopted, they have limitations concerning real-time data integration. For instance, the windows analysis method involves assessing delays by periodically updating the project schedule at specific phases. It is often referred to as the "snapshot technique" or "contemporaneous period analysis", so the process is time-consuming and costly (Alkass, Mazerolle, & Harris, 1996; Gurgun et al., 2024). Time Impact Analysis (TIA) is a variation of the Windows Analysis method, focusing on the impact of individual delay events rather than broader project periods. However, TIA applies real-time Critical Path Method (CPM) analysis and can be used during or after project execution (Gutta, Bammidi, Batchu, & Kanchepu, 2024). Guida and Sacco (2019) stated the Impacted As-Planned method evaluates delays by adding them as activities to the

contractor's original CPM schedule. The delays are inserted in the order they occur to assess how they impact the overall timeline. They added the types of delays are not analysed in this method. Finally, the As Planned vs. As-Built method compares the original planned schedule to the actual as-built schedule, showing delays (including excusable, non-excusable, and concurrent delays) on the as-built schedule. The claimant seeks compensation for the difference between the planned and actual completion dates. Both schedules are used to identify the critical path and the overall delay impact (Guida & Sacco, 2019; Gutta et al., 2024).

Given the limitations of traditional analysis techniques, the *Time Impact Analysis (TIA)* method has been proposed by the Society of Construction Law (SCL) Protocol and endorsed in the AACE International's RP 29R-03 for addressing delay claims and forensic schedule analysis (Çevikbaş & Işık, 2021; Çevikbaş, Okudan, & Işık, 2022). TIA focuses on assessing the impact of changes or delays on the project schedule by inserting delays into the as-planned schedule and recalculating the completion date. This method is particularly effective in addressing real-time issues as it allows for periodic updates and the re-evaluation of potential delays as the project progresses, providing a dynamic and responsive approach to schedule management (Yousri, Sayed, Abdelalim, & Farag, 2024).

In terms of measuring the impact of identified delays at the early stages of a project, earned value metrics such as Schedule Performance Index (SPI) and Cost Performance Index (CPI) are valuable tools (Institute, 2021; Lipke, Zwikael, Henderson, & Anbari, 2009). SPI evaluates the efficiency of time usage relative to the planned schedule, while CPI assesses the cost efficiency of the project (Institute, 2021; Zohoori, Verbraeck, Bagherpour, & Khakdaman, 2019). Both metrics offer insights into how early-stage delays affect project time and cost forecasting (Institute, 2021; Zohoori et al., 2019). For instance, an SPI value below 1 indicates that the project is behind schedule, and this can be used in conjunction with TIA to assess the cumulative effect of delays on the project's expected completion date and budget. Similarly, a CPI value less than 1 signifies cost overruns, which

can be correlated with delays identified in the early stage to forecast their impact on the overall project cost. Furthermore, the five criteria of the RealCONs—Specific, Measurable, Achievable, Relevant, and Time-bound—can be aligned with the TIA method and early-stage delay notifications to enhance project management (Radman, Jelodar, Lovreglio, Ghazizadeh, et al., 2022).

Specific and Measurable aspects ensure that delay notifications are precise and quantifiable, which is essential for accurate impact analysis (PMI, 2018). Achievability ensures that the proposed mitigation strategies are feasible within the project constraints. Relevance ensures that notifications focus on critical aspects of the project, and the Time-bound criterion emphasizes the importance of timely communication (Radman, Babaeian Jelodar, Ghazizadeh, & Wilkinson, 2021b; Radman, Jelodar, Lovreglio, Ghazizadeh, et al., 2022). Incorporating these SMART criteria into TIA can improve the accuracy and timeliness of early-stage delay notifications, thereby reducing the overall impact on the project. By integrating TIA with earned value metrics and aligning with SMART criteria, project managers can gain a comprehensive understanding of how early-stage delays influence the broader project scope, enabling proactive decision-making and more accurate forecasting of project outcomes (Institute, 2021; Perera, Wijewickrama, Goonawardana, & Jayalath, 2021).

1.3 PROBLEM STATEMENT AND RESEARCH QUESTIONS

The increasing scale and complexity of construction projects pose significant challenges in identifying and mitigating delays, especially in their early stages (Kao, Chen, & Ho, 2023; Parsamehr et al., 2023). Delays often result from fragmented data, poor coordination among stakeholders, and reliance on traditional, manual tracking methods that lack real-time responsiveness (Ali, Aibinu, & Paton-Cole, 2024; Mukuka, Aigbavboa, & Thwala, 2015; Radman et al., 2021a; Radman, Jelodar, Lovreglio, Ghazizadeh, et al., 2022). While real-time data integration and IoT technologies offer

potential solutions, existing systems remain underdeveloped, with limited capability to centralise activity- and object-based data for proactive delay management (Abdelalim et al., 2024; Radman et al., 2021a).

This research identifies a need for enhanced Integrated Management Systems (IMS) to act as centralised hubs for tracking and monitoring in dynamic construction sites. These systems must be capable of acquiring both activity, and object-based data. While progress has been made, their full potential remains unrealised. This doctoral thesis addresses this gap by proposing RealCONs, a real-time, data-driven framework designed to improve delay management. Through integrated data acquisition, early notification systems, and predictive analytics, the study aims to enhance communication, minimise delays, and boost overall project performance by fostering real-time collaboration and decision-making. To effectively manage construction projects and mitigate delays especially notifying project key stakeholders at the early stage , six key research gaps must be addressed:

- 1) **Simple and inexpensive approach:** Affordable for projects and easy to learn and quick to use for all.
- 2) **Real time data acquisition and centralisation:** Ensuring all project data is captured timely and stored in a central, accessible location.
- 3) **Real-time Data Analytics:** Analysing project real time data as it's generated to identify potential issues and their analytical impacts on Project's KPIs.
- 4) **Early Notification Systems:** Alerting stakeholders to potential delays as soon as they are detected.
- 5) **Stakeholder Coordination:** Facilitating communication and collaboration among all project participants (head contractors, consultants, subcontractors).
- 6) **Predictive Delay Analytics:** Using real time and historical data to forecast potential future delays.



Without addressing these criteria, delays will continue to disrupt project timelines, leading to cost overruns as measured by EV metrics, such as Cost Performance Index (CPI) and Schedule Performance Index (Ando, Baglio, Castorina, Crispino, & Marletta, 2020). For example, the absence of real-time delay notifications can cause SPI to drop significantly, reflecting time inefficiencies, while poor coordination across data sources can increase actual costs (AC), leading to a lower CPI and overall project inefficiency (Amini et al., 2023; Hasan, Chowdhury, & Akter, 2021). Therefore, the integration of real-time data analysis, early delay notification, and centralised project management platforms is essential to improve the timeliness and cost-efficiency of major construction projects (Radman et al., 2021a).

Furthermore, to rely on a delay management system with reasonable reliability, scalability and timely through using combination of digital technologies, three research questions are therefore developed:

- 1) What causes delays in major construction projects and how they affect stakeholder collaboration?
- 2) How digital technologies being used to improve major construction projects key performance (e.g. delay, risk)?
- 3) How proposed framework to be designed and evaluated (focusing on performance and in-depth early delay detection and their impacts)?

1.4 RESEARCH OBJECTIVES

Based on the above problem statement this research the following objectives have been established. Five objectives (OBJ) belong to the research questions as follows:

Question 1:

OBJ_1: Identify and Analysis Key Stockholders

OBJ_2: Identify & Analysis Key Causes Delay

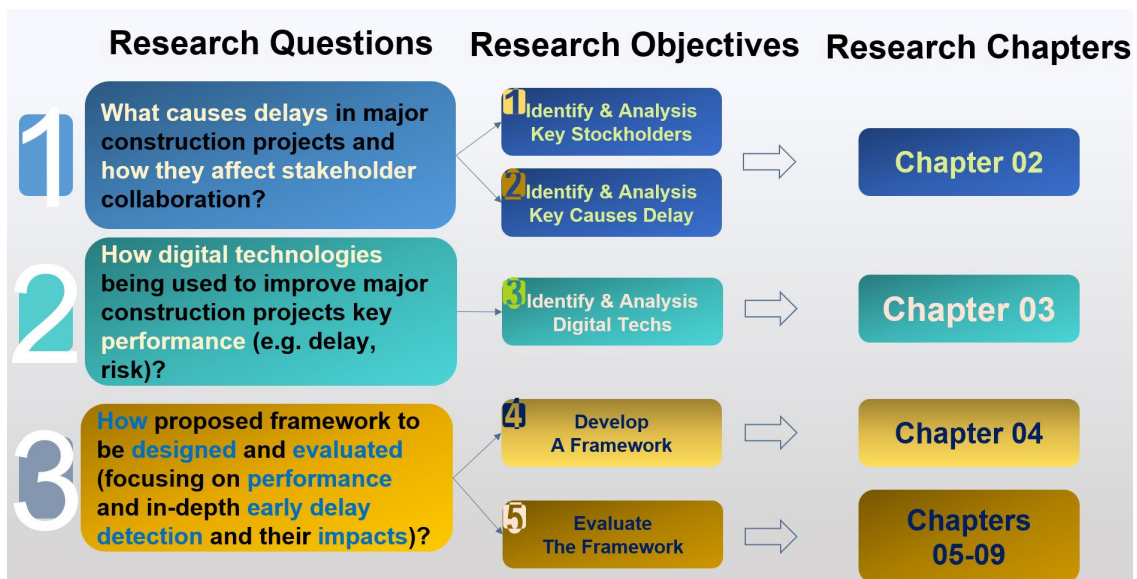
Question 2:

OBJ_3: Identify & Analysis Digital Technologies in construction projects

Question 3:

OBJ_4: Develop a Proposed Framework

OBJ_5: Evaluate the Proposed Framework



1.5 RESEARCH SCOPE

This research tackles the inefficiencies inherent in the delay notification and management processes of major construction projects. Current systems are often fragmented and reactive, presenting a significant challenge. To overcome these limitations, this study aims to enhance early-

stage delay notifications by developing a centralised framework for real-time detection and management. This framework will leverage technologies including IoT sensors, Building Information Modelling (BIM), and API integration. By centralising data acquisition and analysis, the research seeks to streamline communication and facilitate proactive decision-making, ultimately improving project outcomes.

The research seeks to replace traditional tools with a unified platform for tracking and analysing project data in real time. It will also evaluate the framework's impact on performance metrics such as the Schedule Performance Index (SPI) and Cost Performance Index (CPI). The ultimate aim is to enable more efficient and predictable project outcomes. By integrating automated tracking systems, real-time data acquisition, and centralised data analysis, this doctoral research aims to provide an innovative solution to the challenges of delay management in major construction projects through four core phases as follows:

- Phase 1 introduces the research and identifies the core problem by examining the limitations inherent in current construction project delay management systems (Ye et al., 2023). The focus is on understanding why traditional tools fail to provide real-time insights and early warnings (Fadhel et al., 2024; Parsamehr et al., 2023; Radman, Jelodar, Lovreglio, Ghazizadeh, et al., 2022).
- Phase 2 introduces examining technologies using in construction management (Data Acquisition and Analysis Modelling). This phase will investigate methods for collecting and centralising real-time data. It will explore technologies such as IoT devices, cloud platforms, and APIs to understand their potential for improving project tracking and communication (Khan et al., 2023).
- In phase 3 a framework called RealCONs designed and developed. Phase 3 focus here is on creating a centralised, real-time data-driven framework. This framework will integrate various technologies to deliver a unified platform (e.g. UML) for delay detection and management (Cing & Mansor, 2023; Gutta et al., 2024; Saravanan et al., 2022).

- Phase 4 focusing on implementing and verifying the framework. It will implement the framework in major construction projects as a case study to evaluate its effectiveness (Pieterse et al., 2024). It will assess how well it addresses communication challenges and its impact on project performance metrics such as SPI and CPI (Radman et al., 2021a).

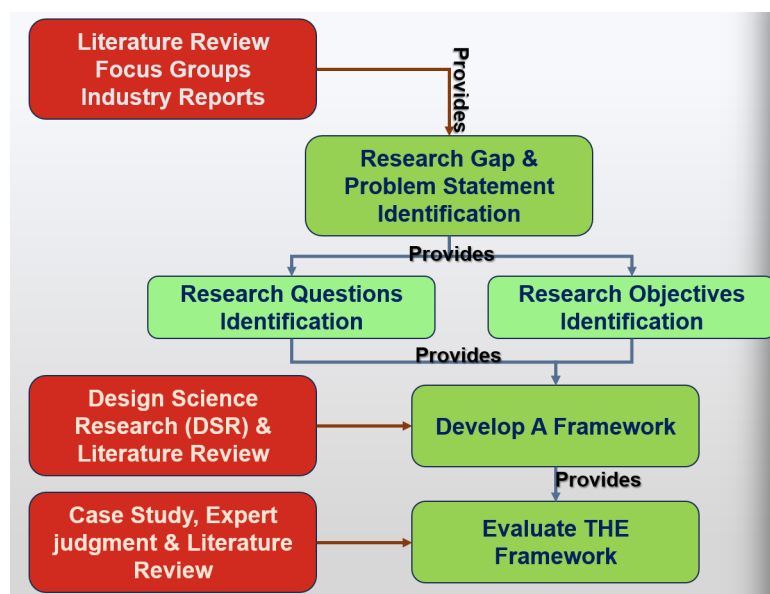
Finally, based on the findings, this phase will propose recommendations for enhancing real-time delay management systems. It will also identify areas for future technological advancements, including AI-based predictive delay analysis.

1.6 RESEARCH METHODOLOGY

The research methodology is a critical foundation for any academic study, as it shapes how data is collected, analysed, and interpreted, ensuring that findings are valid, reliable, and relevant to the research questions (Fellows & Liu, 2021; Saunders, Lewis, & Thornhill, 2016). A well-chosen methodology allows researchers to systematically investigate complex issues and provides a structured pathway for achieving research objectives. In the context of this thesis, the research methodology guides the multi-phase investigation, supporting the development of a comprehensive understanding of project delay impacts within construction.

Equally important is the research philosophy, which underpins the methodological approach by establishing the assumptions and principles that guide the study's interpretation of knowledge (Mbanaso, Abrahams, & Okafor, 2023; Saunders et al., 2016). Considering research philosophy is essential, as it defines the perspective through which data is perceived and shapes the entire research process—from data collection to analysis and conclusions (Al-Ababneh, 2020). For this doctoral thesis, a thorough understanding of research philosophy ensures alignment between theoretical concepts and practical methods, enabling a well-grounded approach to delay analysis.

For this purpose, this section provides a detailed outline of the research methodology and philosophy, divided into the following parts: 1) **Research Philosophy - Overview**: An exploration of various research philosophies, including positivism, interpretivism, and pragmatism, to establish a theoretical foundation for methodological choices; 2) **Research Philosophy - This Doctoral Thesis**: A discussion of the specific research philosophy guiding this thesis, explaining how it aligns with the study's goals and why it is best suited for analysing delay impacts in construction projects; 3) **Research Conceptual Framework**: A comprehensive description of the thesis phases, detailing how each objective is addressed through multiple stages of research. This section explains the interconnectivity of the phases and how each phase builds on previous findings to achieve the overall research objectives; 4) **Adopted Method for Research**: A breakdown of each phase, outlining the methodologies and techniques employed in each stage. This includes qualitative and quantitative methods, mixed methods approach, and data triangulation techniques; 5) **Ethics** and 6) **Data Collection**: A detailed explanation of the data collection process in each phase, addressing ethical considerations and describing the outcomes. This section covers the sources of data, participant selection, data validation, and any limitations encountered. As shown below, the research approach outlines how the research objectives have been targeted and addressed:



1.6.1 Research philosophy - Overview

Research philosophy addresses fundamental principles that guide a study's approach to understanding knowledge (epistemology) and the nature of reality (ontology). Ontology considers what constitutes reality and whether it is objective and independent or socially constructed and subjective. Epistemology concerns what we accept as valid knowledge, determining if knowledge should be gathered objectively (as in natural sciences) or through subjective interpretation (as in social sciences). These distinctions shape research approaches, methods, and data interpretation (Al-Ababneh, 2020; Mbanaso et al., 2023).

Key philosophies include positivism, which assumes an objective reality that can be scientifically measured; interpretivism, which sees reality as socially constructed and thus understood through qualitative, interpretive means; realism, which acknowledges an independent reality but considers that it is imperfectly known; and pragmatism, which uses methods best suited to address the research question, regardless of epistemological stance (Fellows & Liu, 2021). The research onion model is a widely used framework that guides researchers in creating a structured and comprehensive research design. This model proposed by Saunders et al. (2016) to visualises research methodology as layered stages, resembling the layers of an onion. Each layer represents a key component in the research process, helping researchers make sequential decisions on aspects such as philosophical stances, research approaches, research strategies, methodological choices, time horizons, and data collection techniques (Figure 1.1). By moving through each layer systematically, researchers can build a coherent and well-aligned research design (Fellows & Liu, 2021):

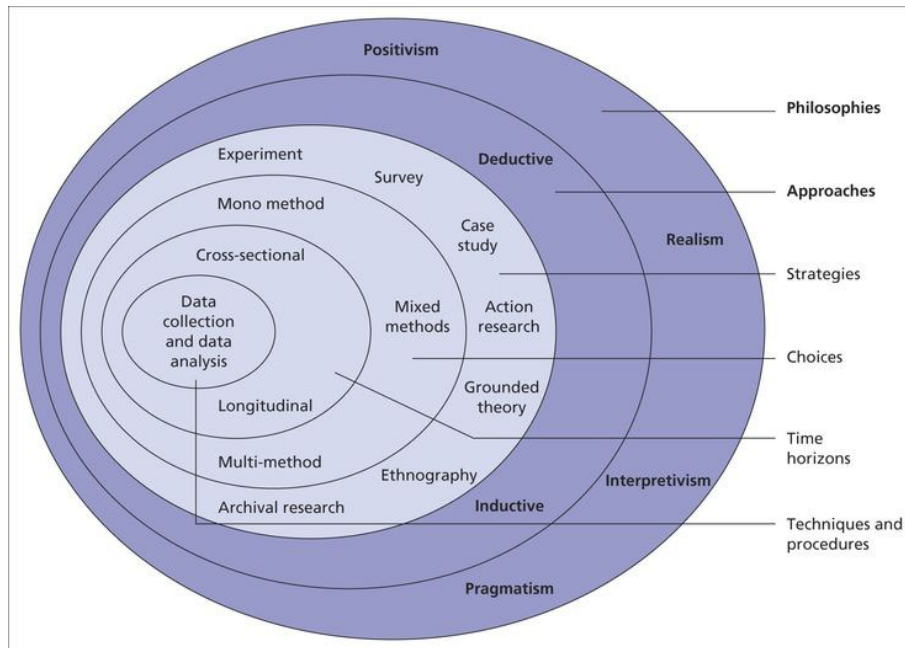


Figure 1.1: Research onion model (Fellows & Liu, 2021)

- **Layer 1 - Philosophies:** The outermost layer represents the research philosophy (positivism, interpretivism, realism, pragmatism), which underpins the researcher’s worldview and informs the entire approach to data and methods.
- **Layer 2 - Approaches:** The second layer denotes research approaches (deductive and inductive). A deductive approach tests existing theories, while an inductive approach develops new theories based on data.
- **Layer 3 - Strategies:** This layer involves choosing a research strategy, such as experiments, surveys, case studies, or ethnography, depending on the nature of the inquiry.
- **Layer 4 - Choices:** It addresses methodological choices, like mono-method, mixed-method, or multi-method approaches, indicating whether the study will utilise one method or combine multiple.
- **Layer 5 - Time Horizons:** Researchers select between cross-sectional (single point in time) or longitudinal (multiple time points) studies based on the research aim.
- **Layer 6 - Techniques and Procedures:** The innermost layer involves the specific techniques for data collection and analysis, like interviews, observations, or statistical analysis.

The Research Onion model thus offers a clear, layered framework that can be customized according to a study's specific goals, ensuring methodological coherence (Fellows & Liu, 2021; Saunders et al., 2016).

1.6.2 Research philosophy - This doctoral thesis

The RealCONs framework, developed for real-time, data-driven project analysis with a focus on early-stage delay notifications, operates within distinct ontological and epistemological foundations that inform its structure and methods. This framework can be aligned effectively with the structured methodology of Saunders' Research Onion, which outlines research design in layers from philosophy to techniques. Analysing RealCONs within this framework not only provides clarity but also emphasizes the systematic application of ontological and epistemological principles in achieving reliable, actionable insights for project management. This approach supports RealCONs' goal of minimising delays through timely, data-informed decision-making. In this section, we discuss the ontological and epistemological underpinnings of this doctoral research alongside Saunders' onion research model as follow:

1.6.2.1 Ontology: The Nature of Reality in RealCONs' Framework

Ontology in research explores the nature of reality and seeks to define what constitutes "truth" or "existence" in a given field. RealCONs' framework assumes a *realist ontology*, operating on the premise that delays, risks, and performance metrics within a project have an objective reality that can be observed, quantified, and influenced. RealCONs' structure, with its focus on tracking and analysing data in real time, reflects an underlying belief that project conditions, risks, and outcomes are measurable and exist independently of the observer.

However, while adopting this realist stance, RealCONs' also acknowledges that the interpretation of project data may involve subjective perspectives, particularly in assessing the potential impacts of delays. Therefore, the framework incorporates a pragmatic approach, recognising the need for both objective data and the subjective judgments of project managers. This pragmatism aligns well with Saunders' Research Onion by situating RealCONs' within a structured process that moves from objective analysis (positivism) to interpretative understanding (interpretivism) as needed for comprehensive insights.

1.6.2.2 Epistemology: What counts as knowledge in RealCONs' framework

Epistemology, or the study of knowledge, shapes the RealCONs' framework by defining what is considered valid knowledge and how it can be acquired. In RealCONs', knowledge about project delays is seen as valid when it is based on empirical, real-time data from multiple sources (e.g., workforce logs, material shipments, and machinery availability). Moreover, RealCONs employs a data-driven, empirical approach that aligns with the positivist philosophy within Saunders' Research Onion, which emphasises observable, measurable, and repeatable evidence.

By capturing and analysing data continuously, RealCONs' aims to provide an objective foundation for predicting and mitigating project delays. The framework's reliance on quantifiable metrics, statistical analysis, and real-time monitoring reflects a commitment to knowledge that is testable and verifiable. In practice, this epistemological approach empowers decision-makers with timely information and allows for an evidence-based understanding of project dynamics. However, RealCONs' does not disregard interpretive knowledge. While objective data is foundational, the interpretation of delays and risks requires subjective expertise, particularly when projecting future scenarios or estimating impact severity. This interpretative element in RealCONs' epistemology

acknowledges that, in complex, fast-paced projects, human insight complements quantitative data for holistic analysis.

1.6.2.3 Aligning RealCONs' Framework with Saunders' Research Onion

Saunders' Research Onion provides a structured approach to research design that parallels the systematic structure of RealCONs' data-driven framework. Each layer of the Onion can be mapped onto RealCONs' methodological components, guiding the framework from its philosophical foundations to its data collection and analysis techniques:

➤ **Layer 1- Philosophical Stance (Outer Layer):**

Given RealCONs' emphasis on real-time data and predictive analysis for early-stage delay notification, a pragmatist philosophy offers an appropriate guiding framework. Pragmatism supports the integration of quantitative and qualitative methods by prioritising solutions that are both practical and effective in addressing real-world challenges. From a quantitative perspective, pragmatism allows for the use of positivist approaches to analyse objective data, such as project schedules, performance metrics, and predictive models. These methods are essential for providing measurable and reliable insights into delays and their potential impacts. Simultaneously, pragmatism accommodates interpretivist elements by recognising the importance of understanding project dynamics, stakeholder interactions, and the contextual nuances that influence decision-making. Qualitative methods, such as interviews or case studies, can provide valuable insights into how stakeholders perceive delays and respond to management strategies.

By balancing these theoretical perspectives, pragmatism bridges the gap between theory and practice. It ensures that the research is not only grounded in robust analytical frameworks but also remains applicable and responsive to the practical demands of construction projects. This dual

approach aligns with RealCONs' goal of enhancing delay management by combining data-driven precision with a nuanced understanding of the complex, dynamic nature of project environments.

➤ **Layer 2- Approaches (Deductive vs. Inductive):**

RealCONs' employs a primarily deductive approach, aligning with Saunders' framework by testing existing project real time tracking approaches about project delays based on historical data patterns. However, as the research progressed, the approach shifted towards inductive reasoning in order to RealCONs' continually updates its model with new data, adapting to emerging trends and potential project-specific risks.

➤ **Layer 3- Strategies (Real-Time Monitoring):**

In Saunders' Research Onion model, selecting a research strategy involves determining the appropriate use of qualitative and quantitative methods. RealCONs' emphasis on real-time, data-driven analysis leans primarily towards quantitative methods, utilizing statistical models and predictive analytics, with qualitative methods introduced as needed for subjective assessment, such as expert judgment on potential impacts. Consequently, the research approach in Layer 2 shifted from a deductive to an inductive reasoning framework.

To generate new insights and develop the RealCONs framework as a proposed solution, the research employed “case study” and focus group strategies, using “surveys” in facilitated workshops. These strategies were chosen because RealCONs has been tested on specific projects or under defined project conditions. This approach allowed for detailed, context-rich analysis, enabling an assessment of RealCONs' performance, particularly its accuracy and flexibility. Additionally, the “Action Research” strategy was well-suited to the RealCONs framework's implementation. As the framework was applied in live projects, Action Research allowed for continual improvement and adaptation while enabling researchers to actively engage in and observe real-time decision-making processes.

➤ **Layer 4- Choices (Mixed-Method):**

RealCONs employs a mixed-methods approach, integrating quantitative data analytics with qualitative insights from multiple project data sources. The framework gathers data from the following resources:

1. **Site_Work**: Real-time and actual site data collected via smartphone and QR codes.
2. **Consultant Team**: Design and engineering input using BIM tools like Revit and Navisworks.
3. **Oracle_P6**: Planning data from the project team using Primavera P6.
4. **Oracle_Aconex**: Document management organized by the head contractor.
5. **Power BI**: Analytical platform consolidating data from all sources.

This mixed approach enables RealCONs to capture objective metrics, such as Schedule Performance Index (SPI) and Cost Performance Index (CPI), while incorporating stakeholder feedback, crucial for understanding and predicting delay impacts from various perspectives. The use of both quantitative data and qualitative insights (e.g., stakeholder perceptions) offers a comprehensive and context-sensitive view of project delays. This aligns with Saunders' Research Onion model, which supports a blended methodology to achieve a more nuanced analysis of complex project delays.

➤ **Layer 5- Time Horizons (Longitudinal):**

Based on Saunders' research onion model, while a cross-sectional approach looks suitable for this doctoral proposed framework, but it would not provide the depth required to assess trends, iterative improvements, or long-term impacts, which are central to the research objectives. Therefore, the longitudinal time horizon is more suitable for the RealCONs framework and the thesis objectives. As a result, the research aims to analyse changes and trends over time, particularly in how delays emerge and impact relationships between construction parties (Objective 1) and how technologies evolve to address these issues (Objectives 3, 4, and 5). A longitudinal approach is also necessary to evaluate the development and performance of the RealCONs framework (Objectives 6, 7, and 8), as this

involves testing its effectiveness and comparing it to existing approaches across different project stages. Furthermore, the focus on cause-and-effect relationships, such as understanding the impact of real-time technologies on delay management (Objectives 2 and 4), aligns with the strengths of a longitudinal study.

1. **Real-Time Tracking and Continuous Data Collection:** The RealCONs framework emphasises real-time data collection, analysis, and adjustment over the life of a project. A longitudinal approach allows for continuous monitoring and assessment of project conditions, performance metrics (e.g., SPI and CPI), and delay impacts over time, which aligns with RealCONs' real-time, adaptive goals.
2. **Monitoring Changes and Trends:** Longitudinal studies are designed to capture changes over time, making them ideal for tracking how different factors—such as stakeholder actions, site conditions, or design updates—affect project delays and outcomes. This provides a deeper understanding of patterns, trends, and potential interventions.
3. **Improved Predictive Insights:** By capturing data at multiple points, a longitudinal study supports the predictive capabilities of RealCONs, which relies on trends and historical performance to anticipate future delays and impacts.
4. **Stakeholder Engagement Over Time:** RealCONs also integrates feedback from multiple stakeholders. A longitudinal study enables ongoing input, helping to capture evolving perspectives and responses to project changes, thereby enhancing the accuracy and flexibility of delay management.

This time horizon allows for a more comprehensive exploration of how the framework performs over time and under varying conditions, ensuring the findings are robust and reflective of real-world case studies.

➤ **Layer 6- Techniques and Procedures (Data Collection and Analysis):**

The innermost layer of Saunders' Onion focuses on specific techniques, where RealCONs utilises real-time data feeds, predictive analytics, and advanced data visualisation. These procedures enable efficient data processing and presentation, allowing project managers to respond promptly to early-stage delay indicators. Therefore, RealCONs needed a multi-faceted data centralisation approach, including:

- Quantitative data from site, consultant, contractors and project management software (MS Project, Primavera) for tracking SPI, CPI, and real-time project metrics.
- Qualitative data from interviews or surveys with project stakeholders (contractors, subcontractors) to assess the framework's usability and relevance in providing timely delay notifications.

In contrast, analysis techniques could include statistical analysis such as T-test, P-value and RII (for assessing performance indicators), thematic analysis using AHP (for understanding qualitative feedback on framework usability), and earned value metrics for project performance analysis for delay prediction.

1.6.2.4 Implications of Ontological and Epistemological Foundations for RealCONs

By grounding RealCONs in a realist ontology and positivist epistemology, the framework is well-positioned to deliver objective, actionable insights on project performance. This alignment with Saunders' Research Onion reinforces RealCONs' structured methodology, enhancing its effectiveness in delay detection and response. The framework's reliance on objective data and systematic monitoring reduces ambiguity, while its interpretative aspects allow managers to apply contextual knowledge to complex, evolving project conditions. The layered structure of Saunders' Research Onion offers a useful lens for understanding RealCONs' development and operational logic, from foundational philosophy to specific data techniques. Through this alignment, RealCONs

achieves a balanced approach, leveraging real-time data within a robust methodological structure, ultimately contributing to more proactive project management and delay mitigation. Figure 1.2 illustrates given choice(s) in each layer tagged as follows:

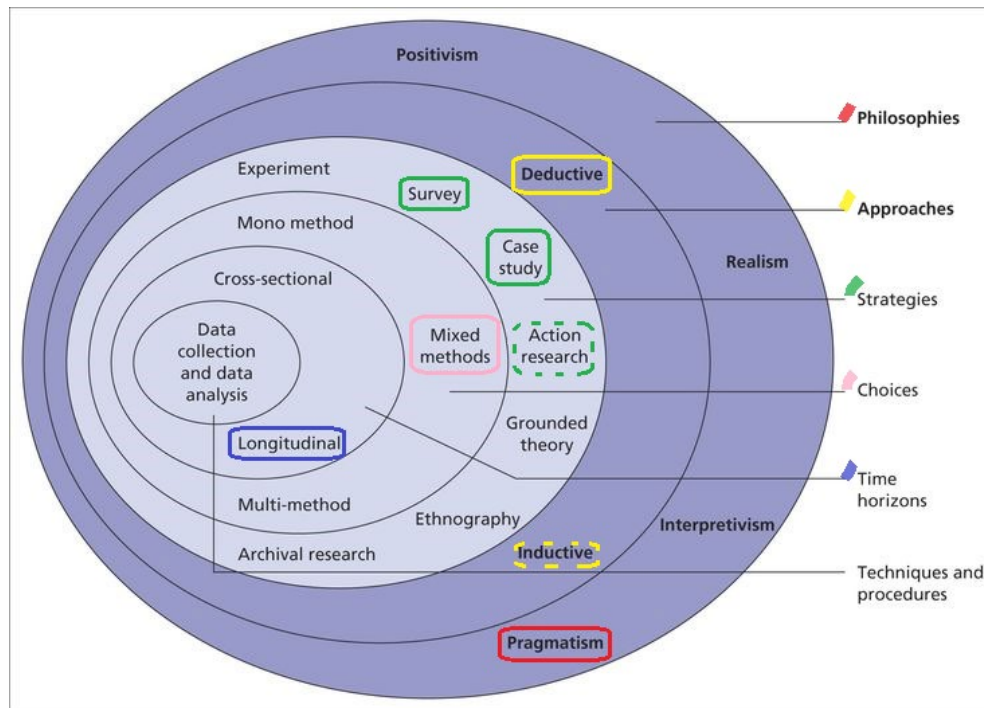


Figure 1.2: This doctoral thesis onion research model

1.6.3 Research conceptual framework

This doctoral thesis is organised around a series of submitted or accepted journal articles and conference papers; each aligned with the research objectives detailed in Section 1.4. While each article provides a methodology specific to its focus, this section presents a brief overview of the overarching research methodology to maintain clarity and coherence across the study. The research addresses the eight (8) objectives through a mixed-method approach, integrating qualitative and quantitative methods to facilitate comprehensive analysis and validation (Kaplan & Duchon, 1988; Mertens, 2023; Venkatesh, Brown, & Bala, 2013). The research process, illustrated in Figure 1.1, progresses through four key phases that structure the thesis objectives and their interrelationships: (1)

identifying research gaps, informing the "Introduction and Problem Identification"; (2) classifying gaps to guide "Data Acquisition and Analysis Solutions" (see Appendix 2); (3) designing and developing the framework; and (4) implementing and verifying the proposed framework through case studies. Each stage builds on the previous, establishing a strong foundation for subsequent phases of research. Figure 1.3 also presents a conceptual framework as “thesis mixed-method onion model process” in alignment with the study’s two primary research questions.

From an overview perspective, Figure 1.3 illustrates a clear progression of objectives from the identification and classification of gaps in delay management (Research Question 1) to the design, implementation, and verification of a framework aimed at improving delay notification (Research Question 2). OB6 acts as the bridging point between the two research questions, linking the framework's design to the findings from the gap analysis. Objective 7 encompasses four distinct evaluation perspectives (OB7_1, OB7_2, OB7_3, OB7_4,) while each contributing to the overall achievement of Objective 7’s goals.

OB8 represents the final objective, culminating in the complete verification of the framework with a focus on early delay notification. The flow from OB1 to OB8 demonstrates a logical and systematic progression, ensuring that the research comprehensively addresses both delay management and early-stage delay notifications. Ultimately, this process aims to develop and validate a robust delay management system that identifies key gaps and provides timely notification of potential project delays, effectively answering both research questions. Therefore, in section 1.6.4 the research will be carried out using four specific methodologies. Section 1.6.6 (data collection) includes translation of Figure 1.3.

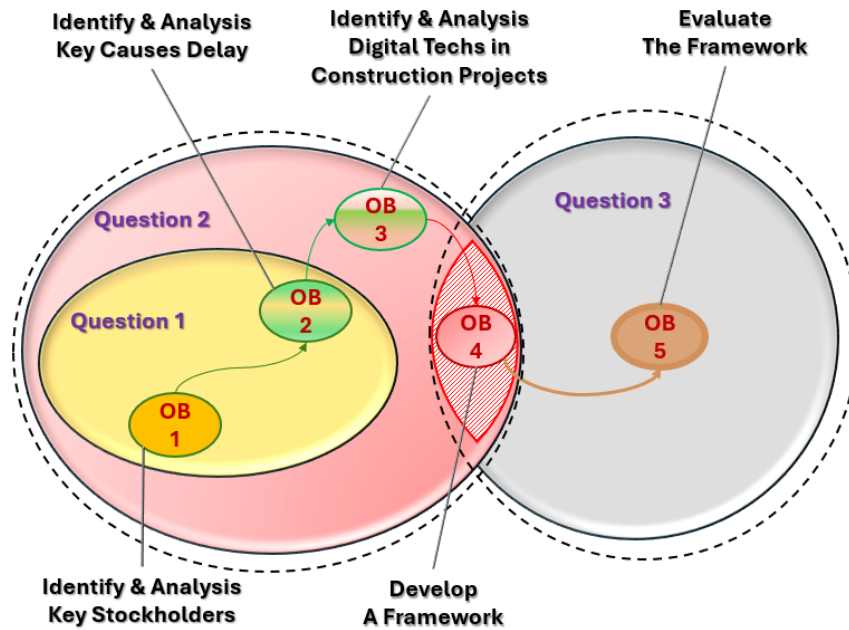


Figure 1.3: Thesis Mixed-Method Onion Model

1.6.4 Adopted methods for the research

The research conceptual process comprising four key phases, forms the foundation for the structure of the nine (9) core chapters in this PhD thesis. As illustrated in Figure 1.3, those four (4) phases demonstrate the theoretical links between the research objectives and the two main questions under investigation, offering a comprehensive overview of the study. This research conceptual framework enhances the understanding of each research phases as a mixed-method onion model process. Figure 1.4 provides a detailed overview, organised as follows: from left to right, it outlines the objectives and indicates the corresponding chapters in which they are discussed. Conversely, from right to left, it illustrates the thesis phases, showing the adopted methodologies and the respective chapters in which each methodology is presented. For further clarity, the methodologies employed are categorized into four distinct types (1) Literature Review, (2) Mixed-methods (Focus Groups: qualitative and Quantitative analysis), (3) Design Science Research (DSR) to design and develop the Framework, and (4) Case Studies to implement and verify the RealCONs framework.

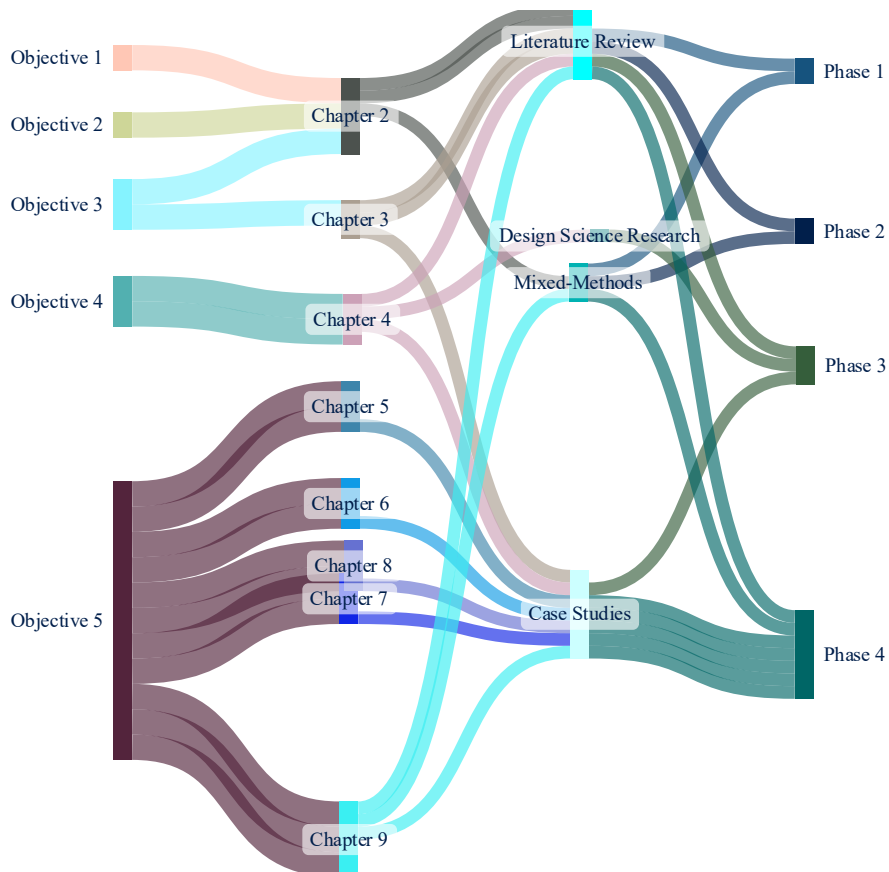


Figure 1.4: Overview of Objectives, Chapters, Phases, and Methodologies Relationships

1.6.4.1 Adopted methodology: Literature review

A comprehensive review of literature from journals, conference proceedings, and government reports was conducted to identify various digital technologies and data-driven delay management processes in construction projects (Lauria & Azzalin, 2024; Radman, Jelodar, Lovreglio, Ghazizadeh, et al., 2022). The review primarily focused on quantitative analysis of articles related to real-time site tracking frameworks and delay management systems in dynamic construction environments, highlighting trends, timelines, and key topics (Rao et al., 2022). The literature review classifies existing research on digital technologies and evolutionary trends within large-scale construction projects. It provides an overview of the status and variety of frameworks used for real-time resource monitoring, material tracking, and project progress (Ekanayake et al., 2021). Additionally, it outlines

future directions in these areas. This methodology offers a detailed examination of digital applications in construction projects, based on high-impact studies from the past decade. The review also presents a critical evaluation of digital technologies used in major construction projects for project management purposes (Popoola, Adama, Okeke, & Akinoso, 2024). It provides an overview of key technologies and their alignment with five key criteria—accuracy (Do, Nguyen, Tran, & Aung, 2023; Nafe Assafi, Hoque, & Hossain, 2024; Parsamehr et al., 2023), real-time data integration (Cing & Mansor, 2023; Karamthulla et al., 2024; Radman, Jelodar, Lovreglio, Wilkinson, & Ghazizadeh, 2022), flexibility (Arantes & Ferreira, 2024; Arefazar, Nazari, Hafezi, & Maghool, 2022; Lalmi, Fernandes, & Souad, 2021), predictive analysis (Gondia et al., 2020; Yousri et al., 2024), and stakeholder communication (Waris, Khan, Abideen, Sorooshian, & Ullah, 2022; Zwikael, Salmona, Meredith, & Zarghami, 2023)—within the context of real-time construction management and their adaptation to various project processes.

While the literature review is essential to this doctoral thesis, this section specifically addresses Objectives 1 and 8 through content and comparative analysis, with Objectives 3 and 5 investigated further through a systematic literature review. Therefore Phase 1 of research covers those and develops a comprehensive, categorised list of both stand-alone and integrated digital technologies in construction project management. The findings provide a conceptual review of general delay causes and their impact on relationships among construction parties throughout the pre-construction, construction, and post-construction phases. This analysis also examines the correlation between delay causes and effects, serving as a foundation for Phase 2 of the research. Chapters 2, 3, and 9 present Phase 1 of research in detail.

1.6.4.2 Adopted methodology: Mixed-methods (focus groups- facilitated workshops)

In phase 2 of this research, it utilised mixed methods such as focus group and facilitated workshops (to collect construction experts feedback) in two key stages: first, for data collection and ranking the root causes of delays and identifying the responsible parties; and second, for the verification of the proposed real-time delay management framework. **Step 1: Data Collection and Root Cause Analysis:** in the first stage, facilitated workshops were used to gather data on the causes of delays and to rank their significance. A total of 27 construction companies, primarily involved in major projects within the Auckland and Waikato regions, were invited to participate. This region was selected due to logistical advantages such as location accessibility. Three workshops were organized, with participation from key stakeholders, including project managers, project engineers (from both design and construction teams), and contract managers. These workshops provided a collaborative platform for discussing and identifying significant causes of delays in construction projects. The facilitated workshops successfully highlighted the most critical delay factors, while also allowing for the refinement of initial findings. Certain causes and details were added based on expert input, while others were excluded as less relevant. To analyse these causes, the Relative Importance Index (RII) and correlation coefficient were employed, ensuring a quantitative assessment of the significance and impact of various delay causes (Wood 2017; Abdollah and Taghipour 2019; Anumba et al. 2020; Su et al. 2020; Gebrehiwet and Hanbin 2017). As an additional audit process, the findings from these workshops were reviewed by the engineering team and construction supervisors, ensuring that the results accurately reflected real-world conditions in smart construction projects.

Step 2: Framework Verification and Delay Analysis: in the second stage, facilitated workshops played a crucial role in verifying the real-time delay management framework designed in this research. A group of 45 participants was invited, comprising 15 individuals from each stakeholder group: head contractors, subcontractors, and consultants (engineers). These workshops focused on

evaluating four key delay analysis methods based on five predefined criteria, with the goal of selecting the most suitable method for integration with a dynamic, real-time framework. To prioritize the results and ensure a structured decision-making process, the Analytical Hierarchy Process (Darko et al., 2019) was used. AHP enabled a systematic comparison of the different delay analysis methods, helping to quantify the advantages and limitations of each (R. W. Saaty, 1987; T. L. Saaty, 1994). This prioritization process ensured that the chosen delay analysis method was both analytically sound and aligned with the research objectives. The final outcome was the selection of a single delay analysis method that met the key criteria identified during the workshops, facilitating a more efficient and real-time approach to delay management in construction projects.

The facilitated workshops offered critical insights for both identifying delay causes and validating the delay management framework. Through a structured combination of expert input, data collection, and quantitative methods such as AHP, the research achieved a comprehensive, practical solution for managing delays in large construction projects.

To address Objective 2, the Relative Importance Index (RII) technique was used to analyse correlations between delay causes and their effects. RII provided a systematic approach to quantifying the importance of various delay factors, allowing for a structured evaluation of how these factors contribute to project delays and highlighting key cause-effect relationships, which are discussed further in Chapter 2. These findings also supported Objective 7, assessing the RealCONs framework's performance through facilitated workshops, leveraging expert feedback in focus groups (Powell & Single, 1996) to engage construction project experts in a structured, interactive setting (Henriques & O'Neill, 2023).

In Chapters 4 and 9, the research further details the validation of RealCONs through AHP and earned value (EV) metrics, demonstrating the framework's effectiveness by applying quantitative

metrics such as Schedule Performance Index (SPI) and Cost Performance Index (CPI) on Time Impact Analysis (TIA).

1.6.4.3 Adopted methodology: Design Science Research (DSR)

A primary goal of this doctoral research is to design and validate a novel framework called RealCONs, using a methodology that systematically structures, conceptualises, and develops the framework. RealCONs aims to support real-time data analysis, predictive capabilities, and early-stage delay notifications to enhance decision-making. Design Science Research (DSR) is a particularly suitable methodology for this framework design as it emphasizes building and evaluating artifacts, such as frameworks, models, or systems, to solve targeted problems (Venable, Pries-Heje, & Baskerville, 2012; Vom Brocke, Hevner, & Maedche, 2020). The DSR process involves identifying the problem, defining objectives, designing the artifact, and refining it through iterative testing.

Why DSR? DSR is more aligned with RealCONs than other methodologies, like Conceptual Modelling, as it is specifically designed to support the development, testing, and refinement of frameworks, models, and artifacts in a structured, solution-focused way (Pries-Heje, Baskerville, & Venable, 2008; Vom Brocke et al., 2020):

- 1- **Problem-Solving Focus:** DSR is oriented toward solving real-world problems by creating practical solutions, such as frameworks or tools. Since RealCONs is designed to address construction project delays through a systematic, real-time management approach, DSR provides the right structure to build a framework that can be applied in practice. The DSR methodology allows RealCONs to be tailored to the complexities and challenges unique to construction delay management, ensuring that it addresses specific project needs effectively.

- 2- **Iterative Design and Evaluation Cycles:** DSR follows iterative cycles of design, testing, and refinement. For RealCONs, this means the framework can be continuously improved based on performance data, feedback from stakeholders, and real-world project outcomes. This cyclical approach ensures that RealCONs evolves to be more accurate and user-friendly, while also validating its reliability and effectiveness in managing delays through real-time data.
- 3- **Integration of Multiple Data Sources and Technologies:** RealCONs relies on integrating various data sources (e.g., Oracle_P6, BIM, Power BI) and using predictive metrics (e.g., SPI, CPI). DSR supports this by providing a structured methodology for designing artifacts that leverage complex data integration, aligning with RealCONs' needs for multi-source data handling and predictive modeling. DSR's structure helps ensure that RealCONs is both technically robust and capable of integrating with various tools used in construction project management.
- 4- **Alignment with Practical and Theoretical Rigor:** DSR places equal importance on theoretical rigor and practical applicability. RealCONs aims to be a theoretically sound framework but also highly practical for use in live construction projects. DSR emphasizes building frameworks that not only meet practical demands but are also grounded in scientific and theoretical principles, aligning well with RealCONs' objective of a structured, scientifically backed, and practically useful tool for real-time delay management.
- 5- **Focus on Usable Artifacts in a Real-World Context:** DSR is centered on creating “artifacts” (like frameworks or tools) that have direct utility in real-world contexts. RealCONs is designed for practical application in construction projects, making DSR ideal because it ensures the framework is built with usability and real-world constraints in mind. DSR's focus on usability means that RealCONs can be rigorously designed to

function effectively within the project management processes and constraints typical in construction.

In contrast, While Conceptual Modeling can be a useful tool within the framework design process (helping visualise RealCONs' structure and components), it lacks the iterative, problem-solving structure that DSR provides. Conceptual Modeling focuses more on defining relationships and structures without the rigorous testing and refinement process essential to DSR. It's better suited as a preliminary phase to visually map out RealCONs' design, but it doesn't offer the comprehensive development and validation framework that DSR does.

The design and development of the real-time delay management framework in this research were based on integrating key concepts from the proposed framework called RealCONs. These frameworks provided the foundation for building a system that addresses early-stage delay notification (Ye et al., 2023), focusing on improving construction project performance through real-time data integration and analysis (Gutta et al., 2024). RealCONs framework with feature of SMART (Specific, Measurable, Achievable, Real-time, and Timely) was designed to enhance decision-making and delay risk management in construction projects by utilising real-time data. The general structure of this framework revolved around three core components: 1) **Real-time data acquisition**: Collecting data from various project sources such as IoT devices, sensors, QR codes, and mobile applications; 2) **Centralised data analysis**: Integrating this data into a centralised platform (e.g., Power BI) where all stakeholders can access and visualise the project's current status; and 3) **Proactive notification system**: Using algorithms and predictive analytics to monitor project performance and send early notifications of potential delays. This structure allowed for real-time tracking and dynamic responses to potential delay risks, ensuring that project managers could act quickly to address delays.

However, the framework's ability to provide early-stage delay notification was one of its most critical functions. By continuously monitoring real-time data from different stakeholders—such as

head contractors, consultants, and subcontractors—the system could identify deviations from the planned schedule early. When a potential delay was detected, an immediate notification was sent to the project manager, along with an analysis of the cause of the delay (e.g., material shortages, labour issues, or design errors) and which party was responsible. This early warning mechanism allowed the project team to take corrective action before the delay escalates, minimising the risk of time overruns. The benefits of this approach were significant in terms of both cost and time savings. Early notification allowed for timely interventions, reducing the likelihood of extended delays that could lead to cost overruns. Moreover, the real-time nature of the system ensures that project managers had up-to-date information, leading to faster decision-making and more efficient resource allocation.

Additionally, regarding matching the 5 criteria (Arantes & Ferreira, 2024; Cing & Mansor, 2023; Do et al., 2023; Yousri et al., 2024; Zwikael et al., 2023), the framework was designed to meet the following five key criteria essential for effective delay management as below:

- **Data Centralisation:** All data from different sources—head contractors (e.g., Aconex), consultants (BIM), and subcontractors—are centralized into one platform for streamlined analysis.
- **Real-time Data Analytics:** The use of real-time data acquisition methods, such as IoT sensors and mobile applications, allows the system to continuously monitor project performance.
- **Early Notification System:** Automated alerts are generated when potential delays are detected, enabling proactive management before delays escalate.
- **Stakeholder Coordination:** The framework enhances communication between project stakeholders by providing a shared platform where all parties can access the same data, improving collaboration.
- **Predictive Delay Analysis:** By utilizing data-driven analytics, the framework predicts future delays, allowing for pre-emptive action and ensuring that the project stays on track.

In conclusion, the framework designed in this research offers a comprehensive solution for early-stage delay notification in construction projects. By integrating real-time data collection and analysis into a centralised platform, it provided project managers with the tools needed to improve time and cost efficiency, while meeting the key criteria necessary for effective delay management.

Objective 6, central to this thesis, is comprehensively addressed in Chapter 4, where a novel, process-based, real-time data-driven construction project analysis framework is introduced, with a particular focus on early-stage delay notification.

1.6.4.4 Adopted methodology: Case Studies

According to Saunders' research onion model, various strategies can be considered for this doctoral research, including Case Study and Grounded Theory methodologies (Fellows & Liu, 2021). However, for the proposed RealCONs framework, Case Study methodology is much more suitable than Grounded Theory. The following points outline the reasons supporting this choice (Saunders et al., 2016):

- 1- Purpose and Application of RealCONs:** RealCONs is designed to be a practical, real-time framework for construction delay management, integrating data sources to aid in decision-making. Case studies are ideal for testing and validating frameworks like RealCONs within real-world settings, allowing researchers to observe how it performs in actual construction projects and gather detailed feedback. While, Grounded Theory, on the other hand, is an exploratory methodology primarily used to generate new theories from qualitative data, typically in areas where little is known. RealCONs, however, requires an applied approach that assesses its usability, effectiveness, and impact, rather than developing new theories.
- 2- Methodological Alignment with RealCONs' Goals:** Case Study Methodology allows RealCONs to be evaluated in the specific context of construction project environments.

Through in-depth analysis of individual cases, researchers can assess how RealCONs interacts with existing project processes, how effective it is in managing delays, and how stakeholders respond to it. This method provides valuable, context-specific insights and enables a comprehensive examination of RealCONs' performance. In contrast, Grounded Theory would not be as effective for RealCONs, as it is not structured for practical testing or validation of frameworks. Instead, Grounded Theory involves iterative coding and analysis of qualitative data to discover patterns or theoretical constructs, which does not align with RealCONs' need for practical evaluation and refinement.

3- Data and Validation Needs: Case studies allow for both qualitative and quantitative data collection, which is crucial for RealCONs. By examining metrics like delay notifications, schedule performance, and user feedback, case studies offer a balanced view that includes measurable outcomes and qualitative insights. While, Grounded Theory lacks this quantitative aspect and would focus primarily on understanding subjective experiences, which is not sufficient for the real-time, data-driven objectives of RealCONs.

As a result, Case Study Methodology is the more appropriate choice for RealCONs because it enables real-world testing and validation of the framework within construction project contexts, providing both practical insights and evidence of its impact. Grounded Theory, while valuable for theory generation, does not align with the applied, performance-focused objectives of RealCONs.

Therefore, Phase 4 of this doctoral research uses Case Studies methodology to implement and verify the proposed RealCONs framework is a central aspect of this research. Case study methodology allows for the practical application of theoretical models in real-world construction settings, offering insights into both the framework's effectiveness and potential areas for improvement. Commonly used in construction management research, case studies provide a deep

understanding of how systems function under actual project conditions (Z. Wu, Ann, & Shen, 2017). This approach allows the research to assess the framework's ability to manage delays, its usability, and its impact on key outcomes such as time and cost savings (Pandey & Pandey, 2021).

An explanatory case study is particularly suitable for this research as it focuses on analysing cause-and-effect relationships. Specifically, it helps examine how the RealCONs framework performs compared to traditional methods by analysing key criteria like accuracy, real-time data integration, and predictive analysis. This methodology also explores the mechanisms through which the framework improves early-stage delay management and aligns with real-time project analysis (Radman et al., 2021; Radman, Jelodar, et al., 2022a; Radman, Jelodar, Lovreglio, Wilkinson, et al., 2022)

The case study method provides a practical and detailed approach to validating the RealCONs framework, offering critical insights into its real-world application. Objectives 7 and 8 address this purpose. Given that RealCONs is a comprehensive, process-based framework integrating diverse data sources and analytical tools, objective 7 is divided into four distinct "cut views" for evaluation:

- 1) **Information Modelling** – assessed through UML modelling and SIPOC Matrix.
- 2) **Data Acquisition Technologies** – evaluated via smartphone apps and Excel BI for analytical purposes.
- 3) **Data Analysis** – assessed using MSP/P6, BIM, and Earned Value (EV) metrics.
- 4) **Data Collection, Analysis, and Visualisation** – evaluated through the establishment of QR codes, custom mobile applications coded in PHP, SQL and Python server connections, API authentication, data models coded in M-code, relationship mapping of components, and early delay notification alarms via EV indexes.

These "cut views" for objective 7 are comprehensively discussed in Chapters 5 through 8. Objective 8, however, is assessed through an in-depth case review using Time Impact Analysis

(TIA) within a comparative analysis methodology, supported by AHP tools. This objective serves to establish RealCONs as an optimization-based framework for early-stage delay identification and analysis, with details provided in Chapter 9.

To cover objectives, the electrical and instrumentation (E&I) trade was chosen as the focus of the case studies due to its critical role in construction timelines and its complexity. E&I installations are highly integrated with other trades, making them especially vulnerable to delays, which can disrupt the entire project (Smith et al., 2019). E&I also involves specialised subcontractors, making it an ideal area for testing the framework's ability to centralise real-time data from multiple sources. By focusing on this trade, the research highlights the framework's capacity to manage complex, multi-trade environments where delays have significant ripple effects. Finally, Table 1.1 and Figure 1.5 summarise the alignment between the research design, objectives, and methodology, including methodologies and analytical methods employed to achieve these research two questions and 8 objectives.

1.6.5 Ethics

The ethical considerations for this doctoral thesis were reviewed and approved by Massey University's Human Ethics Committee, specifically for the expert interviews conducted through focus groups. The application, classified as low risk, was approved on 12 January 2021, for a duration of three years, under reference number 4000023782. The committee stipulated that all data collection through focus groups should be conducted by the researcher.

Throughout the research, various ethical risks were identified, and appropriate mitigation strategies were implemented. One significant risk involved ensuring the privacy and confidentiality of the project data used in the research. Given the sensitive nature of the data, including proprietary project information, steps were taken to anonymize the data and ensure that all identifiers were

removed before analysis. Additionally, all data was stored securely in password-protected files, with access limited to authorized personnel only. Another potential risk involved the informed consent of participants. Clear communication was ensured with all participants regarding the purpose of the research, the voluntary nature of their involvement, and their right to withdraw at any point without consequence. Consent forms were obtained from all participants prior to conducting the interviews.

Additionally, bias and fairness in the selection of expert participants were considered to prevent any conflicts of interest that could affect the research outcomes. The participants were carefully selected from diverse backgrounds to ensure the validity and impartiality of the results. The researcher ensured that all focus group discussions were conducted in a professional and respectful manner, allowing for open and honest dialogue while maintaining the integrity of the data collection process. Relevant ethics documentation, including consent forms, risk assessments, and approval correspondence, is included in Appendix 1 of this thesis.

1.6.6 Data Collection

This doctoral thesis utilises a range of data sets tailored to specific research components, organised across four methodological phases, each detailed in separate chapters. The thesis structure can be outlined as follows: (1) Section 1.4 presents eight core objectives, which are covered in Chapters 2 to 9, and (2) Sections 1.6.1, 1.6.2, and 1.6.3 discuss the overall research philosophy, the philosophy specific to this doctoral study, and the methodological phases, each corresponding to different sections of the thesis.

Figure 1.4 provides a Sankey diagram that illustrates the relationships between research objectives, chapters, and methodologies. Additionally, Figure 1.5, a schematic flowchart, serves as a research roadmap, depicting the start and finish points of the research along with each phase and the chapters involved. It also shows how each chapter aligns with specific objectives, methodologies,

processes, and outcomes. Finally, Table 1.1 translates the conceptual research phases from Figure 1.5 into a comprehensive overview of the thesis structure and body of knowledge.

Table 1.1: Research phases translation

Phases	Description
<u>Phase One: Introduction and Problem Identification in Current Systems</u>	
To identify research gaps and problems, three reviews were conducted: (1) a review of sources and technologies in construction, (2) a review of automated tracking methods, and (3) a review of data collection and analysis methods. To organize the facilitated workshops, the research listed 27 major construction companies in New Zealand (Auckland and Waikato region), including head contractors, subcontractors, consultants (design and engineering), or companies with multiple roles. Out of these, 15 companies participated. In the systematic literature review, 589 studies on the topic were initially found, and after eligibility assessment, 186 articles were selected. These reviews focused on three aims: (i) identifying current trends in real-time technologies in construction, (ii) visualising research approaches (stand-alone and combined technologies), and (iii) structuring a framework of automated technologies in smart construction.	
Outcome: Identified Conceptual Map/Framework	
<u>Phase Two: Data Acquisition and Analysis Modelling</u>	
Digital technologies, both stand-alone and combined, used in construction projects over the past decade were investigated to conceptualize models of data acquisition and centralize data analysis frameworks in construction.	
Outcome: Conceptualised Real-Time Technologies	
<u>Phase Three: Design and Development of the Framework</u>	
Building on the research gaps and existing frameworks identified in Part Two, a new data-driven project analysis framework (RealCONs) was designed to address challenges in delay management. This framework focuses on early-stage delay notification by organising real time data collection, analysis, and visualisation.	
Outcome: Designed a Data-Driven Framework	
<u>Phase Four: Implementation and Verification of the Framework</u>	
The proposed framework was implemented and verified through case studies, with a specific focus on early-stage delay notifications. Performance was assessed using earned value (EV) metrics to evaluate the time and cost impacts.	
Outcome: Verified RealCONs framework and recommendation	

Additionally, Table 1.2 further supports the research road map by detailing the diverse data sources central to the research, providing varied perspectives and enhancing the validity of each thesis section.

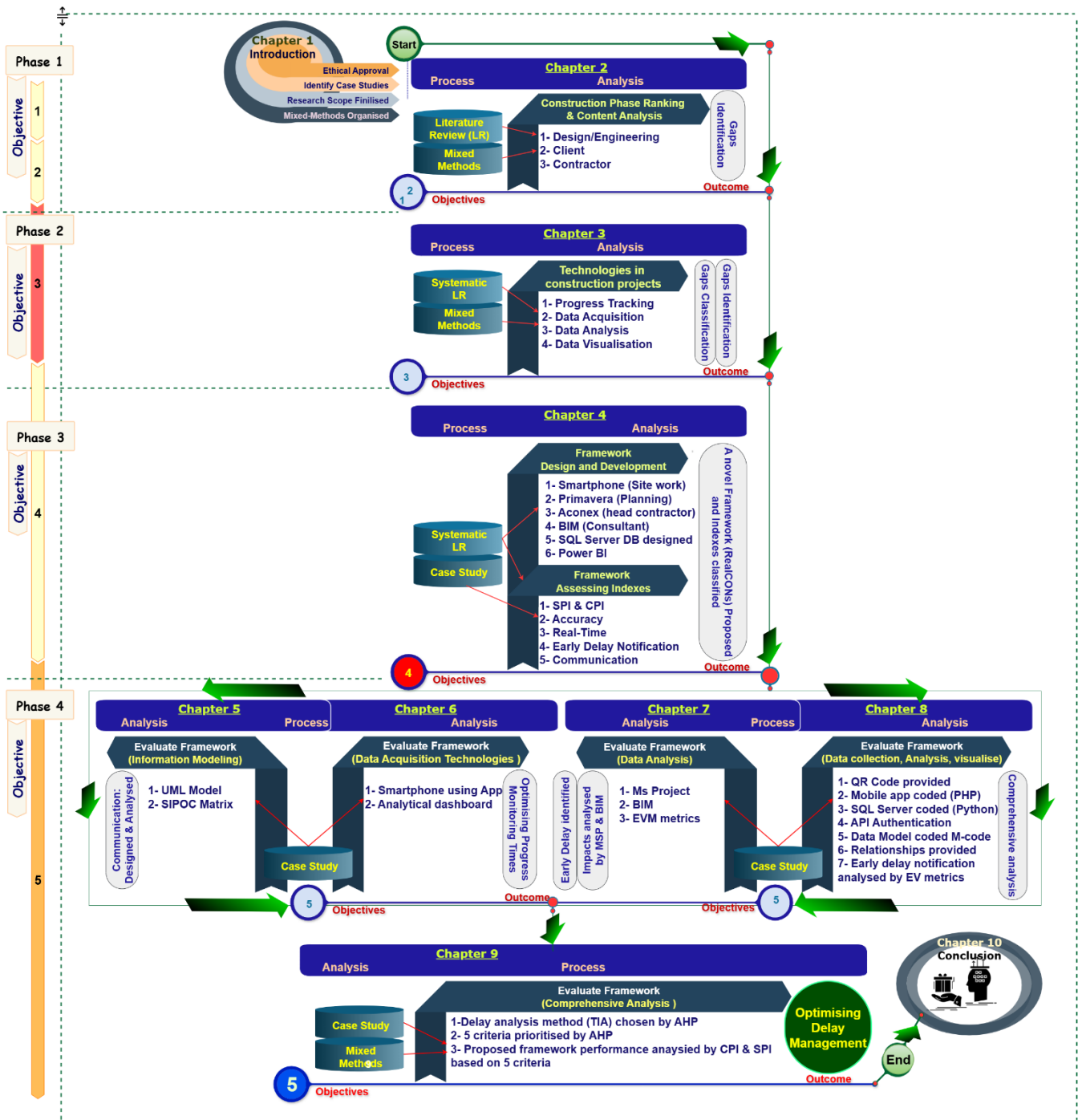


Figure 1.5: Research Road Map

Table 1.2: Doctoral thesis methodology according to each chapter

Chapter number	Chapter Title	Related paper title	Research Objectives	Research Methodology	Method of Analysis	Key Deliverables
1	Introduction		Establishes the scope, context, and significance of the research	Literature review and scoping study	Critical evaluation of existing research and industry practices	Defined research problem, scope, objectives, and significance of the study
2	Delay Causes in Smart and Complex Construction Projects	Causes of Delay in Smart and Complex Construction Projects	OBJ_1: Identify the general causes of delays and their implications on the relationships between construction parties across different stages OBJ_2: Evaluate and analyse the causes and effects of delays in major construction projects OBJ_3:	Literature Review and Mixed methods	- Citation Analysis - Content Analysis - Relative Importance Index (RII)	Identified causes of delays specific to smart and complex projects
3	A systematic review of digital Solutions for Data-Driven Delay Management	Digital Technologies and Data-Driven Delay Management Process for Construction Projects	- Identify and conceptualise real-time technologies used in construction projects, with a focus on delay alert management - Evaluate the advantages of integrating combined digital technologies versus stand-alone systems in construction project tracking management including delay and risk tracking	Literature Review	- Systematic Analysis - Framework Analysis	Assessment of digital technologies and strategies for delay reduction
4	RealCONs: A Novel Framework for Real-Time Construction Project Analysis	Real-Time Data-Driven Construction Project Analysis Framework	OBJ_4: Develop a process based real-time data-driven construction project analysis framework (RealCONs) focus on and classify Early Delay Notifications Indexes using EVM indexes	Design Science Research (DSR) and Expert feedback	- Case Reviews - Comparative Analysis	The framework proposed (RealCONs)
5	UML and relational database for reporting systems	Design and analysis of the real-time progress tracking system: A practical case study				Design and practical application of a real-time progress tracking system
6	Productivity Tracking in Construction Projects	Real-Time Project Productivity Tracking System: Practical Case in Smart Construction Projects	OBJ_5:			Practical insights into the effectiveness of real-time productivity tracking systems
7	Automated Construction Delay Management Mechanism	Automated construction delay management mechanism (Earned Value) of Electrical and Instrument works with BIM and Microsoft tools	- Validate the proposed RealCONs framework for data collection, integration, analysis and visualisation - Evaluation of RealCONs' performance in comparison to existing approaches, using a chosen delay analysis method to address key criteria for real-time project status analysis in early-stage delay notifications	Case Studies, Literature Review and Focus Groups	Case Reviews - Content Analysis - Comparative Analysis - Analytic Hierarchy Process (AHP) Case Reviews	Earned Value Analysis (EVA) and automated delay detection
8	Real Time Data-driven Project Analysis Model for Construction Projects	Real Time Data-driven Project Analysis Model for Construction Projects: A Case Study- Electrical and Instrument Works				Performance analysis of real-time data in project execution
9	Optimising Delay Management in Construction Projects	Optimising Delay Management in Construction: A Comparative Analysis of the real time data driven SMART Framework by Using early-stage delay notification indexes				Performance analysis using early-stage delay notification indexes (SPI, CPI) Testing and validating the framework with real-time data
10	Conclusion and Recommendations		To conclude and show how objectives achieved	Review and deductive reasoning		Limitations of the research and recommendations for future studies

1.7 THESIS ORGANISATION

This doctoral thesis follows Massey University's guidelines for a PhD thesis by publications, consists of ten (10) chapters, including an introduction, 8 core chapters built from published, presented or submitted research papers, and a conclusion. The main body, made up of 8 papers, addresses all the research objectives and is organized chronologically to ensure a clear flow of information.

Chapter 1 introduces the background of the study, identifies the knowledge gap, outlines the research objectives, methodology, and other key aspects. Chapters 2 and 3 investigate the causes of delays in smart and complex construction projects, using content analysis. However, exploring digital technologies for delay management, assessing their effectiveness in real-time data integration and risk tracking.

Chapter 4 introduces RealCONs, a novel real-time data-driven construction project analysis framework, developed through design science research and expert feedback. Chapters 5 to 8 focus on the practical implementation of real-time project tracking and delay management. Chapter 5 outlines the design and implementation of a real-time reporting system using UML and relational databases. Chapter 6 explores real-time productivity tracking, providing practical insights into monitoring construction progress. Chapter 7 introduces an automated delay management mechanism, integrating Earned Value Analysis (EVA) with BIM and Microsoft tools. Finally, Chapter 8 evaluates the effectiveness of real-time data-driven project analysis through a case study on electrical and instrumentation works.

Chapter 9 assesses the performance of the proposed novel framework by analysing early-stage delay notifications through earned value metrics such as Schedule Performance Index (Ando et al., 2020) and Cost Performance Index (CPI). In other words, Chapter 9 compares delay management

performance using RealCONs to traditional delay management approaches through utilising AHP, content analysis, and case reviews to assess its performance in early-stage delay notifications. Chapter 10 provides recommendations for future research and improved contract management, while also discussing the limitations of the study.

Each chapter and the associated research articles are structured as follows:

Chapter 2: Delay Causes in Smart and Complex Construction Projects

Manuscript title: Radman, K., Babaeian Jelodar, M., Ghazizadeh, E., & Wilkinson, S. (2021). Causes of delay in smart and complex construction projects. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, 13(4), 05021006. [https://doi.org/10.1061/\(ASCE\)LA.1943-4170.0000501](https://doi.org/10.1061/(ASCE)LA.1943-4170.0000501)

Manuscript status: Published in Journal of Legal Affairs and Dispute Resolution in Engineering and Construction

Chapter 3: A systematic review of digital Solutions for Data-Driven Delay Management

Manuscript: Radman, K., Jelodar, M. B., Lovreglio, R., Ghazizadeh, E., & Wilkinson, S. (2022). Digital technologies and data-driven delay management process for construction projects. *Frontiers in Built Environment*, 8, 1029586. <https://doi.org/10.3389/fbuil.2022.1029586>.

Manuscript status: Published in Journal of Frontiers in Built Environment

Chapter 4: Real-Time Tracking and Analysis in Construction Projects: A RealCONs Framework

Manuscript: Radman, K., Jelodar, M. B., Lovreglio, R., Ghazizadeh, E., & Wilkinson, S. (2025). Real-Time tracking and analysis in construction projects: A RealCONs framework. *Advanced Engineering Informatics*, 67, 103511. <https://doi.org/10.1016/j.aei.2025.103511>.

Manuscript status: Published in Journal of Advanced Engineering Informatics

✚ **Chapter 5: RealCONs: A Digital Framework for Construction Reporting Accuracy and Early Delay Detection**

Manuscript: Radman K, Babaeian Jelodar M, Lovreglio R (2025). RealCONs: A Digital Framework for Construction Reporting Accuracy and Early Delay Detection, *Journal of Information Technology in Construction: ITcon*, Vol. 30, pg. 745-777, <https://doi.org/10.36680/j.itcon.2025.031>

Manuscript status: Published in Journal of Information Technology in Construction

✚ **Chapter 6: Productivity Tracking in Construction Projects**

Manuscript: Radman, K., Jelodar, M. B., Lovreglio, R., Wilkinson, S., & Ghazizadeh, E. (2022). Real-time project productivity tracking system: Practical case in smart construction projects. In 7TH New Zealand built environment research symposium (p. 409)

Manuscript status: Conference Paper – Accepted/Presented

✚ **Chapter 7: Automated Construction Delay Management Mechanism**

Manuscript: Radman K, Jelodar MB, Lovreglio R, Wilkinson S, Ghazizadeh E. (2023). Automated construction delay management mechanism (Earned Value) of Electrical and Instrument works with BIM and Microsoft tools. Proceedings, 46th Australian Universities Building Education Association Conference (AUBEA 2023), ISBN: 978-1-921047-51-0. https://doi.org/10.1007/978-981-96-2802-5_20

Manuscript status: Published as book chapter in Lecture Notes in Civil Engineering, Springer Nature.

✚ **Chapter 8: A Digital Monitoring, Delay Detection and Visualisation Framework for Construction Projects: RealCONs**

Manuscript: Radman, K., Jelodar, M. B., Lovreglio, R., Ghazizadeh, E., & Wilkinson, S. (2024). A Digital Monitoring, Delay Detection and Visualisation Framework for Construction Projects: RealCONs. Automation in Construction, ID: AUTCON-D-25-02892

Manuscript status: Under Review with Automation in Construction

✚ Chapter 9: Optimising Delay Management in Construction Projects

Manuscript: Radman, K., Jelodar, M. B., Lovreglio, R. (2024). Optimising Delay Management: A Comparative Analysis of the Novel SMART Framework Using Early-Stage Delay Indicators. *Journal of Construction Engineering and Management*, ID: JCEM-D-25-00505

Manuscript status: Under Review with Journal of Construction Engineering and Management

1.8 THESIS KEY DEFINITIONS

❖ **Major Construction Projects:**

- (i). The Treasury New Zealand (www.treasury.govt.nz) & Ministry of Business, Innovation & Employment (MBIE): “Major Construction Projects” represent most complex, high-value investments to complete and cost over \$100 million.
- (ii). Generally, it refers to large-scale, complex construction, including significant investment (250M AU\$, 100M £UK, 1B US\$), resources, and impact on the surrounding environment and community.


❖ **Smart Construction** refers to the use of digital technologies, IoT, ICT, and industrialised methods in design, construction, and operation. It transforms traditional construction into a data-driven, integrated, and user-focused process.

❖ **Key Delay Analysis Techniques:** Windows Analysis, Time Impact Analysis, Impacted As-Planned Analysis, and As Planned vs. As-Built Analysis

❖ **Why Time Impact Analysis (TIA):** From SCL Protocol and AACE RP29R-03:

- (i). TIA’s methodology is rooted in schedule updates, critical path analysis, and delay modelling fits for real-time project tracking.
- (ii). Highly suitable, reacts to events in real-time
- (iii). Widely accepted for claims
- (iv). Easy to insert fragments and simulate delay scenarios
- (v). Event-driven Vs Time-driven
- (vi). Highly prospective (while retrospective is ok)

STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.			
Student name:	Kambiz Rdaman		
Name and title of main supervisor:	Mostafa Babaeian Jelodar		
In which chapter is the manuscript/published work?	Chapter 2		
Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work: ¹ Ratio of student to supervisory team 80:20, Student: Brought and Structured idea, Captured data, created model, Analysed, Drafted and Finilised Text Supervisory team: Conducted Study, Improved conceptual model, Reviewed and Finilised Text			
Please select one of the following three options:			
<input checked="" type="radio"/>	The manuscript/published work is published or in press Please provide the full reference of the research output: Radman, K., Babaeian Jelodar, M., Ghazizadeh, E., & Wilkinson, S. (2021). Causes of delay in smart and complex construction projects. <i>Journal of Legal Affairs and Dispute Resolution in Engineering and Construction</i> , 13(4), 05021006.		
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Student's signature:	Kambiz Radman Digitally signed by Kambiz Radman Date: 2025.02.13 23:00:30 +13'00'	Main supervisor's signature:	 Digitally signed by Mostafa Babaeian Jelodar Date: 2025.02.15 08:54:59 +13'00'
<i>This form should be placed at the beginning of each relevant thesis chapter.</i>			

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Chapter 2: DELAY CAUSES IN SMART AND COMPLEX CONSTRUCTION PROJECTS

The current chapter is based on the following article:

Radman, K., Babaeian Jelodar, M., Ghazizadeh, E., & Wilkinson, S. (2021). Causes of delay in smart and complex construction projects. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, 13(4), 05021006. [https://doi.org/10.1061/\(ASCE\)LA.1943-4170.0000501](https://doi.org/10.1061/(ASCE)LA.1943-4170.0000501)

Published in Journal of Legal Affairs and Dispute Resolution in Engineering and Construction



Objectives should be covered:

OBJ_1: Identify and Analysis Key Stockholders

OBJ_2: Identify & Analysis Key Causes Delay

2.1 SUMMARY

The construction sector is categorised into core organisations which are directly involved in the construction process and related services. As the sector is a significant economic contributor to New Zealand's employment, GDP and business units; it relies on different tools and potential technological advancements to reduce the adverse effects of delays and associated problems. This requires coordinated efforts and greater alignment in using technology and IT infrastructure provisions in complex and smart construction projects and operations. However, construction projects experience indicates delays as a reoccurring issue that requires constant assessing of these delays' causes and impact. Many delay analysis methods and caused factors are being recognised, but none

of them has considered whether ICT infrastructure such as software and smart platforms affect these delay causes and events. This paper aims to identify and rank the causes of delay, which happened through using software and ICT platforms in smart and complex construction projects in New Zealand. Initially, the delay causes were classified, and 15 executed smart construction projects were identified and studied. Accordingly, the project managers and engineers involved participated in a survey on the actual delay causes within these projects. This study utilised the Correlation Coefficient and Ranking of Relative Importance Index (RII) to prioritise the causes of delay. The result presented a list of 20 factors in three classes of Design/Engineering (DE), Client (CL) and Contractor (CO). The results revealed that issues such as retrieving information; gather and screening real-time data in the site; lack of multi-communication channels between parties and stages (pre/post-construction) could be significant causes of delay in smart construction projects with the expansion of smart tools and techniques in construction. Meanwhile, consents and ethics can potentially become another potential cause of delay, which requires further attention.

2.2 INTRODUCTION

Often in construction projects, uncertain and uncontrolled events caused delay situations deemed an inevitable part of these projects. Lost productivity, increased costs, termination, Extend of Time, and acceleration are critical impacts of delay in the construction area (Shahinmoghadam & Motamedi, 2021). All involved parties are responsible for recovering significant delay impacts such as time, cost within the project, and some force major and non-human intervention causes unforeseen conditions. Delay process most of the time is complicated as many root-causes might contribute to the formation of other delays(I. C. Wu & Liu, 2019).

On the other side, construction projects are developing very fast, and computer-aid in construction areas initially started by drawing tools such as CAD has been growing and

deploying to 3D and 4D such as Revit, BIM. Concurrently, scheduling and budgeting software such as Primavera and MS Project have been essential parts of construction projects. Application of IoT and digital transformation in safety, real-time supply chain, and project management are also some of the remarkable growth of technology throughout the construction environment (Al-Saeed, Parn, Edwards, & Scaysbrook, 2019).

Smarter construction processes need intelligent tools, processing power, where research has shown that Artificial intelligence (AI) and Business intelligence (BI) will be making a significant revolution in digitalisation approach (S.-K. Lee & Yu, 2012). For instance, a hot topic in the field is a visualisation of construction projects to detect clashes; it is estimated to reduce reworking in pre-construction and construction phases by 65% on average (S.-K. Lee & Yu, 2012). Project analysts can provide schedule analysis Critical Path Method (CPM) to utilise float consumption, critical effects, and lost opportunities as a useful tool to evaluate the impact of delays; this can be integrated with other tools such as Primavera and MS Project as well as Building Information Management (BIM).

In terms of "state of national knowledge report", implementing technological approaches capture barriers such as financial risk, technology adaptation by industries, succession planning, cultural complexity, risk of being rejected by workers (National-Science-Challenge-Report, 2014). Furthermore, a combination of "Smart" concept into construction is vital for the growth of urban areas; to enhance the capability of the sector for New Zealand's future population growth in these areas. Projections to 2043 show main cities' population will increase rapidly, so 75% of the growth of New Zealand's total working-age population would be over the next 30 years (National-Science-Challenge-Report, 2014)). Therefore, IT-based infrastructures (software, applications, devices) are being utilised to manage projects for changes, delays and variations which may occur. Nevertheless, this research contrasted the mentioned advantages with their own failure in delays, technologically or management approaches either (Ministry of

Business, 2017).

The study's outcomes, through OBJ_1 and OBJ_2 subjected above, will provide a comprehensive understanding of delay causes and their impact on stakeholder (e.g. contractors, subcontractors, engineering/design, project managers, project analysts, planners) relationships across different project stages. By evaluating and analysing delay factors in major construction projects in New Zealand, the research will offer insights into their effects on project performance. The findings will contribute to developing strategies for mitigating delays and improving project management efficiency in complex construction environments.

2.3 BACKGROUND

Project Management Institute (PMI) has proposed a relatively recent definition of the "project" that should be inclusive and exclusive. "Inclusive" means it should not be possible to identify any undertaking generally thought of as a project that does not fit the definition. In contrast, "exclusive" points out that should not be possible to describe any undertaking which satisfies the definition and is not generally thought of as a project (Craig & Sommerville, 2006).

According to "project" concept defined by PMI a construction project (e.g. residential, commercial, industrial, heavy) is essentially a temporary endeavour with specified time & cost, initiated to create a unique product, service or result, tend to be limited edition. Furthermore, the involvement of advanced technologies and owner-desired-changes makes it even more challenging to keep a project on the scheduled track (Pritchard, 2015). Therefore changes, delays and variations are common in construction projects. Control measures and management of these events require different strategies as project complexity increases, and smart tools and technologies are used.

However, "variations" such as addition, omission, deletion, substitution or changes are the

projects' nature, even the scope of work is initially specified in the contract. Moreover, sometimes variation is referred to as a change. The precise nature of the construction process makes the subject of variations an important one. Inevitably, because the parties cannot anticipate everything that may happen or where a contract is agreed before design/scope of works is fully finalised, frequent changes are often required (Tang, Ma, Zhang, Guan, & Chen, 2020). Unless a variation is instructed, a contractor is required to follow the works as initially specified; otherwise, it would be in breach of contract (Hwang, Shan, & Looi, 2018).

As mentioned, variations are an inevitable aspect of construction projects. Seldom projects are completed without any changes being requested or enforced. Some key steps which ensure variations do not drain the profitability out of a project are listed such as plan in advance (forecast revenue Vs actual revenue) and the importance of comprehensive budgeting at the outset cannot be overstated; check the project key data as often as possible (e.g. labour, material and installation progress); monitor sub-contractor behaviour for late costs, and do not presume variations will deliver a profit.

(Ding, Liu, Liao, & Zhang, 2019): these considerations and measures are required to effectively manage variation orders in construction projects (Hwang et al., 2018). Generally, a delay means to be late or behind in movement or progress. The delay implies a holding back, usually by interference, from completion or arrival. For instance, bad weather delayed our arrival retard suggests reducing speed without actually stopping (Shahsavand, Marefat, & Parchamijalal, 2018). In construction, the delay can be defined as the extra time required or incurred either beyond the stipulated completion date or beyond the date that the project stakeholders agreed upon to complete the project. In other words, construction delays are considered as time lag in completion of activities from its specified time as per contract or can be defined as late completion or late start of activities to the baseline schedule, directly affecting specified cost(Yap, Abdul-Rahman, & Chen, 2017).

Furthermore, some key recognised reasons could delay a project such as a change in project scope, project complexity, inadequate planning, design variation, inaccurate engineering estimate, inefficient technological tools, payment methods, lack/less communication among parties, and weather, strikes, governmental or owner interference (Bucchiarone et al., 2019). As a result, there will be extensions of time required which will further result in subtly increased cost due to inflation, termination of the contract, court cases etc. or combinations of above-stated factors, resulting in delay damages. The larger the scale of projects, the more severe these issues; therefore, large-scale management with higher value investment requires more intense monitoring and application of modern tools for delay control.

Ultimately, large-scale projects comprise complexity, value over \$1 billion, and substantial completion takes longer to develop. These projects have multiple stakeholders of public and/or private who are impacted by and/or impact many people, as well as closely related to high-tech requirements, critical attributes as same as multi-disciplinary construction projects ((UK), 2018; Niu, 2016). Smart construction is building Design, Construction and Operation that through collaborative partnerships, it uses digital technologies and industrialised manufacturing techniques to improve productivity, minimise whole life cost, improve sustainability and maximise user benefits. This way of working can transform the construction industry and maximise the benefits of projects for the occupants and provide them with a better quality of life. Furthermore, "Smart Construction" defines as using an Internet of Things (IoT) and ICT approaches from supporting the realisation and management of dynamic and adaptable applications specifically suitable for construction sites (Bucchiarone et al., 2019; Construction Leadership Council 2018). Moreover, literature investigation shows that no research has been undertaken to show up these kinds of study into smart construction projects. This study reviewed 50 both construction delay and technology to bridge this gap, such as Cyber-Physical Systems (CPS), BIM, big data, cloud computing, MS Project and Primavera literature into construction

process (Anumba, Akanmu, Yuan, & Kan, 2020; Corrêa & Maciel, 2018). From a technologist point of view, literally technological infrastructure in the construction area must mitigate many of the critical challenges to the safe side. Means, challenges such as changes and variations cause delays which have to be identified, prioritised as well as optimises risks and increases productivity (e.g., minimising delays) through a connection to appropriate tools and ICT infrastructure on the site (Ferrari et al., 2018; I. C. Wu & Liu, 2019; Xu, Li, Chen, & Wei, 2018).

2.4 LITERATURE REVIEW

Delay in construction is inevitable and a well-established topic of discussion among many researchers (Bajjou & Chafi, 2018; Basak, Perrons, & Coffey, 2019; Bonga, 2017; Durdyev, Ismail, & Kandymov, 2018; Su, Lucko, & Thompson, 2020; Zhao, Seppänen, Peltokorpi, Badihi, & Olivieri, 2019; Zidane & Andersen, 2018). In the US, Canada, and Singapore construction industries, especially in managing big projects, assessing time and cost are key points and maintaining high-quality performance is often considered (Barbosa & de Ávila Rodrigues, 2020; Chofreh, Goni, Malik, Khan, & Klemeš, 2019; Jergeas, 2008; Ramazani & Jergeas, 2015).

Studies showed that the main factors, such as financial, complicated planning, inappropriate scheduling, owner change order, and frequent design changes, would cause a significant delay in the construction industry. Improper feasibility study, risk management, budgeting, and time forecasting can cause construction project delays (Abbasi, Noorzai, Gharouni Jafari, & Golabchi, 2020; Zarei, Sharifi, & Chaghoeue, 2017). Moreover, studies show that rushing to the execution phase will mean carelessness and less consideration in the planning phase; therefore, some failure factors include: project reworking, frequently re-scheduling, multi-baseline, multiple testing and less configuration management (Camacho, Cañizares, Estévez, & Núñez, 2018). Construction is a high-risk business, as schedule management has a high risk for owners and

contractors. Losing opportunity in project tasks may implicate valuable cost on construction projects (Muizz O. Sanni-Anibire, Mohamad Zin, & Olatunji, 2020; Xu et al., 2018). Furthermore, focusing on delay causes in the preliminary stage of design phase revealed that the most important cause of delay is caused by changes in client's requirement or uncertainty perspective of the project from the point of client's view S. M. E. Sepasgozar et al. (2019).

According to Durdyev and Hosseini (2019); Jalali Yazdi, Maghrebi, and Bolouri Bazaz (2018) and National-Science-Challenge-Report (2014), construction delays frequently occur on projects; however, the governmental and public projects have been experiencing and reporting the worst of these delays and disruptions. About 85% of all construction projects with the common problems and causes of delays are those projects tagged under the government/public sector. Public projects generally follow government management methods, legislation, and policies. Therefore, as a common main problem; significant causes of delay are driven from top to bottom (e.g. from the government to sub-contractors).

On the other side, automated progress tracking is used to increase efficiency and effectiveness of construction monitoring; where, reducing traditional time-consuming tracking systems in smart construction areas is critical to construction management (Moselhi, Bardareh, & Zhu, 2020a). Moreover, construction project management uses modern technologies to monitor and control software (labour) and hardware (plant and material) throughout the project to supervise and track activities and productivities on the site (Durdyev & Hosseini, 2019; Ferrari et al., 2018; Khair, Mohamed, Mohammad, Farouk, & Ahmed, 2017; S.-K. Lee & Yu, 2012; Moselhi et al., 2020a; Safwan Moubaydeen, 2014; Muizz O. Sanni-Anibire et al., 2020; Y. Amare, 2017). As a result, tools, or software such as Primavera and MSP are used to minimise delay through stages of planning, scheduling, and monitoring (Ashwini Arun Salunkhe, 2014; E. Elfi, 2020; Khair et al., 2017). For modelling, BIM use in construction projects either pre or post-construction, will be increasingly key factors of success such as efficiency and quality of construction

projects(Gamil & Rahman, 2019).

Generally, the construction sector's acquisition of information is one of the keys and most challenging steps. Therefore, IoT based technologies such as BIM, GIS, RFID, and combination with scheduling tools are suggested to minimise delay and create a smarter construction setting. It is well documented that decreasing the risk of misunderstanding by clarified data is a key to evaluate construction project progress (Alizadehsalehi & Yitmen, 2018; Fan, Zhang, Li, & Fu, 2020; Haupt, Akinlolu, & Raliile, 2019; Zeng, Wang, & Zhou, 2018). Studies show that the suitable and adequate devices such as wearable watches, mobiles, drones, laptops, sensors, and cameras might increase the chance of delay minimising in construction projects (Y. F. Huang et al., 2018; Khair et al., 2017; Zidane & Andersen, 2018). This is because ICT based technology equipment is being widely used and expanding different construction work aspects (E. Elfi, 2020; Haupt et al., 2019). The authors have analysed and evaluated relevant and state of the art studies over the past six years. The most significant delay factors/criteria have been identified and classified; in addition, the measure and methods recommended and identified for minimising theme have been captured in Table 2.1.

From Table 2.1, providing a clear and detailed enough drawing and Schedule of Quantity (SoQ) earlier, defining an understandable scope of work, proper planning, and scheduling either through software or design tools, can be recognised as the root cause of delays that can affect resource, design, project management stages. In contrast, some research has recommended that the depth studies are required to develop methods such as the combination of BIM with IoT-based devices; BIM and Scheduling; Primavera web-based; MS Project and MS Office for SoQ. However, no evidence is being dealt with advantages, requirements, and disadvantages of developing methods. In this study, two main criteria of minimising delay factors in construction areas have been selected through literature reviews from the contractor's perspective.

Table 2.1: Delay factors and methods into five classes

Class	Method for minimising
Schedule Management	<ul style="list-style-type: none"> • Specification of a realistic duration to execute the project (Abbasi et al., 2020; S. Li, Fang, & Wu, 2020; Sacks, Radosavljevic, & Barak, 2010; Safapour & Kermanshachi, 2019). • Proper planning and scheduling (Camacho et al., 2018; Jalali Yazdi et al., 2018; Zarei et al., 2017). • Case studies in Hong Kong construction projects and the Malaysian construction industry (Mrugenkumar K. Patel, 2020)
Monitor and control Management	<ul style="list-style-type: none"> • Obtaining the required approvals of the project from authorities (Chofreh et al., 2019; Khair et al., 2017; Lessing, Thurnell, & Durdyev, 2017; Su et al., 2020). • Development of an exemplary system for site management and supervision (Abdullah, Yaman, Mohammad, & Hassan, 2018; Bajjou & Chafi, 2018; Basak et al., 2019; Eadie, Browne, Odeyinka, McKeown, & McNiff, 2013; Fallahnejad, 2013; Pall, Bridge, Gray, & Skitmore, 2019). • Case studies in Nigerian construction projects and building construction projects in Egypt (Arditi, Nayak, & Damci, 2017)
Administration	<ul style="list-style-type: none"> • Construction management companies to help minimise delays or their impacts (Fan et al., 2020; Ferrari et al., 2018; Y. F. Huang et al., 2018; Newsham et al., 2017). • Joint efforts of participants in the construction (Abbasi et al., 2020) • Site conditions must be improved (Jalali Yazdi et al., 2018; Shah, Chen, Yin, Khan, & Ahmad, 2018)
Resource Management (e.g. Financial, Software and hardware)	<ul style="list-style-type: none"> • Payment to the contractor on time for the work being carried and finished based on contract (Chong & Diamantopoulos, 2020; Humiras Hardi Purba 2020). • Ensure the adequate and available source of finance (Chofreh et al., 2019; Gebrehiwet & Luo, 2017) • Improving cash flow & plan the cash flow before start project (Aaron M. Costin, Jochen Teizer, & Schoner, 2015; Kelm et al., 2013; Newsham et al., 2017) • Employ employer based on their work/skills speciation in a construction project (Project Management Institute, 2017) • Work scope needs to be well defined (Pritchard, 2015; Sievert, 1998; Su et al., 2020; Zidane & Andersen, 2018)
Technical aspects (e.g. Engineering and Design)	<ul style="list-style-type: none"> • Prepare an accurate clear and adequate detail drawing and BoQ (Bill of quantity) (Acampora, Cook, Rashidi, & Vasilakos, 2013; Barrett & Baldry, 2003; Dmitry G Korzun, Ilya Nikolaevskiy, & Gurtov, 2015) • Accurate initial study and design (Bajjou & Chafi, 2018; Mrugenkumar K. Patel, 2020; NAZMUS SAKIB, EKLAS HOSSAIN2, & AHAMED, 2020; Zeng et al., 2018)

The first one is technology, and the second one is technical and management skills. All factors comprise a different type of construction project belong to private or governmental projects either. Finally, those factors have been applied and assessed in "Smart" construction projects. The role of using technology and management skills in orchestrating delay management into "smart" construction project is divided into the construction and pre-construction phases.

2.5 RESEARCH METHODOLOGY AND DATA COLLECTION

To further explore delays in smart and complex construction projects, major construction projects were selected as the focus of this study. The selection of these projects was based on the smart systems and technologies they use for multiple purposes. They have ICT-based systems, methods, and techniques within their construction practice to collaborate with involved parties such as design, contractor, and subcontractor from preconstruction to practical completion stages

for sharing their information and experience. The current study's research methodology includes two core objectives : 1) Identify the general causes of delays and their implications on the relationships between construction parties across different stages; and 2) Evaluate and analyse the causes and effects of delays in major construction projects. For these purposes, five steps taken as :(1) identifying and choosing relevant causes of delay with significant effects; (2) using purposive sampling (emphasis on similarity); (3) assessing the established facilitated workshops; (4) comparing approach through correlation coefficient; and (5) analysing data in conjunction with causes and effects of delay through a relative importance index (RII) (Gebrehiwet & Luo, 2017; Khatib, Poh, & El-Shafie, 2020).

For determining the current study's data collection, three facilitated workshops were performed. The respondents were chosen among experienced construction experts who were representatives of companies involved in pre- and postconstruction project phases in New Zealand. All these companies were involved in applying smart methods of construction and digital tools. The selection criteria were based on smart construction involvement:

- Auckland Waikato region-based projects
- ICT infrastructure-based projects such as Microsoft Project or Primavera for scheduling and project control, SiteDocs web-based documentation app, Aconex as a contractual communication channel and documents control, partial BIM for clash detection, and Microsoft Outlook for email and correspondence
- The data source within construction projects includes correspondence, workflow reports, progress claims report, contracts, timelines and work breakdown structure at medium level, variation, and delay registers.

To further explore delays in smart and complex construction projects, mega construction projects have been selected as the focus of this study. The selection of these projects was based on the smart systems and technologies they used for multiple purposes. They have ICT based

systems, methods, and techniques within their construction practice to collaborate with involved parties such as design, contractor, sub-contractor from pre-construction to practical completion stages for sharing their information and experience. Finally, the authors could select 15 projects out of 27 invited projects as Case Studies. These projects are based in New Zealand and focus on ICT infrastructures and applications such as MS Project, Primavera for scheduling and project control; SiteDocs web-based documentation app, Aconex as a contractual communication channel and documents control; partially BIM for clash detection; outlook for email and correspondences.

This study intends to present critical IT-based causes of delay in smart construction projects in New Zealand. The source of data within the 15 smart construction projects includes correspondence, workflow reports, progress claims report, contracts, timelines/ WBS in medium level, variation, and delay registers. Finally, based on the literature review and project dossiers, an equitably complete table of delay causes was listed. To organise and establish the facilitated workshops, this study listed all potential companies with the attributes mentioned as the smart construction in New Zealand (Auckland Waikato region). Ultimately, 27 companies were chosen in the Auckland Waikato region due to location and access restriction. These included the main contractor, subcontractor, consultant (design, engineering), or companies with multiple roles. All 27 companies were contacted and invited to participate in this research: four did not respond, three project managers and two companies were unwilling to collaborate, and the rest initially agreed to participate in the facilitated workshops.

Finally, 15 of the original 27 participated. The respondents' feedback was collected through the mentioned facilitated workshops (e.g., focus groups), where existing applications, tools, and methodologies used in their projects were discussed and documented. Furthermore, all processes of the facilitated workshops were clearly explained and managed for every participant involved in the data collection process such as setting a clear goal, defining the purpose, sharing an

agenda, understanding ground rules, and collaborating with all people, so that the results could be analysed from all construction projects experts' points of view.

Finally, based on the literature review and project dossiers, an equitably complete table of delay causes was formed. To further explore the delay causes and minimization methods identified in Table 2.2, three facilitated workshops that included project managers, project engineers (from design and construction site), and contract managers were organized.

As a result, all of the items in Table 2.2 were screened and scrutinized and remarkable causes were identified; consequently, some items and details were added, and some were excluded. Accordingly, the RII and the correlation coefficients were used to analyse causes and effects of delay into smart construction projects (Abdi & Taghipour, 2019; Anumba et al., 2020; Gebrehiwet & Luo, 2017; Su et al., 2020; Wood, 2017). Meanwhile, the owners' engineering team and construction supervisors checked the facilitated workshops' results as an audit process.

The literature that has captured the Relative Importance Index (RII) and Spearman's rank correlation coefficient for computation and ranking factors have used a similar formula. The works of Ali et al. (2020); Basak et al. (2019); Fallahnejad (2013); Y. F. Huang et al. (2018); Pall et al. (2019) and Sambasivan (2007) have all used and agreed on the following formula which is used as the basis of this study too

$$RII = \frac{\sum_{k=0}^n W_k F_k}{A \times N} \text{ and } RII \in]0,1] \quad (1)$$

where k = class index; W_k = respondents' weight; weight factor F_k = frequency of responses; A = highest weight; and N = total number of respondents. Eq. (1) computes the higher value of RII that presents the important cause or effect of delay using a 5-point Likert scale.

Table 2.2: List of delay coded causes and classes

Class	Cause	Code	ICT view
Design/ Engineering	1. Frequently variation on drawings	DE1	BIM
	2. Number of non-responded RFI	DE2	Outlook
	3. Waiting time for approval/ comments on shop drawings and drawings	DE3	Microsoft Project
	4. Using a different source of information	DE4	Aconex
	5. Cultural diversity between design and client team	DE5	

	6. BIM programme is behind project schedule	DE6	
	7. Low experience in using main features of Aconex, BIM	DE7	
	8. Passive meetings (even frequently)	DE8	
Client	9. A load of RFI workflow	CL1	Navisworks Freedom 2020
	10. Technology for getting real-time data from the site	CL2	Primavera (only planner)
	11. Inconsistency among project managers	CL3	Microsoft Project
	12. Using multiple project scheduling software (MSP, P6 or excel)	CL4	(most of the departments)
	13. Lack of coordination skills between various parties working on the project	CL5	Aconex
	14. The delay between what happens on-site and what will return from involved parties	CL6	Outlook
	15. Using BIM, Aconex, MSP, P6 but no clue of integrity among them	CL7	
	16. Long and mistakenly process of assessing progress claim even using Aconex and BIM	CL8	
	17. Low experience in using at least the main features of Aconex, BIM	CL9	
	18. Inconsistency between submitted and assessed progress claims (not integrated database)	CL10	
Contractor	19. No ling-up between contractor and client programmes	CO1	Navisworks Freedom 2020
	20. Low experience in using main features of Aconex, BIM	CO2	Microsoft Project Aconex Outlook

The results of the test are presented in Table 2.3. Therefore, the relationship between variables should be assessed (Baskar, Dhulipala, Shakeel, Sridhar, & Kumar, 2019; Makowski, Ben-Shachar, Patil, & Lüdecke, 2020). Therefore, Eq. (2) is used to compute Spearman's rank correlation coefficient as follows:

$$R = 1 - \frac{6\sum d^2}{n^3 - n} \text{ and } R \in [-1,1] \quad (2)$$

where d = rank difference; n = number of ranks; and $R=0$ means no correlation. The results of the test are illustrated in Table 2.4.

2.6 RESULTS AND DISCUSSION

The results of facilitated workshops were the primary source of data collection. A set of design/engineering, client, contractor, and owner representatives participated in this study to identify the causes of delay in smart construction projects. The participant classes and their identified causes of delays were coded and are summarized in Table 2.2. A code was assigned to each delay causes, where DE represents design/engineering-related cause, CL is for client-related causes, and CO is for contractor-related causes. Furthermore, the results of the RII analysis are included in Table 2.3. As mentioned, Eq. (1) is used to scale a value somewhere

between $1/X$ and 1, where X is the number of response categories. Therefore, Eq. (2) may also just compute the mean score for each code of Table 2.3, and that will sort the items from most to least in precisely the same way as would the RII values. For instance, Table 2.5 illustrates a sample of RII calculation for clause 4. To present different parties' points of view, the general ranking of the essential factors and classes is extracted and included in Table 2.4. This table illustrates that causes of delay are not the same within different classes and shows the degree of importance of typical causes of delay at each stage of smart construction projects. For instance, retrieving information, gathering and screening real-time data on-site, lacking multi-communication between parties, and crossed functions between parties and stages have been highlighted as critical items of delays.

Table 2.3: Relative Importance Indexes and rankings

Classes	Codes	Pre-Construction		Construction		Average	
		RII	Ranking	RII	Ranking	RII	Ranking
Design/ Engineering	DE1	0.18	20	0.21	20	0.195	20
	DE2	0.61	6	0.58	13	0.595	14
	DE3	0.37	19	0.42	19	0.395	19
	DE4	0.7	1	0.65	2	0.675	1
	DE5	0.5	17	0.56	15	0.53	16
	DE6	0.68	3	0.6	11	0.64	4
	DE7	0.62	5	0.57	14	0.595	9
	DE8	0.65	4	0.47	17	0.56	15
Client	CL1	0.5	17	0.45	18	0.475	18
	CL2	0.57	9	0.75	1	0.66	3
	CL3	0.52	14	0.62	7	0.57	12
	CL4	0.6	7	0.62	7	0.61	5
	CL5	0.52	14	0.62	7	0.57	13
	CL6	0.54	13	0.5	16	0.52	17
	CL7	0.69	2	0.64	4	0.665	2
	CL8	0.55	11	0.6	11	0.575	11
	CL9	0.52	14	0.63	6	0.575	10
	CL10	0.59	8	0.62	7	0.605	7
Contractor	CO1	0.57	9	0.64	4	0.605	6
	CO2	0.55	11	0.65	2	0.6	8

Table 2.3 indicates relative importance indexes and rankings through a 5-point of Likert scale ranging from 1 to 5, where 1 is significantly low impact and 5 is a very significant impact to design and structure causes of delay in the smart construction area. Furthermore, by using Eq. (2) and statistical computer-based programming, Tables 2.6 and 2.7 present degrees of correlation between classes and stages as well as the degree of agreement between each of the classes, respectively. For instance, from Table 2.6, the presented values determine that the preconstruction stage has correlated 42% with the contractor’s class while the construction stage from the client’s point of view has a 97% correlation. In contrast, a 53% correlation between the design/engineering class and the construction stage can be reported. This means that the portion of the collaboration of the contractor in the preconstruction stage is significantly low. Furthermore, Table 2.7 shows a low degree of correlation between the design/engineering and contractors, indicating that even though the design/engineering class has used high spec tools such as BIM and the combined ones, the correlation between them and contractor class is lower than other classes, e.g., 23%. Significantly, multiple crossed relations between classes need to be paid more attention.

Table 2.4: General ranking list of essential factors and classes

Codes	RII (Average)	Ranking in stage		
		General	Construction	Pre-construction
DE4	0.675	1	2	1
CL7	0.665	2	4	2
CL2	0.66	3	1	9
DE6	0.64	4	11	3
CL4	0.61	5	7	7
CO1	0.605	6	7	8
CL10	0.605	6	4	9
CO2	0.6	8	2	11
DE7	0.595	9	13	6
CL9	0.595	9	14	5
CL8	0.575	11	11	11
CL3	0.575	11	6	14
CL5	0.57	13	7	14
DE2	0.57	13	7	14
DE8	0.56	15	17	4

DE5	0.53	16	15	17
CL6	0.52	17	16	13
CL1	0.475	18	18	17
DE3	0.395	19	19	19
DE1	0.195	20	20	20

Table 2.5: Sample of RII calculation

Cause#	Cause	RII factors					Computed values, given the five frequency entries			
		Frequency of "5" response (P1)	Frequency of "4" responses (P2)	Frequency of "3" responses (P3)	Frequency of "2" responses (P4)	Frequency of "1" responses (P5)	Total respondents (N)	Weighted total (WT)	RII	Item Mean
4	Using different source of information	1	2	5	4	1	=SUM(p1:P2)	=5*P1+4*P2+3*P3+2*P4+1*P5	=N/(5*WT)	=N/WT

Table 2.6: Spearman importance rank correlations between classes and stages

Class/stage	Pre-construction (%)	Construction (%)
Design/Engineering	95	53
Client	62	97
Contractor	42	95

Table 2.7: Spearman importance rank correlations between classes

Class/class	Design/Engineering (%)	Client (%)	Contractor (%)
Design/Engineering	100	-	-
Client	60	100	-
Contractor	23	83	100

Generally, Tables 2.3 and 2.4 illustrate RII calculation results based on Eq. (2), so using high-tech and expensive smart construction tools can be a bottleneck to cause delays, especially if the necessary skills and requirements are not available. This may be because of using a different source of information (more than 67%), lack of integrity information systems (more than 68%), ignoring or less attending real-time data flowing throughout the site for all parties, insufficient training, or less-skilled employees using critical features

of the software and communication devices. The correlation between client and contractor is more than 83%, potentially signifying knowledge sharing and good communication. However,

the contractor and design team struggle to communicate and share the project knowledge mindset, which is demonstrated by the significantly lower correlation of 25%. A big data management circulation gap appears in the project in which the client needs to take on all responsibilities. This research's essential contribution is to perform and recognize the state-of-the-art review and experimental study on the current literature and executed projects categorized in the smart level of the construction industry in New Zealand. Furthermore, the presented method can measure the correlation between variables in large-scale projects where the number of delay factors might be more.

2.7 CONCLUSION

While previous literature has considered the common and general causes of delay, this study introduced a new perspective into delays at the preconstruction and construction stages of smart and complex construction projects. Generally, the effects of delay are dictated on time, cost, and even quality of deliverables in construction areas, but when smarter methods are introduced, the projects are expected to become nimble or at least have much more controllable delays.

This study focused on presenting how and why smart construction projects suffer from delays, even using high-tech and smart tools. For instance, retrieving information, gathering and screening real-time data on-site, lacking multi-communication channels between parties, and crossed functions between parties and stages have been highlighted as critical items of delays. This study classified the leading significant causes and effects of delays in smart construction projects in New Zealand; the results can be considered in other industries or locations with the same features and attributes. The causes of delay have been categorized into three classes: design/engineering, client, and contractor, where coded with 20 causes.


Also, the RII and Spearman's rank correlation coefficient were used to prioritize the causes

of identified delay. RII also presented the acute effects of delay investigated, retrieved information gathered and real-time data screened on-site, and lack of multi-communication channels between parties and stages (pre and post-construction) as the most severe causes. In other words, the lack of an integrity system between the used technological tools and encountering different data sources illustrates a 70% impact on project delay. Moreover, the correlation between the contractor and design team decreased dramatically to less than 25%, while the correlation between the main contract, client, and design is reasonable, 60%. In contrast, client and contractors have more than 80% satisfaction, which shows a weak management cycle is running across the project (design to construction and vice versa) through the client's side.

Considering that in only the first 9 months a variation of around NZ\$8 million for electrical services was recorded, the projects were delayed by around 101 days. Meanwhile, those projects budgeted around NZ\$1.5 million for Aconex to keep the projects at low risk of delays (at least design and interaction delays), but the reality is those projects still struggle with the lack of a real-time communication channel. This research used a content validity measurement technique due to limitations in the quantity of data collection. Thus, the authors enlisted the owners' engineering team and construction supervisors to check the facilitated workshops' results as an audit process. Additionally, the authors could not get access to more than 27 projects because of two limitations: the first is that many projects of such size, value, and common features as mentioned are performed a few times a year, and second, there is not sufficient documentation regarding delays in projects accomplished before 2018.

STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name:	Kambiz Rdaman		
Name and title of main supervisor:	Mostafa Babaeian Jelodar		
In which chapter is the manuscript/published work?	Chapter 3		
Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work: ¹ Ratio of student to supervisory team 90:10, Student: Brought and Structured idea, Captured data, created model, Analysed, Drafted and Finilised Text Supervisory team: Conducted Study, Improved conceptual model, Reviewed and Finilised Text			
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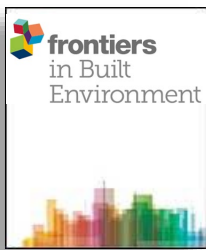
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Chapter 3: A SYSTEMATIC REVIEW OF DIGITAL TECHNOLOGIES IN CONSTRUCTION PROJECTS

The current chapter is based on the following article:

Radman, K., Jelodar, M. B., Lovreglio, R., Ghazizadeh, E., & Wilkinson, S. (2022). Digital technologies and data-driven delay management process for construction projects. *Frontiers in Built Environment*, 8, 1029586. <https://doi.org/10.3389/fbuil.2022.1029586>



Published in Journal of Frontiers in Built Environment

Objectives should be covered:

OBJ_3: Identify & Analysis Digital Technologies in construction projects

3.1 SUMMARY

One of the main challenges of construction projects is managing delays; there is still a lot to overcome to reach near-zero delay (mitigation of delays) in all construction projects. As technology and different platforms are applied to support high volume of data flow acquired from multiple resources during the construction project life cycle; how can these automated and digital progress tracking systems be considered for more effective construction delay management? The aim is to investigate the current state of real-time technologies and their applications and assess how specific attributes of these disruptive technologies can significantly alter delay management in construction industries. Therefore, this study presents a new process-

based framework for using technologies with a data lifecycle viewpoint. This research uses a four-step systematic literature review which involves, identification, screening, extortion-eligibility check, and finally selection-inclusion. This is then followed up by thematic content analysis on using new technologies to mitigate delays in construction projects. Key trends, themes, areas of concern for research, and limitations identified in previous literature as research gaps and future needs were documented and structure. This work presents a novel process of comprehensive classification of real-time technologies that are being used in the construction industry to acquire data, screen/analyses data, and present information through an Industry 4.0 application: IoT technologies such as sensors, RFID etc., smartphones, planning/scheduling tools (Ms Project, Primavera), and BIM. The developed process-based framework serves as a roadmap for key stakeholders in construction projects. This framework can cover the lack of strategic real-time communication between project knowledge areas and phases for incorporating a dynamic analytical tracking process into construction project delay management and resulting in enhance construction productivity.

3.2 INTRODUCTION

Delay is still one of the key challenges of construction projects. Construction projects are trailing different technologies to reach near-zero delay in all project life cycles; therefore, technologies have a significant role in improving productivity and reducing project timeframes as much as possible. Delays can lead to negative impacts such as broken communication among stakeholders (client, contractors), contract termination, low productivity and loss of revenue (Sepasgozar et al., 2015). Construction projects have complex and dynamic site jobs with many activities and resources, including software (manpower) and hardware (plant, equipment, and materials). Between 2006 and 2021, some statistical reports presented that cost overruns and

schedule delays are common problems, frequently leading to disputes and costly claims in construction project delivery (Perttula et al., 2006; Pinto et al., 2011; Li et al., 2016; Soltanmohammadlou et al., 2019; Shirowzhan et al., 2020; Brusselaers et al., 2021). In contrast, although construction projects use digital/real-time technologies, construction sites still experience many delays (Li et al., 2016; Gunduz and Laitinen, 2018; Bakeli and Hafidi, 2020).

Moreover, access to real-time project progress status reports is one of the key concerns for construction project decision makers (Gunduz and Laitinen, 2018; Getuli et al., 2020). Radman et al. (2021) have presented an analytical study to prioritise key factors causing delay and impacting project timely decisions regardless of using progress tracking systems in smart construction projects. In terms of “smart” terms in construction projects, a widely accepted definition of smart construction is “building design, construction and operation that through collaborative partnerships makes full use of digital technologies and industrialised manufacturing techniques to improve productivity, minimise whole life cost, improve sustainability and maximise user benefits” (Construction Leadership Council 2018; Bucchiarone et al., 2019; Radman et al., 2021).

Substantial research has been carried out on automated technologies in construction projects, such as the use of remote sensing technologies from 2D photo-feature extraction to 3D laser scanners; Radio Frequency Identification (RFID) tags for automated data acquisition in construction job sites; Ultra-wideband (UWB) for data detecting, acquiring, and monitoring; and access to real-time data Industry 4.0 focuses on digital technologies with the help of interconnectivity through using the Internet of Things (IoT) applications/technologies in the supply chain, safety, and project management concepts (Li et al., 2016; Asadi et al., 2018; Al-Saeed et al., 2019; Ghosh et al., 2020). Karmakar and Delhi 2021 have summarised the knowledge advancement of construction 4.0 to present technologies, and process conceptualisation that is nowadays associated with Industry 4.0 reverberate in construction 4.0

(Karmakar and Delhi, 2021). However, IoT-based sensors and technologies often lead to the generation of large datasets captured through construction scheduling, tracking, localisation, and 4D/5D-BIM in construction projects (Benjaoran and Bhokha, 2010; Omar and Nehdi, 2016; Karmakar and Delhi, 2021). From a scheduling point of view, automated technologies mitigate the potential negative impact of schedule delays and cost overruns, but they can also help improve safety and productivity on site (Cheng et al., 2017; Fujisaki, 2019; Yoshigai and Fujisaki, 2020). While the previous reviews present technologies for data collection and progress tracking systems, some concepts, such as management systems and automated and integrated management system applications, have received limited attention (Feng and Golparvar-Fard, 2019; Moselhi et al., 2020). For instance, Kazemian (2019) tried to present an efficient integrated management application, but it did not cover timely delay reports, disruption, clashes, productivity, and percentage completion from the site (Kazemian et al., 2019). In 2020, a comprehensive review of the digital twin concept was done by Sacks et al. (2020). They offered digital twin construction to manage production in construction by leveraging data streaming from various Industry 4.0 ideas. It was for site monitoring to accurately yield information status and analyse ongoing design, planning, and production proactively. However, some gaps have remained in their research: designing a suitable data storage mechanism, making each part of the system compatible with AI functions, decreasing the interpretation of multiple data streams during the project; and considering a commercial model (Sacks et al., 2020). However, regardless of a great work, some gaps can be recognised in Sacks' research such as a proposed workflow to support project stakeholders to proceed the decision-making process faster is not clearly mentioned.

While each of the mentioned research streams have provided a wealth of knowledge, these areas of knowledge are significantly fragmented and unconnected to each other. Some studies have focused on the particular role of automated management systems in analysing delays caused

by the location of workers, storage, equipment, and materials (Golparvar-Fard et al., 2009; Shahi et al., 2012; Guo et al., 2017; Kropp et al., 2018; Bortolini et al., 2019; Kazemian et al., 2019; Sheikhhoshkar et al., 2019). Furthermore, using automated project tracking systems such as expanding from single sensory analysis to multi-sensory, activity-based-data-fusion models and objective-based-data-fusion models (Li and Becerik-Gerber, 2011; Choe et al., 2014; Shahi et al., 2015; Omar and Nehdi, 2016; Choe and Leite, 2017; Hamledari et al., 2017; Labant et al., 2017; Kanan et al., 2018).

There is a need to clearly identify process(s) of state-of-the-art real-time data acquisition systems and fusion methodologies applicable for delay mitigation in construction projects and their associated challenges. Therefore, this study contributes to providing construction project decision makers with a deeper and richer understanding of the relationship between automated/real-time technologies and their role in each phase of project data flow (e.g. data collection; data screening; data fusing; data visualisation), to facilitate the application and integrated utilisation of these technologies. As a result, current research presents a novel process-based perspective using technologies through the data processing lifecycle that can prevent or mitigate site work delay(s) in construction projects. The study aims to provide a delay prevention roadmap via recommending and structuring fit for purpose technologies in right situation and right time. Accordingly, this work has highlighted the growing interest in reviewed literature through three classes and five key study streams which follows this research three core objectives will be mentioned in the next section:

Three classified classes: (1) data collection, (2) data screen and (3) data analysis.

Five study streams: (1) Identifying relevant trends of digital technologies across different thematic areas; (2) classifying the range of automated technologies in construction focusing on productivity/delay management; (3) classifying pros and cons according to real-time progress tracking and data management technologies to support delay management; and (4) proposing a

process-based framework of using digital technologies regarding delay management in the construction industry.

3.3 RESEARCH METHODOLOGY

This research addressed three core objectives: 1) Identify and conceptualise real-time technologies used in construction projects, with a focus on delay alert management; 2) Evaluate the advantages of integrating combined digital technologies versus stand-alone systems in construction project tracking management including delay and risk tracking; and 3) Evaluate digital technologies for managing data acquisition, screening, analysis, and presentation in construction projects, with an emphasis on delay alerts. For these purposes, through the systematic literature review, a significant amount of data holistically collected, assessed, synthesised, and converted into theoretical findings, specific gaps and requirements of the knowledge areas (Agudelo et al., 2019; Fink, 2019; Shafiee et al., 2019). More detailed investigation of study subjects through review of previous works enables the extraction of novel and new ideas (Kupiainen and Jansson, 2017; Kong et al., 2018). To perform an effective systematic review, four common steps suggested by Denyer et al. (Tranfield et al., 2003; Denyer and Tranfield, 2009; Briner and Denyer, 2012) as well as other authors have adopted a feature of the PRISMA statement (Moher et al., 2009; Page et al., 2021):

- Step one, identification: identify the main keywords and context based on the research objectives.
- Step two, screening: find relative publications based on the keyword identified in step one.
- Step three, extraction/eligibility: develop selection criteria for screening publications and identify the most relevant and critical publications.

- Step four, selection/inclusion: report the results of the review.

Figure 3.1 demonstrates a breakdown of the research strategy flowchart based on the four-step methodology: identify the need for the review; screen (based on title and Summary); extract (comprehensive, accessible research); and select (report the results).

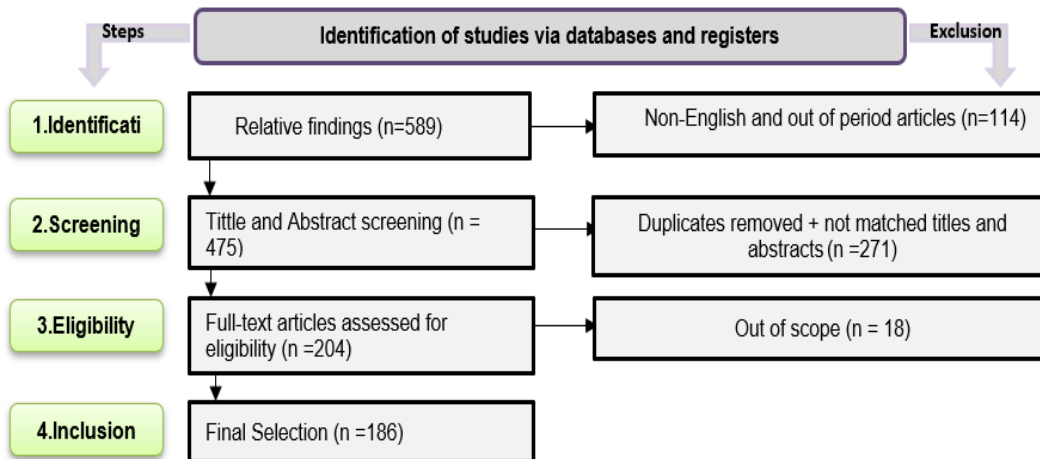


Figure 3.1: Search strategy flowchart

Several electronic databases were chosen to find the related publications/presentations: Scopus, Discover, Google Scholar, Web of Science, Elsevier, Taylor & Francis, Emerald, Springer, and American Society of Civil Engineers. To address our primary research objectives through four steps (Figure 1), the articles were searched through the title, Summary, or keywords during the last ten years to specify how eligible and relevant they were. The research strings for utilising introductory browsing are demonstrated according to the main subject under review. Hence, all scholarly papers that address strings were highlighted (Table 3.2). Due to the availability of a large amount of literature related to this study, step 3- Figure 3.1 (full-text articles) was defined as an eligibility criterion to evaluate independently by the authors based on a set of defined inclusion and exclusion criteria such as relevant date, language, document type limitation and subject areas (Table 3.1). Moreover, the current articles considered the topic of construction stages of a project lifecycle such as pre-construction, construction and post-construction; therefore, this research filtered the articles only focusing on the construction phase

purpose.

Table 3.1: Research Selection Criteria: Inclusion and Exclusion.

Research selection Criteria	Research Inclusion	Research Exclusion
Relevant dates and topics	Period: 2010 to 2022 Single and multiple sensory progress monitoring, automated systems in construction, delay management, productivity, smart construction project, Wireless Sensor networks, digital applications, Object detection, Activity detection, Tacking systems, delay in construction, Industry 4.0.	Out of period, type of technologies related to underground services and machinery.
Document type	Research articles containing literature Review, conceptual framework, case study (experimental, analytical, and modelling studies), thesis	Reports, Conference papers
Language	Full accessible studies in English	Non-English
Subject areas	Construction: site, project, industry	Post and Pre-construction phases of building lifecycle; studies referring to ONLY technologies in construction projects alone.

Post this stage, all potentially relevant articles were filtered by themes while those studies that fulfil the following criteria alongside the delay concept in the construction industry:

- focus on the progress tracking of construction projects
- focus on data management and
- focus on technology in construction management.

The selected keywords were classified into three themes for searching articles. The themes and selection of keywords are demonstrated in Table 3.2.

Table 3.2: Research strategy- Strings

Theme	Search strings	Boolean operator
Construction progress tracking	real-time^ OR progress tracking^ OR construction management systems^ OR smart construction^ OR automat^ OR delay management^ OR productivity	AND
Data management	Integrated management Systems^ OR data collection^ OR analysed data^ OR DBMS	AND
Digital technologies in construction productivity management	IoT technologies^ OR delay analysis^ OR sensory progress tracking^ OR non-sensory progress tracking^ OR technology	

Accordingly, all articles and documents meeting the inclusion criteria were selected for this study (Figure 3.1 - step 4). Furthermore, it included peer-reviewed journal articles and all of the

scholarly literature that addressed real-time, delay, automated, progress tracking, Industry 4.0 (IoT-based technologies) such as RFID, Global Positioning System (GPS), Ultra-Wideband (UWB), data acquisition and fusion, and/or their relevant terms in the field of construction job sites. Furthermore, a close examination of the articles and publications was conducted to identify and finalise the most relevant research area.

3.4 FINDINGS AND RESULTS

According to the steps defined in Figure 1, between 2010 and 2022, the total number of annually published studies on the current study topic is 589. Also, after applying the eligibility assessment (step 3 - Figure 1), 186 published articles were initially identified. The descriptive analysis was broken down into three aims as follows: (i) demonstrate insights according to current work trends in real-time technologies in the construction industry (Section 3.1); (ii) visualise the research approaches: stand-alone and combined based real-time technologies (Section 3.2); (iii) structure a framework of automated technologies in smart construction (Section 3.3).

3.4.1. Publications based on date and themes

The findings are structured in a brief description of publication sources, journals, research methods and smart technologies. Figure 3.2 summarises the 186 published studies on construction management topics from 2010 to 2022 (quarter 1). Overall, the outcome shows a growing research interest since 2014 over the studied time span specially after 2018. Approximately 52% of the studies are from 2018 onwards.



Figure 3.2: A number of publications Vs. published years

Figure 3.3 shows that publications with themes “Construction Progress Tracking” and “Technology in construction productivity management” have around 69% of the considered literature released in the time span (129 published out of 186). In contrast, in construction, “Data management” is the next place, with 57 articles (about 31%). This reveals there is a wide range of technologies for data acquisition/tracking within construction sites while managing data for specific purposes such as delay management, earned value management and smart progress tracking platforms is still growing.

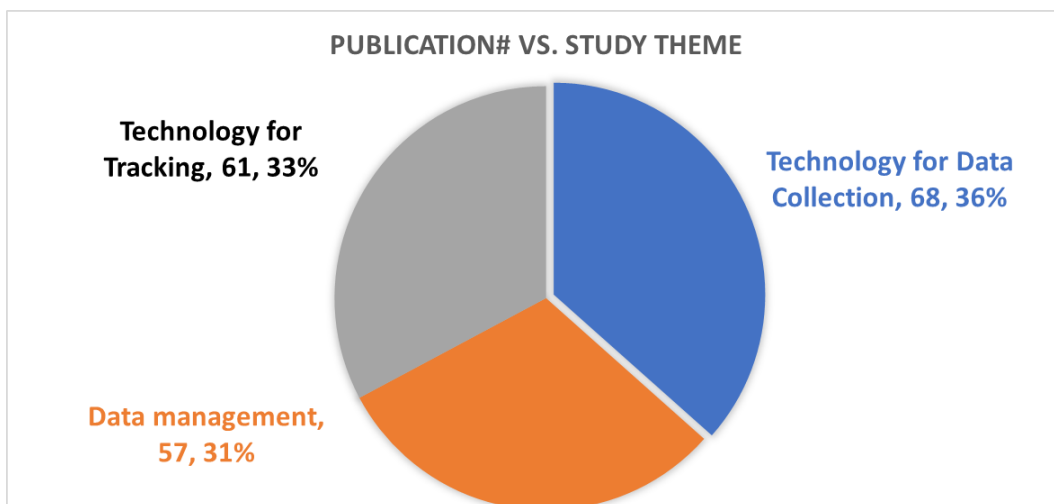


Figure 3.3: A number of publications Vs. Study Theme.

3.5 RESEARCH APPROACHES

Figure 3.4 illustrates different research approaches; those can be classified into two major groups and split into tools and technologies distributed from 2010 until 2022 (1st quarter). The first group includes 114 studies (62%) focused on stand-alone technologies and tools, which can vary depending on the data type (e.g., text, photo, number, drawing), data accuracy and the environmental situation in data acquiring. Primarily, this group provided a framework, model, and case study for approach(s) verification through site experiments or lab simulations. The second group consist of 72 articles with the focus on combined technologies regarding data acquisition and tracking systems. These articles have applied a hybrid method consisting of tools development or case-study for the survey. In general, the trend analysis indicates that the research trend in this topic is significantly chasing expanding promising real-time approaches of construction project management through developing novel and prototype tools and processes.

Method year	Standalone Technologies/Tools											Combined Technologies/Tools											
	Barcode	GPS, Bluetooth	Infrared	Laser scanning	Photo/Videogrammetry	RFID	Robotic total station	UWB	BIM	Smart Device	Sensore	**Planning Software (PS)	GPS + Barcode	GPS + RFID	Laser scanning + UWB	Photo/videogrammetry + UWB	Photogrammetry + laser scanning	Photogrammetry+ RTS station	RFID + Laser Scanning	RFID + WSN***	BIM + other applications****	Sensores + othe applications	
Total	114											72											
2010	2	1		2	2	1			1	1	1	1	1				2					1	1
2011	1				1	2		1	1		1	1			1		1					2	2
2012				2	1	2	1	1		2	2	1		1	1		1	1	1			1	1
2013		1			2	2	1		1			1	1	1	2			1		2			
2014		2		1		2		3	2		2			1	1							2	2
2015			1			1		1	3	1	2	1		2					1	1		2	2
2016					1	1		1	2	1		2		1								3	1
2017		1		2		1			3		2		1				1					2	1
2018		2			1	1			2	3	1									1		2	2
2019				1	1				2		2	1				1			1			2	
2020									3	2	1				1				1			2	2
2021									3	1	1	1					1		1			2	2
*2022									3		3											3	2

Figure 3.4: Publication distribution by research method and technologies.

Moreover, 46 articles validated their proposal using tools and technologies in the construction

industry through case-study in construction sites such as commercial buildings, road projects, or civil projects. However, material tracking systems use RFID Devices and Barcodes (QR) to identify materials in the supply chain management cycle (Juliana S Álvares & Costa, 2018; Han, Degol, & Golparvar-Fard, 2018; Tezel & Aziz, 2017). Vision-based technologies such as photogrammetry or video-grammetry and laser scanning were used to automate progress reporting and make 3D models in the construction industry (Cho, Park, & Kim, 2018). Augmented Reality (AR) is known as live, computer-generated imagery and physical view (direct or indirect) to augment the real-world environment in virtual elements. However, some key practical challenges of AR mobility still need to be considered, such as less user-friendly, power concerns, ability to function in harsh environments, uncontrolled conditions for robust image registration and noise filtering (A.-P. Wang, Chen, & Hsu, 2004) (JeeWoong Park, Chen, & Cho, 2017). Furthermore, BIM tools such as Revit, ArchiCAD, Navisworks and BIM360 can be used as data acquisition features for smart information systems in construction projects. For instance, BIM360 is a cloud-based app to collaborate and report information such as marked-up drawings, modified drawings, and record modifications to manage real-time data from a cost viewpoint (H. K. Eliwa, Jelodar, & Poshdar, 2022; A.-P. Wang et al., 2004).

In contrast, construction progress monitoring is supported by a variety of tools and technologies such as (i) project management tools (e.g. Primavera, Ms project, Team planner) to monitor progress, track status and delays through the project; (ii) 4D-BIM (integration of scheduling tools such as primavera/Ms project and BIM); (iii) photogrammetric 3D mapping such as using Unmanned Arial System imagery and performance indicators; (iv) a combination of schedule tolls with 3D sensing technologies and 4D CAD modelling (H. Eliwa, Jelodar, & Poshdar, 2018a; Changyoon Kim, Kim, & Kim, 2013; Turkan, Bosche, Haas, & Haas, 2012) and using sensors to optimise resource tracking by applying electromagnetic stimulation (Cho et al., 2018). Some hybrid-tracking systems integrate BIM, Bluetooth Low Energy (BLE)

technology and motion sensors to acquire location awareness of assets (JeeWoong Park et al., 2017). In regards to vehicle tracking system, A.-P. Wang et al. (2004) used three ultrasonic sensors alongside a laser radar which are integrated with the CAN bus, a Controller Area Network is a robust vehicle bus standard designed to apply microcontrollers and devices to be able to communicate with each other's applications without having host computers.

They used CAN bus to build the in-vehicle network architecture to illustrate different directions to the driver. Around 2011 an algorithm was presented and utilised for real-time safety management in construction sites (Carbonari, Giretti, & Naticchia, 2011). Accordingly, key Industry 4.0 technologies (Turner, Oyekan, Stergioulas, & Griffin, 2020) such as IoT devices (e.g. smartphones, sensors, robots and cameras), artificial intelligence, cloud, fog and edge computing technologies offer new opportunities to provide the essential dependability to time-critical smart construction projects such as construction site management (e.g. process tracking, workers' locations, BIM) and construction monitoring (e.g. quantitative status, trades positions, terrain reconstruction). Some challenges still exist and need to be addressed, such as the application of fast application performance vs. requirements for low cost operations; or fusing data requirements vs. data privacy requirements (Štefanič & Stankovski, 2018; Zambrano, Perez, Palau, & Esteve, 2014). Therefore, Irizarry et al. (2013) presented how digital technologies such as BIM, GIS, GPS, UWB, RFID, AR/VR, and LADAR imaging have been used in real-time data acquisition. They focused on integrating BIM and GIS, which are used to improve the construction visual monitoring regarding supply chain management. GIS technology may deliver location information that can eliminate site workers' intensive data collection and labour costs and reduce data entry errors (Irizarry, Karan, & Jalaei, 2013).

Nowadays, smartphones come with modern sensors, onboard storage, computing processes and communication facilities. Smartphone-driven monitoring systems have been used in healthcare systems (Mahmud, Wang, Esfar-E-Alam, & Fang, 2017); localisation solutions for

construction site management (De Dominicis, Depari, Flammini, Rinaldi, & Sisinni, 2013; Enck et al., 2014); vehicle tracking systems (S. Lee, Tewolde, & Kwon, 2014); unsupervised construction of an indoor floor plan (Shin, Chon, & Cha, 2011) and remote indoor construction progress monitoring (Khairadeen Ali, Lee, Lee, & Park, 2021). While dozens of studies focus on modern smartphone features (e.g. sensors) and applications (such as live chat, email, photo, and video) through instruments with a variety of sensing modules, several of the existing studies merely utilise the data acquiring (methods and process) by smartphone technologies. Moreover, smartphones can drive timely decision processes faster for project managers in smart construction projects (Alavi & Buttlar, 2019; Villalba, Orozco, Corripio, & Hernandez-Castro, 2017).

Through previous literature reviews, X. Li, Wu, Shen, Wang, and Teng (2017), Oraee, Hosseini, Papadonikolaki, Palliyaguru, and Arashpour (2017) and X. Wang, Truijens, Hou, Wang, and Zhou (2014) have presented the similar concept of “location systems” but in different situations and purposes; for example:

- Real-time location systems are based on the Time-Of-Arrival functionality such as GPS, Ultra-Wideband (UWB), and Robotic Total Station.
- People and object tracking, and localisation systems are using Wi-Fi/Bluetooth technologies to measure occupancy.
- Location estimation systems use location and behavioural algorithms through smart devices (phone and watch) and Bluetooth headsets to track the changes in the received electromagnetic waves related to the number of people or vehicles on site.

In general, some articles have involved more than one type of tool or utilised a combination of them. 40 papers out of 72 (56% of combined technologies/tools) applied a variety of BIM or sensors with other applications/technologies such as Industry 4.0 (IoT, robotics, artificial intelligence, BIM, automation, digital twin, sensors and wearables), RFID, augmented reality,

and planning software that has the most frequency. For effective delay management (site productivity), timely availability of accurate data is essential. Project stakeholders, especially project managers, would be able to make timely decisions to manage delays and disruptions in the project (T. Omar & Nehdi, 2016; Ramachandran & Perumal, 2018). For instance, one of the most encountered methods related to the construction delay claims is comparison of “As-Planned” vs. “As-Built” events and data. This method simply can compare what was supposed to happen to what happened actually. Therefore, “data” power and role must be significantly considered (Atanasov, Greenwood, & Robson; El-Samadony, Tantawy, & Atta, 2020; Türkakın, Manisalı, & Arditi, 2020). In contrast, it is worth noting that the real-time data tracking approach is categorised as part of automation topics in the construction industry. It has been increasingly investigated in the last decade (Kropp, Koch, & König, 2018; N. Li & Becerik-Gerber, 2011). Furthermore, Turner et al. (2020) addressed a comprehensive review of Industry 4.0 technologies adopted within the construction industry. While the complexity of construction projects is increasing, it illustrates how industrial connectivity tries to make sure all Industry 4.0 technologies keep interconnecting for higher productivity within the construction industry. (2019) reviewed the vital benefits and barriers of digital technologies being used in New Zealand to improve construction industry productivity, focusing on cost reduction engineering and Ubiquitous Digital Access.

3.6 DISCUSSION

As illustrated, previous literature have focused on how to obtain data from construction sites via digital technologies to track site progress, people, locations and productivity (Radman, Jelodar, Lovreglio, Wilkinson, et al., 2022). However, these studies have different views of the role of data in construction delay management, and there is no streamlined process of data

collection to data analysis/presentation cycle for this purpose. Accordingly, based on the literature evidence gathered a process-based framework is proposed to facilitate decision making, manage data obtained and mitigate possible delays in a timely and effective manner (Figure 3.5). But, before demonstrating the proposed framework in detail, some of those technologies use and patterns of the combined technologies through each step of data collection to data analysis have been identified for certain purposes:

Communication devices: The general form of communication is defined as “Media”, which comprises documents, audio, and videos. From a real-time perspective, smart industries are progressively interested in coping with media communication as an easier and faster way to collect data (T. Omar & Nehdi, 2016). Literature shows that since 2010, digital communication channels such as audio recordings, low pixel digital photographs and low size videos have been used for analysing delays in the construction industry. The project team usually attach them as a support document to activities scheduled through the construction programme (Abdelrehim, 2013; T. Omar & Nehdi, 2016). From the visualisation point of view, multimedia is very popular and desirable due to its capability to highlight problems understandably (T Hegazy, Attalla, Hayter, & Penny, 2008; Kamarah, 2019; T. Omar & Nehdi, 2017). Another way to collect information is smartphone features such as QR code scanning and many other applications capable of construction site teams entering where they have started and finished assigned tasks with low maintenance requirements and infrastructure costs (Babaeian Jelodar & Shu, 2021; Mohagheghi-Fard, 2019; Zhao et al., 2019). Moreover, email communication is an official channel to keep all workflow tracking evidence for future claims (Dhiwar, 2021; Feather, 2007; Morales & Beis, 2021). However, the sender and recipient can have enough time to review inquiries and resolve any issues in time. While there are many advantages for projects to uptake this class of technologies, there are some limitations. For instance, access to a stable and fast Internet connection is required. The ability to add features by means of typing is limited, easy

typo mistakes on smart devices can happen, and privacy on video chat depending on the type of project also is a concern (Leung, Mak, & Lee, 2008; H. Omar, Mahdjoubi, & Kheder, 2018). Hence, further dedicated research to minimise limitations and risks in addition to increasing efficiency is required.

RFID and Wireless Sensor Networks (WSN): In the integrated system based on RFID and WSN, all assigned sensor nodes can identify and detect tagged objects through readers (Q. Zhu & Cai, 2021). The smart node readers detect the tagged objects to recall them conveniently (Bae & Han, 2019; Nunnally, 2014). However, sensors and RFID tags must communicate conveniently to increase tracking system efficiency and productivity, so targeting and embedding a wide range of sensor nodes with RFID tags and readers is necessary (Ibrahim, 2015; Salama, Salah, & Moselhi, 2021). Furthermore, the hybrid approach of RFID and WSN prepares for better communication between RFID tags, RFID readers, and tag-readers by increasing positioning accuracy and enhancing the tracking system's efficiency (Landaluce et al., 2020). Table 4.6 shows the advantages and disadvantages of RFID and WSN technologies.

RFID and Laser Scanning (LS): The combination of LS and RFID technologies could be utilised to gather the type of information required from each object or activity (Ando et al., 2020; Fu et al., 2020). In other words, this combination has an acceptable accuracy by measuring angular error and localisation setup within acceptable degrees and a few centimetres. So, for point cloud data acquisition, the process of object recognition is facilitated. Moreover, Table 4.6 shows some advantages and disadvantages of each of them individually: LS and RFID combined can process object recognition out of the point cloud data; hence it would not necessarily be limited to non-structural or structural components. This combination of technology can generate 3D models of each piece of the object on the site (Marocco & Garofolo, 2021). However, some limitations can occur, such as degraded localization accuracy based on objects' location. For instance, at the corners or blind angles, data acquisition and tracking will be challenging.

Creating a database that captures all available objects onsite is a key predecessor of a complete and accurate model (Cheung, Lin, & Lin, 2018; Khosrowshahi, 2017; Yan, Sedykh, Wang, Yan, & Zhu, 2020).

Laser Scanning (LS) and Ultra-Wideband (UWB): One type of indoor positioning system is called Ultra-wideband. The high bandwidth and high frequency are UWB system features, so a large amount of data could be transmitted during a short period (Maalek & Sadeghpour, 2013; Svalastog, 2007; F. Zhu et al., 2014). Furthermore, the accuracy of LS in measurement is about 2% volumetric error while, depending on the application, up to a few centimetres in range. Table 4.6 illustrates a few capabilities and limitations of each of them briefly. Conversely, as a capability, the integrated application of LS and UWB provides less accumulated error and facilitates having prior technical knowledge.

Photogrammetry/Videogrammetry (PVG) and Laser Scanning (LS): LS and PVG offer real-time data acquisition capability, reduced scanning time, and robust procedures for images. Accordingly, more accurate and acceptable 3D model outputs are achieved (Sommer & Seiffert, 2022; C. Wang et al., 2021).

Remote systems (RS) technologies: This study has reviewed and classified a wide range of remote systems (RS) technologies for automated data acquisition and fusion in the construction industry. More specifically, those methods integrate various RS technologies to increase productivity and data accuracy on site. Therefore, according to popularity in data accuracy and affordability, Table 3.3 provides an overview of those technologies along with some of the benefits and drawbacks such as pairing of radio frequency identification (RFID) and Wireless Sensor Networks (WSN); RFID and Laser Scanning (LS); Laser Scanning (LS) and Ultra-Wideband (UWB); and Photogrammetry/Videogrammetry (PVG) and Laser Scanning (LS) (Bansal, 2021; Boje, Guerriero, Kubicki, & Rezgui, 2020; Ekanayake et al., 2021; Liu, Liu, Yang, Hao, & Bao, 2021; Moselhi et al., 2020b; Naghshbandi, Varga, & Hu, 2021; Razavi &

Haas, 2011; Valinejadshoubi, Moselhi, Bagchi, & Salem, 2021). Moreover, Kopsida et al. (2015), Han et al. (2018) and Álvares and Costa (2018) published that there is a significant growing recognition among a wide range of researchers that utilise visual data technologies/tools to improve communication and measuring of the construction progress. However, they acknowledge that still a lot of work needs to be done to formalise, develop, implement and validate methods based on technologies/tools such as 3D mapping (e.g. BIM) for optimisation of the construction progress tracking (Juliana Sampaio Álvares, Costa, & de Melo, 2018; Han et al., 2018; Kopsida, Brilakis, & Vela, 2015).

4D Scheduling (3D plus project management tools): The integration of 3D models with project management scheduling tools (PMST) such as Primavera or Ms Project is called a 4D scheduling model (Ando et al., 2020; Asri & Susetyo, 2020; Kakde & Desai, 2017; Romigh, Kim, & Sattineni, 2017; Vanhanen, 2021). As a result, the project team can see how the project is planned, what the final post-construction facility is going to look like and, at the same time, monitor project time and cost. It has changed and enhanced monitoring processes such as earned value management. Several commercial software packages for project management systems are available. However, Oracle and Microsoft are the most popular providers of project management software such as Primavera and Ms Project to schedule and track project progress as accurately as possible (Vanhanen, 2021; Waszkiewicz & Gumienny, 2021). Moreover, most project management tools have a web-based version because it is accessible to onboard users, providing a login, unlimited access to real-time data, and up-to-date tools/software (Habuzza, Khalil, Zaki, Alnajjar, & Gochoo, 2020). All are stunning matters unless data acquisition and fusion mechanisms are reliable and upgraded. A most comprehensive review of digital technologies in the construction industry in terms of productivity improvement view is Chowdhury et al.'s (2019) work. So, despite the considerable quantity of publications on digital technologies/applications in the construction industry, studies on the process-based functional

roles of digital technologies to directly address delay management through productivity managing or cost control are scattered. Thirty two identified digital technologies with key functions outlined were compared (Chowdhury et al., 2019). The current study has used those comparisons and has summed up those digital technologies that have been highlighted regarding productivity concerns in construction projects. Tables 3 and 4 list the key advantages and disadvantages of single and combined digital technologies.

Table 3.3: key advantages and disadvantages: single digital technologies

Technology	Advantages	Disadvantages
RFID	<ul style="list-style-type: none"> • Light tags • Batch readability of tags • cost-efficient location information 	<ul style="list-style-type: none"> • limited coverage • for active tags, battery replacement is required. • Lack of accuracy (around 3%)
<i>Reference</i>	<i>Rashid and Louis 2019; El-Omari and Moselhi 2011; Bae and Han 2019; Pătrăucean et al. 2015; Kim, Son, and Kim 2013; Turkan et al. 2012</i>	
WSN	offers good radio coverage	low positioning accuracy (2.5%) due to high noise on Received Signal Strength Index (RSSI) measurements
<i>Reference</i>	<i>Subedi, Pauls, and Zhang 2017; Maneesilp et al. 2012; Moretti et al. 2019; Valero and Adán 2016; Elghaish et al. 2019</i>	
LS	Compatible with: CAD, BIM, Point cloud data	<ul style="list-style-type: none"> • do not address the need for modelling all available objects • Room to be as empty as possible when scanned • Less accuracy (around 4.6%)
<i>Reference</i>	<i>Moselhi, Bardareh, and Zhu 2020; Raza 2017; Baronti et al. 2018; Mendoza-Silva, Torres-Sospedra, and Huerta 2019; Ruiz and Granja 2017; Abdelhafiz and Mostafa 2020; Julin et al. 2019; Alshawabkeh 2006; Hamledari et al. 2017; Shahi et al. 2012</i>	
UWB	Large bandwidth, High accuracy (achieved centimetre) and low power consumption	<ul style="list-style-type: none"> • not reach 100% of coverage for the area tested • line-of-sight technical issues
<i>Reference</i>	<i>Shahi et al. 2012; Aryan, Bosché, and Tang 2021; Kapogiannis et al.; Golparvar-Fard et al. 2011; Chen et al. 2019; Park, Cho, and Martinez 2016</i>	
PVG	Easy interpretation, Probability, Recognisable objects colour, material and texture and Suitable references for inspection	<ul style="list-style-type: none"> • 2% error in volumetric measurement • Objects' configuration error with unclear geometric • Less accurate (~2%) than laser scanners
<i>Reference</i>	<i>Moussa and Fritsch 2010; Akmalia et al. 2014; Julin et al. 2019; Liu and Kang 2014; Brunetaud et al. 2012; Zhang and Lin 2017; Moselhi, Bardareh, and Zhu 2020; Arslan, Cruz, and Ginhac 2019; Feng and Golparvar-Fard 2019; Shahi et al. 2012; Kapogiannis et al</i>	
BIM	<ul style="list-style-type: none"> • Cloud-based • Record daily reports • Track daily Ready for Information (RFIs) • Notes and photos are attached • Marked up drawings are attached 	<ul style="list-style-type: none"> • Not automatic links between progress reports and the planned schedule • Expensive (licence based) • Need skilled and experienced people • Access Internet for cloud-base version • Marked up drawings are not linked to related activities.
<i>Reference</i>	<i>(Bortolini, Formoso, & Viana, 2019; Hamledari, McCabe, Davari, & Shahi, 2017; Kropp et al., 2018; Mirzaei, Nasirzadeh, Parchami Jalal, & Zamani, 2018; Sheikhhoshkar, Rahimian, Kaveh, Hosseini, & Edwards, 2019)</i>	
PMST	<ul style="list-style-type: none"> • Popular to use • Match Ms Office (e.g. Excel) • Cloud-based • Track progress and EVM 	<ul style="list-style-type: none"> • Expensive (licence based) • Need skilled and experienced people • Access Internet for cloud-base version • Different engines with different software compatibility
<i>Reference</i>	<i>(Ando et al., 2020; Asri & Susetyo, 2020; Kakde & Desai, 2017; Romigh et al., 2017; Vanhanen, 2021).</i>	

Table 3.4: key advantages and disadvantages: combined digital technologies

Technology	Advantages	Disadvantages	Reference
Real-Time Communication Channels	Review questions and answers; Attach media and documents; Visual data recording; Quick responses; Timesaving, efficiency, and convenience	Internet Access; Probably manual process; Time shortage to respond; Mistaken responses	(Al-Halafī, Oubei, Ooi, & Shihada, 2017; Parag, Taghavi, & Chamberland, 2017; Salazar-Gomez et al., 2017)
Photogrammetry + laser scanning	Easy scanning; Less computational effort; Object recognition capabilities; Convenient for modelling objects; Accuracy in the localisation of edge points; 3D modelling geometry and visual quality; Cameras Self-calibrating	Expensive; Georeferencing issue; Less effective in a crowded site	(Agha & Monnet, 2019; Alshawabkeh, 2006; El-Omari, 2008; Ibrahim, 2015; Khatiwada & Budge, 2019; Moselhi et al., 2020b; Raza, 2017; Zou, Gonzalez, Lim, Amor, Guo, & Jelodar, 2019)
Laser scanning + UWB	High visibility against fog and dust; Less accumulated error; Ease of need for prior knowledge or control inputs	Accuracy of UWB mapping; High implementation cost	(Cai, Jeon, Cai, & Li, 2020; Moselhi et al., 2020b; Shahi, Safa, Haas, & West, 2015)
UWB + Photogrammetry / videogrammetry	Reliable positioning; High accuracy; Timely information; Less computational effort; Portability	Calibration difficulties; Error propagation phenomenon; Less accuracy against georeferenced technologies	(Z. Ahmad, Thaheem, & Maqsoom, 2018; H. Li et al., 2013; Masiero, Fissore, & Vettore, 2017; Moselhi et al., 2020b; Shule, Almansa, Queralta, Zou, & Westerlund, 2020; Siddiqui, 2014)
RFID + laser scanning	In 3D modelling: robust recognition and fast positioning; high accuracy in a crowded environment	Poor performance for corner positioning; relatively expensive; objects availability is required	(Ekanayake et al., 2021; Lu & Lee, 2017; Ma & Liu, 2018; Valero, Adán, & Bosché, 2016; Valero, Adan, & Cerrada, 2012; Q. Wang & Kim, 2019)
RFID + WSN	Tags communication; negotiation of RFID; readers together; high positioning accuracy; less energy consumption	Passive sensors; wide range using high energy	(Ashraf & Osama, 2019; Cheung et al., 2018; Ibrahim, 2015; Moselhi et al., 2020b; W. Wu, Yang, Li, & Chew, 2013)
4D Scheduling Technologies	Complete detail; compatibility with technologies; timesaving. possible to make future maintenance; easy plan management	High cost: unique apps needed; skill-based	(Dallasega, Rojas, Bruno, & Rauch, 2019; Hartmann, Gao, & Fischer, 2008; Changmin Kim, Son, & Kim, 2013; Mirzaei et al., 2018; Pătrăucean et al., 2015; Turkan et al., 2012)

3.7 PROPOSED FRAMEWORK

All From the selected literature, a set of insights can be derived for delay management

purposes. This involves the shortcomings of real-time process-based technologies, applications, and usability across smart construction industries. In addition, As seen in section 4, automated technologies for progress tracking and timely reports on construction projects are embraced in many research studies and provide various opportunities for the sector regarding increasing or optimising productivity through managing delays, reducing costs or people monitoring. However, issues and challenges also arise similar to other technologies emerging across various industries. In addition, there are gaps in the literature and industry documentation that require further development. Some of these areas are accordingly discussed from different vantage points:

- **Delay management viewpoint:** It needs to be considered that the captured data from the site through single and multiple sensors have to be integrated, screened and analysed accurately. Figure 3.5 (proposed framework) illustrates an overview of an interactive dynamic relationship between class(es), database(s) and decision-making layers. It shows how this is essential to be defined and customised within the unique scopes of projects. For instance, the progress tracking process in Figure 3.5 shows an overlapping between data acquisition and data screening. It means once finalising data screening, there still needs to be awareness of the source of the data and their level of accuracy.
- **Process-based digital technologies viewpoint:** Figure 3.5 depicts a process-based framework of key classes and their applications through the data life cycle. Meanwhile, Table 3.4 addresses some benefits and drawbacks of digital technologies/applications from a real-time data acquisition and fusion perspective. This means real-time applications such as timely communication tools, sensory technologies and project management tools can be used to make real-time decisions. Moreover, all layers are being used with slight overlapping based on the data cycle nature.
- **Real-time integrated delay management systems:** As seen in Figure 3.5, the integrated

methods might be identified, applied, and validated in the construction industry. This means throughout the project the process and data life cycle have to be monitored and developed based on the project's needs. In other words, delay and risk factors can be monitored and analysed timely and continually by tracking critical indexes such as Baseline Variances; Earned Schedule (ES); Earned Value Management (EVM): Cost Performance Index (CPI), Schedule Performance Index (SPI); and Delay caused/causing item(s) such as lack of resources, clashes, incidents, material, invoices. (Decision Making layer in Figure 3.5). As a result, Figure 3.5 proposes a blueprint of the framework that shows the key interactive dynamic relationship between class(es), database(s) and decision-making layers which were mapped in three layers, including their tools and technologies as follows:

(i). Layer 1 – Classes:

Class 1 (Data Collection) comprises real-time communication channels (or at least with less transmission latency) such as smartphone features and applications or smart devices (e.g., handheld computing) and augmented reality such as HoloLens. Class 2 (Data Screening) includes the combined Industry 4.0 technologies/tools such as IoT, robotics, artificial intelligence, BIM, automation, digital twin (Boje et al., 2020; Shirowzhan, Tan, & Sepasgozar, 2020), sensors and wearables, or some other samples such as photogrammetry + Laser scanning, Laser scanning + UWB, Laser scanning + RFID and Photogrammetry + UWB. Class 3 (Data Analysis/Presentation); presents 4D technologies/tools such as BIM and project management scheduling tools (PMST), Primavera and BI tools (PowerBI, ExcleBI), augmented reality (e.g., HoloLens) and BIM and PMST.

Layer 2 in the proposed framework (Figure 3.5) shows a straightforward pre-processing process (into classes), repairing, analysing, and storing the data acquired from the class 1 data streams. Throughout the framework, a relational DBMS is defined to store data and develop analytical query language, which is translatable into structural query language (SQL)

expressions. The proposed DBMS has the potential to extend the use of multiple data flowing among classes to (i) record site status progress, document management, scheduling, and quantity of site productivity in construction projects; and (ii) analyse delays through the recorded/stored data by decision makers. Therefore, from a construction management professional’s perspective, DBMS design knowledge and its manipulation must be highly considered.

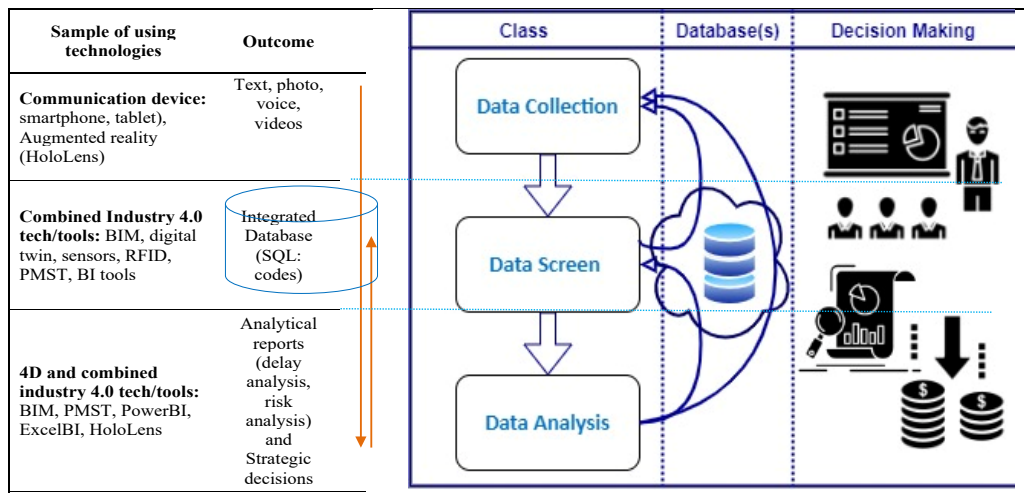


Figure 3.5: The Proposed Framework

(ii).Layer 2 – Database(s):

In Figure 3.5, all classes must communicate and collaborate through a central cloud-based database, so new queries can be created to manipulate the scope of the streamed data, which is achieved and screened through class technologies and tools. The framework supports discovering real-time project delays, identification and analysis of construction site activities. As a result, to cover previous review gaps in terms of lack of a process-based view, we found having a database-based framework must be practical relational DBMS as generalised infrastructures.

(iii). Layer 3 – Decision-Making

Data is raw and constitutes the certainty's values, while information is interpreted from the collected data. However, knowledge is key to bringing up the right actions through the decisions taken based on the generated information (Allen & Terry, 2005). In the proposed framework,

layer three can use 4D technologies supported by relevant tools and technologies to enable decision makers to identify delays and analyse them timely. Therefore, data should be organised throughout the classes and database to provide a set of usable information. Thus, in light of reached out information, timely and reliable knowledge enables decision makers to specify and analyse project progress and delays (Allen & Terry, 2005; Turner et al., 2020). DBMS are vast in use between layers for diagramming of data modelling, a transition of data to reliable information, definition and design of the required structure of data in terms of delay identification (Bilgin, Eken, Dikmen, & Birgonul, 2015; Özyurt, 2018).

3.8 CONCLUSIONS

Delay management through tracking productivity (cost and schedule) is still a significant concern in the construction industry. Construction project managers encounter a notable delay in project delivery from a cost and/or schedule point of view. Many technologies are available to assist project key stakeholders via digital information flow by providing timely and accurate reports on the progress of construction projects. To mitigate the risk of delays, all project key stakeholders need to access timely, more frequent, and precise information, then make the updated progress reports, including earned value management analysis, to track delays during construction projects. Hence, studies are abundant in conjunction with automated data acquired from construction sites that address the mentioned challenge through a more accurate integrated digital technologies proposal. The chosen technologies are presented and compared based on various factors such as data acquisition effort, processing time, affordability, data accuracy and reliability, and scalability. Furthermore, this study presents a different view of a process-based perspective on the data life cycle: data collection, data screening, data analysis and data presentation (Figure 3.5). As a result, the proposed framework includes three-layer classes,

databases and decision makers. This DBMS-based system plays an integrated management system role in order for data be processed and updated continually, is a user-friendly design, entity relationship diagrams provide valuable information for DBMS developers and also is user-friendly for non-technical people to get insight into the data model (Oppel, 2010; Ptitsyn, Radko, & Lankin, 2016).


On the other hand, timely accessible DBMS makes capable project decision makers establish delay knowledge and real-time coping with delays in construction projects. Moreover, relevant key trends, themes and technologies in construction projects and their advantages and limitations in previous literature are allocated in each class. The novelty of this research refers to an integrated “process-based framework” of the data life cycle (data flow) from acquisition to real-time analysis and presentation via using the proper applications/technologies alongside cloud base DBMS in the right place to protect the project against site delays. This type of view has been rarely discussed through previous literature reviews to identify research gaps and future exploration. However, the current study found that focusing on dynamic data processing is key, but it has been rarely investigated previously.

Therefore, for this purpose, the process of data acquisition, analysis, and presentation to real-time decision making should be reviewed from a delay management perspective to achieve timely and accurate purposes in the projects. Purposely, Figure 3.5 has structured a simple process to (i) identify the progress tracking process from data collection to make a timely report (for a real-time delay management approach); (ii) classify the type of technologies/tools used in each of those processes; (iii) find gaps and do re-structuring.

The proposed framework can be used in all phases of the project life cycle to get insight into projects' risky/critical activities. Apart from a facilitating information capture tool for creating a delay/risk log; it can be used as a vast pool of lessons learned from obstacles/bottlenecks encountered. However, it needs more investigation in the future, such as into integrated

management systems, relationships, types of entities, sorts of data flow, and so on.

STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.			
Student name:	Kambiz Rdaman		
Name and title of main supervisor:	Mostafa Babaeian Jelodar		
In which chapter is the manuscript/published work?	Chapter 4		
Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work: ¹ Ratio of student to supervisory team 90:10, Student: Brought and Structured idea, Captured data, created model, Analysed, Drafted and Finilised Text Supervisory team: Conducted Study, Improved conceptual model, Reviewed and Finilised Text			
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Chapter 4: Real-Time Tracking and Analysis in Construction Projects: A RealCONs Framework

The current chapter is based on the following article:

Radman, K., Jelodar, M. B., Lovreglio, R., Ghazizadeh, E., & Wilkinson, S. (2025). Real-Time tracking and analysis in construction projects: A RealCONs framework. *Advanced Engineering Informatics*, 67, 103511. <https://doi.org/10.1016/j.aei.2025.103511>



Published in Journal of Advanced Engineering Informatics

Objective should be covered:

OBJ_4: Develop a Proposed Framework

4.1 SUMMARY

Construction projects increasingly rely on processing vast amounts of data from multiple sources, including consultants (BIM), cloud-based project management platforms (e.g., Acoex), planning departments, construction sites, main contractors, and subcontractors. However, inefficiencies in data acquisition and reliance on manual data entry hinder real-time project analysis, delay notifications, and decision-making. This study introduces the Real-Time Data-Driven Construction Project Analysis Framework (RealCONs) to address these challenges by streamlining data flow and enhancing project performance. A comparative analysis used eight case studies four employing the existing approach and four utilising RealCONs—to assess improvements in data integration, early delay identification, and decision-making efficiency.

The results, validated through Earned Value Management (EVM) and Earned Schedule Management (ESM) metrics, demonstrate that RealCONs significantly enhance project forecasting accuracy, schedule adherence, and cost management. Additionally, statistical analyses, including the Shapiro-Wilk test and the Wilcoxon Signed-Rank analysis, confirm that RealCONs outperform the existing approach by reducing data collection and decision-making delays, enabling project managers to implement proactive mitigation strategies. These findings highlight RealCONs' potential to improve project efficiency, reduce costs, and optimise real-time construction management.

4.2 INTRODUCTION

Construction project management continues to face persistent challenges, notably delays, cost overruns, safety risks, and inefficiencies in resource allocation [1-4]. A critical underlying issue is the lack of real-time, integrated information, which undermines timely decision-making and effective project control [5, 6]. Traditional project management methods, reliant on manual data entry and periodic reporting, are often inadequate for modern construction environments' dynamic and fast-paced nature. Although technologies such as Building Information Modelling (BIM), the Internet of Things (IoT), Geographic Information Systems (GIS), and cloud platforms have introduced promising tools for digital project management, their application remains fragmented and limited [7-12]. BIM is frequently restricted to specific project phases and lacks the capacity for real-time, multi-stakeholder integration [13]. Similarly, platforms like Aconex support collaboration but struggle with cost-efficiency, interoperability, and underutilisation [12, 14]. Emerging solutions—such as AI, digital twins, and real-time analytics—have shown potential in academic literature [6, 15, 16], yet practical implementation across construction projects remains limited. A key gap persists: the absence of an integrated framework that enables

real-time data acquisition, processing, and dissemination across stakeholders. This limitation is particularly evident in delay analysis, where a lack of automation and predictive systems hinders early risk detection and timely intervention [17, 18]. Recent research has highlighted the value of real-time technologies in enhancing decision-making and risk mitigation. IoT-enabled systems, for instance, have improved site safety through live monitoring, such as those by Li, Su [19], Zhang, Guo [20] and Liao, He [21], while AI models have demonstrated capabilities in predictive risk management [16, 22]. Despite this, the construction industry still lacks an integrated, centralised approach to real-time project tracking, especially one that reduces dependency on individual managerial knowledge and enhances data continuity. These advancements are particularly relevant given the significant financial and operational consequences of delays, as evidenced by recent case studies. For instance, analyse delays in mega-projects, revealing substantial cost overruns and schedule deviations that could have been mitigated through proactive, data-driven management [23-25]. Furthermore, Kalf, Ibrid [26] and Guo and Lu [27] quantified the impact of inefficiencies in construction supply chains, demonstrating how delays ripple through projects, leading to increased costs and reduced client satisfaction.

Despite the availability of advanced technologies, integrating real-time data analysis into construction practices remains a challenge. Many existing systems, such as cloud-based project management platforms and BIM-integrated tools, are limited in their ability to provide comprehensive project analysis and budget control. It is primarily due to the lack of reliable real-time data from multiple sources, including engineering teams, subcontractors, and clients [14, 28, 29]. Moreover, the dynamic nature of construction projects, with frequent changes and variations, makes it difficult to synchronise updates across all parties involved [17, 30]. While technologies like IoT and BIM have improved project management, there is still a need for a centralised real-time data integration system that can support strategic planning and decision-

making[19, 31, 32]. Moreover, although technologies are crucial in construction management, collecting and cleansing data for analysis and preservation for future projects as lessons learned are of utmost importance.

However, establishing a system less dependent on human orientation presents another challenge. It means that if an experienced or project manager quits, it is often challenging for future or current projects to understand data trends, and their successors may struggle to access and map the same level of knowledge and experience [33]. From literature reviews [34-36], emerging frameworks illustrate how real-time transparency can address inefficiencies and foster stakeholder collaboration. Collectively, these advancements underscore the urgency of adopting real-time data analysis frameworks to address the persistent challenges of delays and inefficiencies in construction projects [36, 37]. Despite advancements in digital technologies and project management methodologies, construction projects face significant challenges in real-time delay analysis and decision-making. Moreover, delay analysis methods for integrating multiple data resources into major construction projects have often been reported as lacking automation, real-time data integration, and comprehensive traceability, leading to inefficiencies in identifying and mitigating project delays.

In response to these challenges, this study proposes the Real-Time Data-Driven Construction Project Analysis Framework (RealCONs)—a novel framework designed to integrate real-time data collection, predictive analytics, and centralised communication for enhanced delay management in construction projects. This research is guided by three key questions: RQ1) How can multiple resourced data be integrated into major construction projects? RQ2) How can RealCONs improve real-time delay identification and management in construction projects? and RQ3) To what extent do automated data collection, centralised communication, and predictive analytics enhance decision-making in project delay management?

The unique contribution of this research lies in the development of a comprehensive and

practical framework that i) identifies the information needs of key stakeholders—such as contractors, subcontractors, engineers, and planners; ii) addresses them through automated data collection mechanisms using APIs and SQL-based systems; iii) RealCONs consolidates multi-sourced data into a centralised model, enhancing accessibility, traceability, and decision-making efficiency; iv) it incorporates earned value performance metrics, including earned value and earned schedule performance indicators [38], enabling early detection of project delays and proactive interventions, and v) framework is empirically validated through comparative case studies, demonstrating its ability to improve project transparency, responsiveness, and overall performance. RealCONs contributes significantly to advancing construction project management practices and fostering the industry's shift towards integrated real-time analytics by offering a structured, scalable, and data-driven approach.

By mapping these critical challenges, this research contributes to advancing real-time tracking and analysis in construction projects and supports the industry's transition towards data-driven project management solutions. Section 2 outlines the research methodology, which is structured into four key steps: Research Design, Data Collection, Data Analysis, and Validation and Reliability. These steps demonstrate how the research questions and contributions will be addressed throughout the study. Section 3 presents eight case studies, divided into two subsections, which cover the background of the projects and the problem statements related to the existing tracking systems. Following this, Section 4 introduces the RealCONs framework in detail, explaining its components and how they systematically address the research questions. The subsequent sections discuss and analyse the results of a comparative study between the RealCONs framework and the existing systems. This comparison is conducted across similar projects, with four case studies using the existing systems and the remaining four applying the RealCONs framework.

4.3 RESEARCH METHODOLOGY

This study adopts a multi-stage methodology grounded in pragmatic principles [39], recognising the complexity of construction delays and the need for practical solutions. It integrates qualitative and quantitative techniques to develop, implement, and validate the Real-Time Data-Driven Construction Project Analysis Framework (RealCONs). The methodology aligns with the research questions and contributions and is broken down into four steps: 1) Research Design, 2) Data Collection, 3) Data Analysis, and 4) Validation and Reliability. Figure 4.1 illustrates the methodology's steps:

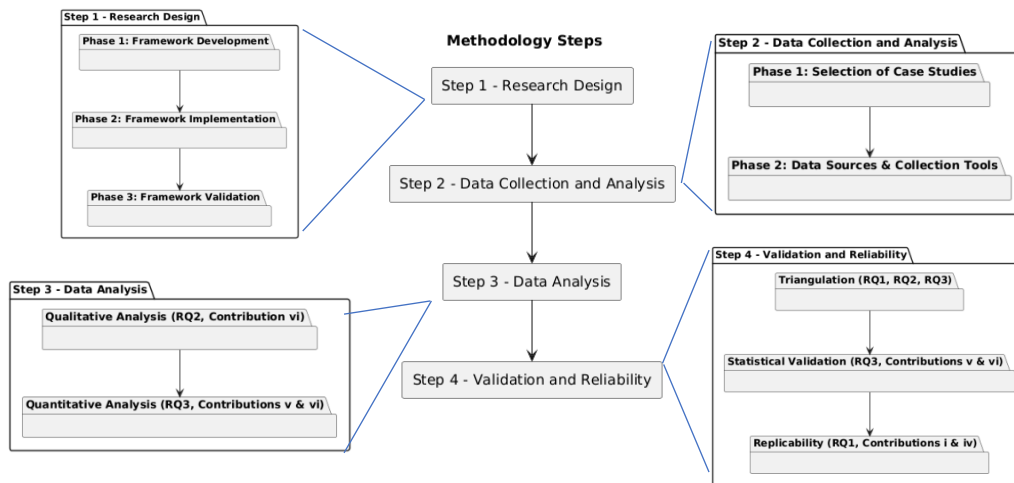


Figure 4.1: Methodology's Steps

• Step 1 - Research Design

It includes three phases as below:

Phase 1: Framework Development: The first phase tackles RQ1 by developing an automated framework for integrating multi-source data into construction projects, aligning with contributions (i)-(iv). A literature review identified gaps in real-time data systems, informing the design of RealCONs. This framework incorporates construction site data, SQL databases, BIM, Oracle P6/Aconex, and Power BI to address interoperability, data acquisition, and delay notification challenges. By establishing structured processes for real-time data collection and analysis, the system provides a robust foundation for enhanced project management.

Phase 2: Framework Implementation: The second phase examines RQ2 by evaluating RealCONs' effectiveness in real-time delay management supporting contributions (i, iii-v). The framework was implemented in four projects (P-E to P-H) and benchmarked against four control projects (P-A to P-D) using conventional systems. The solution automated data collection and integration through QR codes, smartphones, and APIs, substantially improving delay identification. Comprehensive implementation protocols were documented to ensure replicability, demonstrating the system's practical application and scalability for construction project management. The results highlight RealCONs' potential to transform delay management through enhanced automation and data-driven decision-making.

Phase 3: Framework Validation: The third phase investigates RQ3 by quantitatively assessing RealCONs' impact on delay management (contributions v-vi). Over 90 days, the system's performance was compared against traditional methods using KPIs (CPI, SPI) and statistical analysis (Shapiro-Wilk test and Wilcoxon Signed-Rank analysis). Results demonstrated significant improvements in delay identification and project outcomes, empirically validating the benefits of automated data collection, centralized communication, and predictive analytics. This phase provided measurable evidence of RealCONs' effectiveness in enhancing decision-making processes for construction project delays.

- **Step 2 - Data Collection and Analysis**

Eight construction projects were selected as case studies based on three criteria: at least 85% completion, high data flow (progress reports, RFIs, drawings), and E&I contracts value exceeding \$100M. Data was gathered from multiple integrated sources to validate RealCONs' robustness, including:

- Construction Area: On-site progress is captured via QR codes and smartphones.
- SQL Database: Labour hours, material costs, and progress percentages processed for real-time analysis.
- BIM: Integrated 3D models and clash detection reports.
- Oracle P6: Planning and scheduling data for real-time monitoring.

- Oracle Aconex: RFIs, delay notifications, and communication records to assess workflow efficiency.
- Power BI: Data centralisation, processing, and visualisation for real-time decision-making.
- **Step 3 - Data Analysis**

This study employed mixed methods to address its research questions. Qualitative analysis (RQ2) examined RealCONs' design and implementation, assessing usability through stakeholder feedback from managers, subcontractors, and engineers. Quantitative analysis (RQ3) evaluated project performance using SPI, CPI, and Earned Schedule Variance metrics, with statistical validation through the Shapiro-Wilk test and Wilcoxon Signed-Rank analysis. Power BI dashboards provided real-time visualisation of project status and predictive delay alerts. The integrated approach combined empirical performance measurement with practical usability assessment, validating the framework's effectiveness in construction project management. This dual methodology ensured comprehensive analysis of both operational implementation and measurable outcomes.

- **Step 4 - Validation and Reliability: case studies justification**

This investigation employs eight Electrical and Instrumentation (E&I) construction projects (designated P-A through P-H) as case studies to develop an empirically grounded framework for enhancing status-tracking systems in complex construction environments. The case study approach ensures the validity and reliability of the findings through rigorous analysis of real-world project data. The selected projects, all contracted under comparable terms in mid-2024, provide an ideal testbed due to their mandated use of integrated digital platforms: Aconex (Oracle) for document management and communication, complemented by Primavera and MS Project for scheduling analytics. This technological ecosystem enables comprehensive tracking of critical workflows, including RFI management, federated 3D model coordination (utilising Revit and Navisworks formats), and multi-stakeholder documentation processes. The validation was conducted by comparing eight case studies, four implementing the RealCONs approach and four utilising conventional methods. This research presents results from one representative

project per approach, deliberately selected to reflect worst-case reporting scenarios. Therefore, this study employed triangulation (RQ1–RQ3) to ensure robustness, drawing data from construction sites, SQL databases, BIM models, Oracle P6, and Power BI, with qualitative and quantitative cross-verification. Statistical validation (RQ3) via the Shapiro-Wilk test and Wilcoxon Signed-Rank analysis confirmed RealCONs’ superior accuracy in early delay detection (Contributions v–vi). Replicability (RQ1, Contributions i–iv) was ensured through detailed documentation and scalable tools (e.g., QR codes, APIs, Power BI), enabling adaptation across construction contexts.

This methodological approach accentuates the RealCONs framework's comparative advantages under particularly challenging operational conditions. Therefore, the case selection adhered to six stringent criteria: 1) Project Scale and Value; 2) Electrical Scope Complexity; 3) Geographic and Operational Similarity; 4) Availability of Project Data; 5) Similarity; 6) Stakeholder Diversity, which all will be explained in the section 3. Including worst-case scenarios - particularly delayed RFI responses and model clash incidents in the baseline cases - offers robust validation of the RealCONs methodology. This approach aligns with Flyvbjerg [40] principles of information-oriented case selection, where extreme cases prove particularly revealing about underlying operational mechanisms[41].

4.4 CASE STUDY SELECTION AND DATA PROCESSING

As part of Step 2 – Data Collection and Analysis of the Methodology, this section presents the testing of the RealCONs framework through the analysis of multiple case studies. The section has two main stages: case study selection and data flow processes. These case studies serve to validate the RealCONs framework under real-world constraints and complexities commonly encountered in large-scale, high-security construction environments.

4.4.1. Case Study Selection

All case studies involve two-storey buildings with a floor plan of approximately 900 m². These buildings are designed for high-security purposes, necessitating close monitoring and reporting time, cost, and quality throughout the project lifecycle: 1) materials and labour are among the most expensive resources, and 2) project timelines should be closely monitored and analysed. Therefore, daily tracking of the project's productivity is essential to maintain efficiency and ensure the project stays on schedule. However, due to strict security protocols, drones and RFID tags are entirely prohibited, limiting the methods available for data collection and monitoring. The selection of case studies was based on several key criteria to ensure that the projects effectively represent the challenges that the RealCONs framework aims to address, such as 1) Project Scale and Value – The projects range from \$100M to \$115M in value, covering mid-to-large-scale construction developments. It ensures a diverse representation of project complexities; 2) Electrical Scope Complexity – The case studies include projects with varying levels of cabling (10,890m – 14,000m), containment (12,000m – 15,800m), and fittings installations (120 – 150 units). These variations provide a robust dataset for analysing delay factors related to different scopes of work; 3) Geographic and Operational Similarity – All selected projects were executed under similar contract structures and construction environments, making them comparable for evaluating the RealCONs framework; 4) Availability of Project Data – The projects have been generating various project status reports, including progress reports (prepared using manual data forms, MS Excel, and MS Project/Primavera), claim reports (using MS Excel), RFI registers (using MS Excel and Aconex), delay and risk logs (using MS Excel and MS Project/Primavera), and a drawings database (using Aconex and MS Excel). However, the reliance on multiple data sources has reduced data accuracy, increased the difficulty of preparing reports on time and increased time delays in internal and external interactions. For example, response delays occur between subcontractors and the design team

(external interactions) and between site supervisors and project managers (internal interactions);

5) Similarity – The roofing work has been completed for all projects, allowing the E&I teams access to the site. All projects have reached over 85% construction completion. Additionally, each project is managed by two executive teams comprising 15 members. All projects’ reporting mechanism is the same (item 4); 6) Stakeholder Diversity – Each project involved multiple contractors, subcontractors, and consultants, aligning with the RealCONs framework’s objective of improving stakeholder communication.

The main reason for prioritising the Electrical and Instrumentation (E&I) trade is that E&I tasks must be completed earlier than other service trades, such as mechanical and security activities. This is because other trades require power for their equipment during commissioning and testing. Some overlapping tasks may be acceptable, but E&I work remains a high priority. As a result, progress is closely monitored, and early identification of issues is actively managed. Table 1 demonstrates that all eight projects are similar in scale and value.

Table 4.1: Selected Projects Details: E&I Value and Scale per Project

Project	P-A	P-B	P-C	P-D	P-E	P-F	P-G	P-H
Value (Million \$)	100	105	110	115	102	106	101	108
Cabling (meter)	12,000	11,320	10,890	12,200	13,000	11,890	14,000	11,000
Containment (meter)	12,800	12,800	12,000	13,800	14,000	12,800	15,800	12,300
Fittings (no)	125	120	145	125	137	125	150	145

4.4.2. Case Studies and Current Data Flow Processes

To exemplify the data flow processes throughout projects, Figures 2 and 3 illustrate the interactions among three key actors: the consultant (responsible for BIM, design, and engineering), subcontractors, and the head contractor. Figure 4.2 shows the consultant initiating interactions involving drawings, 3D models, revisions, RFIs, and changes. The head contractor forwards these documents to subcontractors via Aconex, breaking the direct link between the consultant and subcontractors. Consequently, the head contractor manages subcontractor RFIs, communicates with the consultant, and relays responses. Aconex automatically notifies relevant parties at each step, such as when new drawings are sent or approved. If subcontractors identify

on-site clashes, they must create an RFI through Aconex, restarting the communication cycle. This process can lead to delays due to the lack of real-time decision-making. While Aconex is used for communication, it primarily serves as a data backup and correspondence tool, operating independently from the consultant’s BIM management.

Figure 4.3 outlines the data interactions among the three parties: Party 1) The consultant, contributing to the isolation mentioned earlier; Party 2) The head contractor (HC), using Aconex for communication with subcontractors (SC) and Primavera (P6) for planning and scheduling; and Party 3) The subcontractors (SC), who handle data collection and decision-making through tools such as SQL databases, Primavera (P6), Aconex, and MS Excel files. The SQL database records labour and material costs, weekly site progress, and the RFI register. Primavera (P6) manages planning and scheduling, updated via site progress sheets. Aconex handles all communication with the head contractor, and MS Excel serves as the primary input for the database, which is scanned and forwarded for entry.

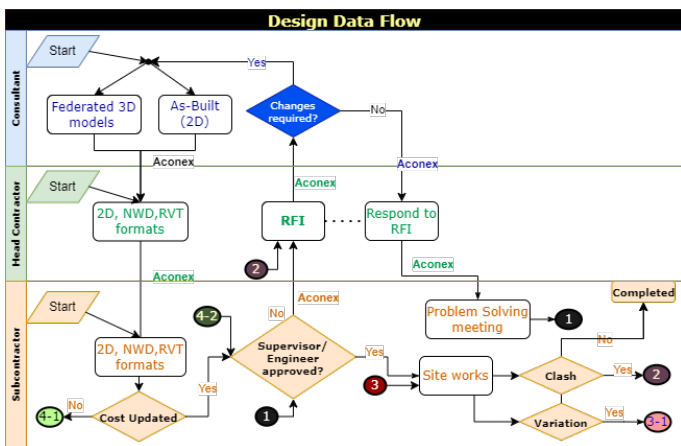


Figure 4.2: Existing Drawings/3D Data Flow

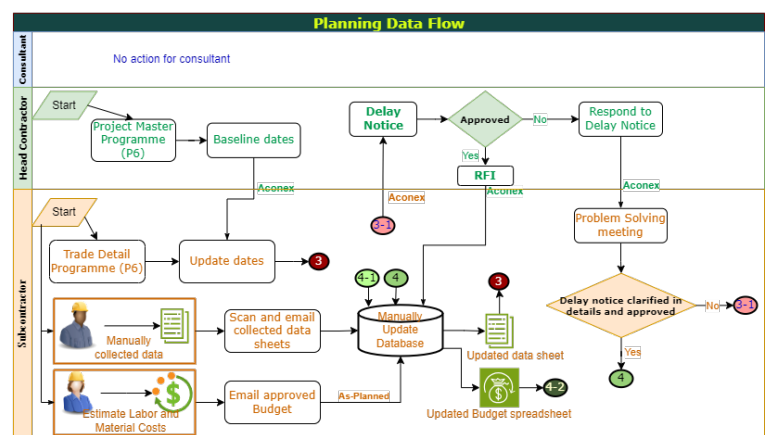


Figure 4.3: Existing Project Data Flow Interaction

Based on Figures 4.2 and 4.3, the following key limitations and gaps in the current data flow process for projects have been identified:

- a) Data Collection and Updates: Data collection is not performed daily due to high workloads. Necessary data, such as site progress and project costs, are transmitted manually, creating time gaps and increasing the risk of human error.
- b) Weak or Broken Interactions: While 3D models and Aconex are used, these platforms are isolated and do not update simultaneously. For example, subcontractors might use as-built

revision one while the consultant works on revision two based on some clash detection reported already. So, it increases reworking risk and slows problem resolution during the installation phase.

- c) **Difficulty of Traceability:** Data processing gaps lead to non-traceable data. For instance, site works (Point 3 in Figure 4.2) are not logged through Aconex, and the head contractor’s programme is only updated when RFIs (Point 2) or notices (Point 3-1) are required. This disconnect makes it difficult to trace reliable data inputs.
- d) **Non-Integrated Analytical Reports:** Manual data collection and limited interaction delay analytical reports. Subcontractors struggle to manage data flow and verify accuracy, hindering real-time decision-making. For instance, a clash identified in the morning may only be reported by the afternoon, causing delays in issue resolution and complicating project status analysis.

In addition to the previous explanation, Figures 4.4 and 4.5 illustrate the activity and sequence diagrams to visualize the data flow processes outlined in Figures 4.2 and 4.3. The process begins with the site supervisor collecting performance data, which the project admin enters into the internal platform. If delays are identified, the Project Manager assesses their impact. Otherwise, the Project Analyst prepares a detailed report for approval. The report is sent to the head contractor and project team upon final approval for dissemination, ensuring accurate data capture, timely decision-making, and early delay identification.

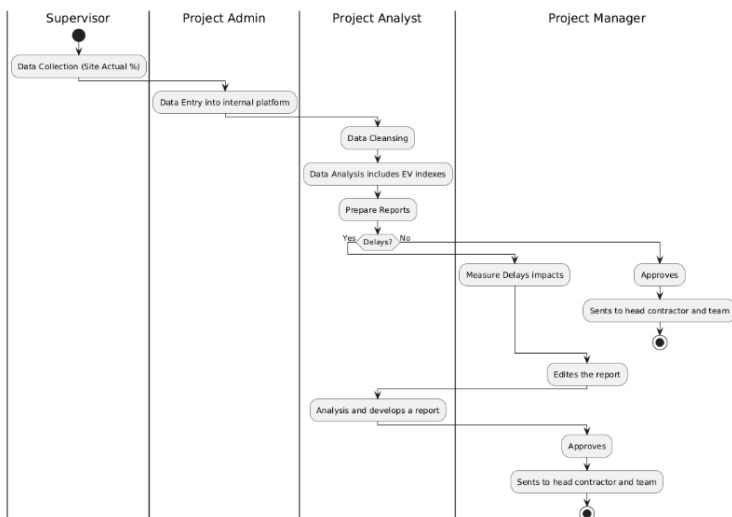


Figure 4.4: Existing Process Activity Diagram

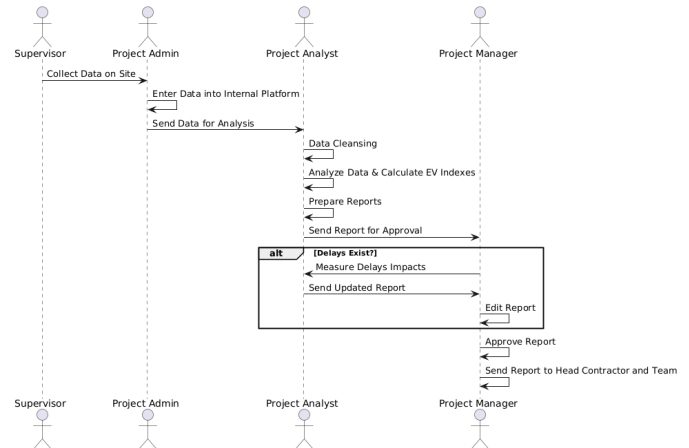


Figure 4.5: Existing Process Sequence Diagram

4.5 THE PROPOSED CONCEPTUAL FRAMEWORK

Based on Section 3 (Case Study) and an in-depth analysis [28, 42], the RealCONs framework is designed to address key limitations in the existing data flow process for construction project management with a particular focus on delay identification. Its primary objectives are to streamline data collection and updates, enhance system interactions, improve data traceability, facilitate integrated analytical reporting, optimise project management efficiency, and support real-time decision-making. By automating data collection, the framework ensures daily updates on site progress, project costs, and potential clashes or design issues, thereby reducing manual errors and time gaps. It integrates previously isolated platforms, such as 3D models, Primavera, and Aconex, enabling simultaneous system updates. This minimises the risk of rework and enhances problem resolution during the implementation phase. Additionally, the framework establishes a dynamic data flow, ensuring that all site activities, including updates from external parties (e.g., head contractors and BIM consultants), are logged and traceable. This reduces discrepancies and enhances the reliability of data inputs. This section presents two key subsections: framework components and their interactions, and six discrete subsections outlining the RealCONs framework components as follows:

4.5.1. Framework components and interactions

As illustrated in Figure 4.6, the RealCONs framework comprises six core components that operate in continuous interaction to minimise project delays and disruptions. These are: (i) the Construction Area, where real-time progress data is collected via QR codes; (ii) the SQL Database, which centralises and organises site data for processing and storage; (iii) BIM (Consultant), offering 3D modelling and clash detection to ensure spatial coordination; (iv) Oracle Primavera P6, responsible for project scheduling and aligning actual progress with planned timelines; (v) Oracle Aconex, which manages documentation and formal

communication; and (vi) Power BI, which integrates data from all sources to produce real-time, actionable insights through interactive visualisation.

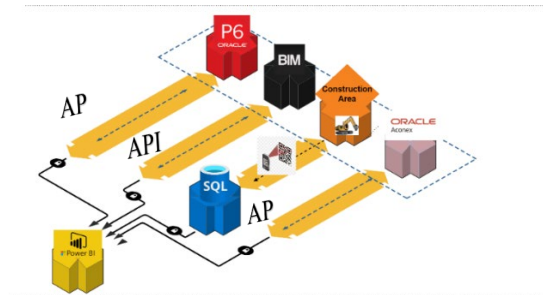


Figure 4.6: The Conceptual Framework of RealCONs

These components are linked via an Application Programming Interface (API) layer that automates data flow. For instance, site data collected from QR scans is transferred to the SQL database, where it is processed and passed on to Power BI for visualisation. Simultaneously, the SQL database feeds actual progress data to Oracle P6, enabling schedule updates and performance tracking. This feedback loop maintains alignment between planned and actual progress, supporting accurate delay analysis. Oracle Aconex ensures contractual and communication records—such as RFIs and delay notices—are accessible and traceable. These records are integrated into Power BI for comprehensive oversight. BIM contributes real-time 3D updates and spatial insights, enhancing clash detection and coordination with other project elements.

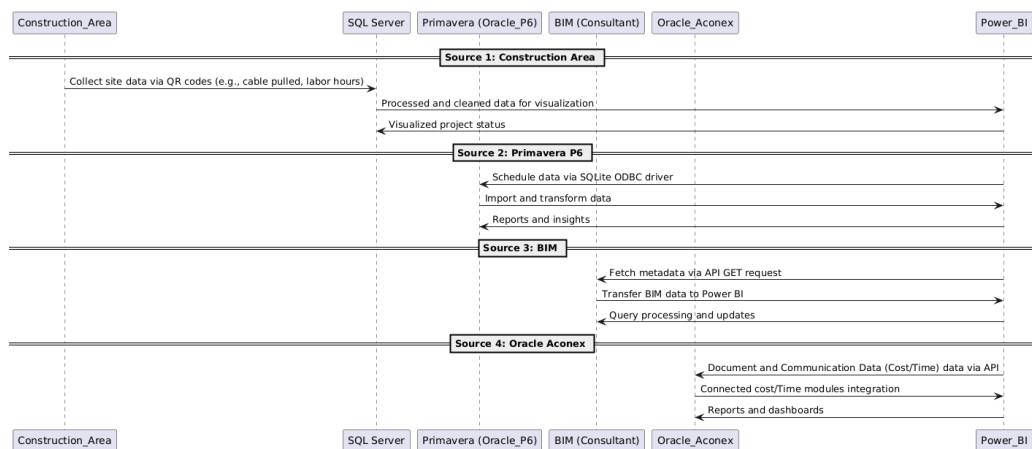
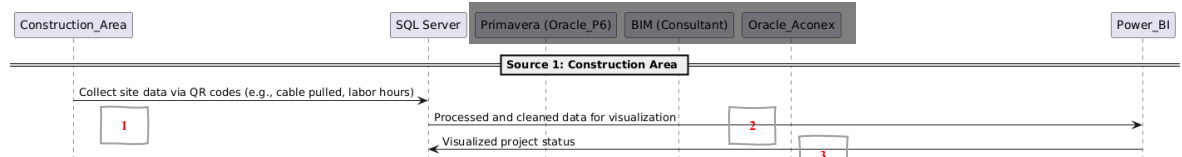


Figure 4.7: Type and Direction of Data Flow Throughout RealCONs Framework

At the centre of this framework lies the Data Model, which consolidates all project identifiers,

and the Analytic Table, which defines relationships across data sources. These structures feed into Power BI, where data is cleaned, synchronised, and visualised. Figure 4.7 details the flow and direction of this data exchange, where all interactions except from the Construction Area to SQL are API-driven.



The integration allows subcontractors, for example, to log technical issues in Aconex, which are then retrieved and analysed in Power BI alongside data from BIM and Primavera. This accelerates issue resolution and ensures consistent, up-to-date information is available across all teams. RealCONs is an integrated digital ecosystem that automates data exchange and decision support across construction platforms. Power BI is the analytical backbone, transforming multi-source data into coherent insights for proactive project control. The following subsections (4.2–4.7) provide a detailed explanation of each component:

4.5.2. Construction area

Figure 4.8 maps this section's approaches: data capture by smart devices sent to SQL Server and Power BI. On the subcontractor (SC) side, real-time site progress data, such as installed items and resource usage, is collected and forwarded to an SQL database. Smartphone and tablet applications, developed using PHP and Python, serve as front-end tools focusing on UI/UX design. The application, compatible with MySQL and SQL Server, features a Graphical User Interface (GUI) for data collection, including QR code scanning, security layers, and tracking installation dates and quantities.

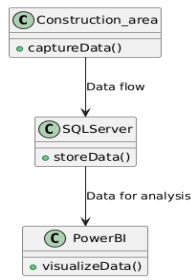


Figure 4.8:
Section 4.1
Mapping



Figure 4.9: GUI On Smart
Devices

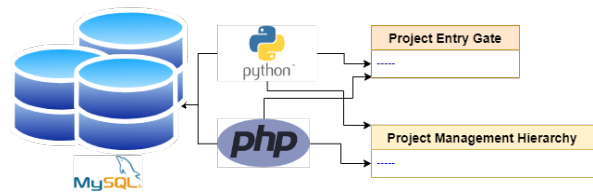


Figure 4.10: Interaction Languages

Figures 4.8- 4.10 illustrate the workflow within the model architecture, focusing on SQL Server and its connections. They demonstrate the interaction between two groups via Python, PHP, and MySQL to integrate source files into executable files. The model processes data input for three key functions: establishing baselines, supporting scheduling calculations, and generating analytical reports. The data includes WBS, CBS, RBS, weekly tasks, and delay notices. Power BI presents the output, enabling project managers and stakeholders to monitor progress, especially delays, for effective project management and early delay mitigation.

4.5.3. SQL-Database (Project Database)

The SQL database (Project Database) is a cornerstone of the RealCONs framework, playing a pivotal role in ensuring seamless data flow and analysis. As a back-end tool, it supports the front-end application by managing and storing critical project data, which analytical components like Power BI use for real-time reporting and decision-making. The SQL database has key capabilities, including user authentication, back-end system integration, and data services for collecting and storing essential project information, such as site progress percentages, RFIs, WBS, CBS, and RBS codes, labour hours, material costs, and labour roles. During pre-construction, stakeholders insert and monitor cost codes (Consultant via BIM, Subcontractor, Head Contractor) through the Schedule of Quantities (SoQ). The database ensures reliable and accurate data storage, forming the baseline for comparing planned versus actual project status. Timely communication between the consultant and subcontractor is essential to maintain data

accuracy, especially during project changes. This ensures real-time updates of project status. The SQL database processes and transfers this data to Power BI, enabling the generation of comprehensive reports for informed decision-making. In summary, the SQL database is the backbone of RealCONs, integrating with BIM and Power BI to enhance efficiency, accuracy, and collaboration in construction project management.

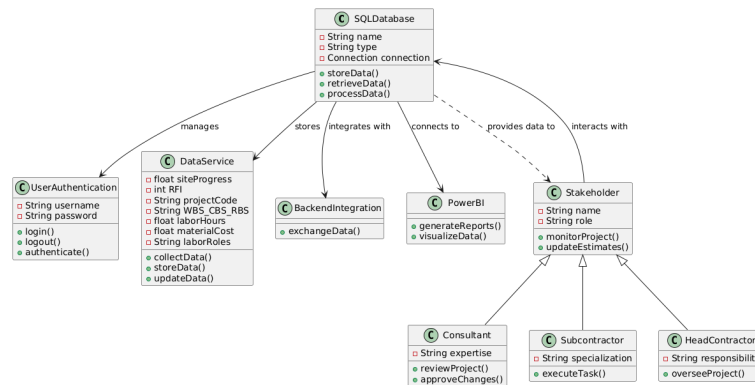


Figure 4.11: SQL_Database Mapping

4.5.4. **BIM (Consultant)**

As shown in Figure 4.12, BIM (Building Information Modeling) is crucial in the RealCONs framework, ensuring accurate data acquisition and integration throughout the project lifecycle. BIM provides reliable data sources, particularly planned material quantities and costs, which are essential for dynamic construction projects. BIM automates data management, unlike traditional systems relying on manual data entry in Excel. In RealCONs, the project database (SQL) serves as the central hub, maintaining an updated interface between BIM and the construction area, including WBS/CBS codes, changing registers, schedules of quantities, and more, ensuring timely, accurate information for all stakeholders.

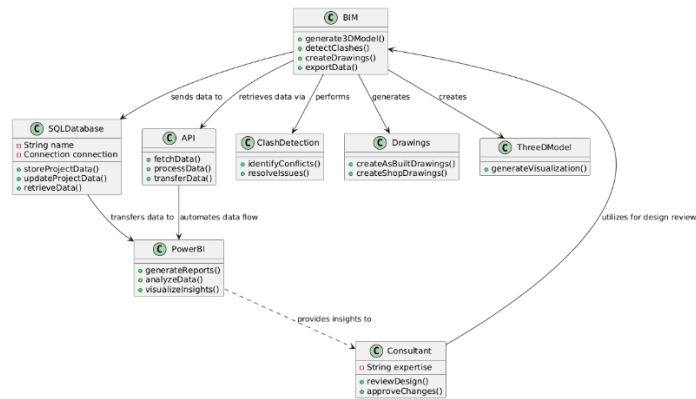


Figure 4.12: BIM_Consultant Mapping

The consultant, using BIM, provides key capabilities: 1) Clash Detection and Resolution Reports to resolve design conflicts before construction; 2) Drawings, including as-built and shop drawings for accurate execution; and 3) 3D Models for visual and functional project reference. BIM continuously communicates with the SQL database, ensuring seamless data flow to Power BI. This integration generates real-time reports, alerting project managers to delays, risks, and procurement issues. Through APIs, BIM data is retrieved and processed by Power BI, eliminating manual work and ensuring reliable, up-to-date information for informed decision-making.

4.5.5. Oracle-P6 (Primavera)

Oracle-P6 represents the planning and scheduling department for project monitoring and control aspects. It is a vital component of the RealCONs framework. It serves as a powerful tool for managing project timelines (WBS), resources (RBS), and costs (CBS), ensuring that construction projects stay on track and within budget. In RealCONs, Primavera integrates key project structures such as the WBS, CBS, and RBS. These structures help organise project activities, costs, and responsibilities, providing a clear framework for project execution. Additionally, Oracle_P6 uses activity codes and task sequence logic to define the relationships and dependencies between tasks, ensuring a logical workflow. Figure 4.13 illustrates the RealCONs oracle_P6 component mapping approach.

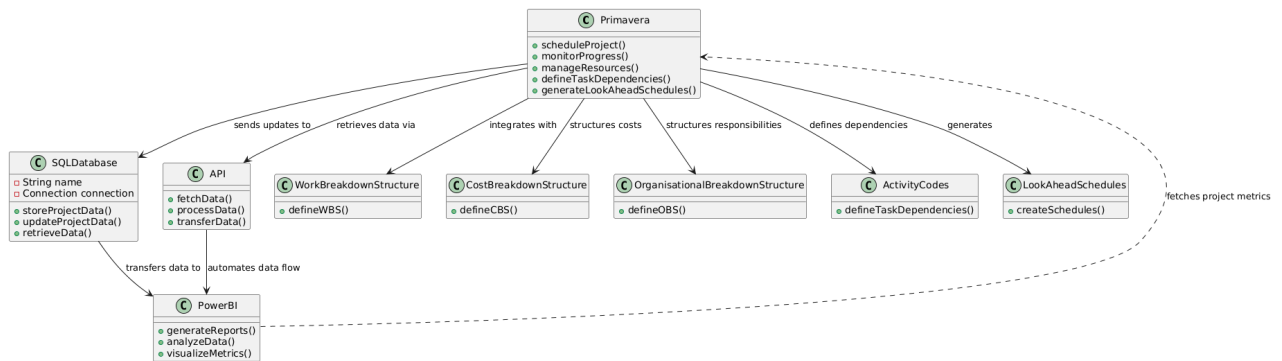


Figure 4.13: Oracle_P6 Mapping

One of Primavera’s standout features is its ability to calculate activity progress percentages based on real-time data collected from the construction site. This data aligns with WBS codes in the project database (SQL), ensuring progress updates accurately reflect completed work. Primavera generates look-ahead schedules for site teams, providing a clear roadmap of upcoming tasks. Oracle-P6 sends the latest updates, including CBS, WBS, and RBS codes, to the SQL Server, which checks and updates the data. Through Power BI, key project data such as durations, actual start/finish dates, and baselines are fetched via APIs from Primavera. Power BI centralizes and integrates this data, enabling the creation of analytical dashboards that provide insights into schedule slippages, delay impacts, and other project metrics. In summary, Primavera plays a crucial role in RealCONs by providing robust planning capabilities, ensuring accurate, up-to-date, and actionable project data. Power BI processes this data for real-time decision-making.

4.5.6. Oracle-Aconex

As shown in Figure 4.14, Oracle-Aconex is a critical component of the RealCONs framework, serving as a centralised platform for contractual communication and document management. It tracks and threads all correspondence among project parties, including the consultant, subcontractor (SC), and head contractor (HC). Oracle-Aconex stores essential project documents, such as versions of drawings, delay and disruption notices, RFI/RFQ threads, and risk/delay registers. The platform enables real-time decisions based on direct and up-to-date

information, providing a unified communication channel. In RealCONs, it streamlines communication and document updates. For example, when the consultant updates the 3D model and as-built drawings based on SC inquiries, this data is stored in Oracle-Aconex, retrieved via APIs, and processed by Power BI for further analysis. This integration ensures that the SC and other parties use the latest data. Oracle-Aconex simplifies addressing clashes or issues: in traditional systems, SCs must send delay or RFI notices to the HC, who escalates them to the consultant. In RealCONs, SCs lodge claims directly through Oracle-Aconex. Once the consultant resolves the issue, data is fetched into Power BI and compared with data from other components (e.g., SQL and BIM), ensuring a comprehensive project view. This integration reduces delays and enhances collaboration.

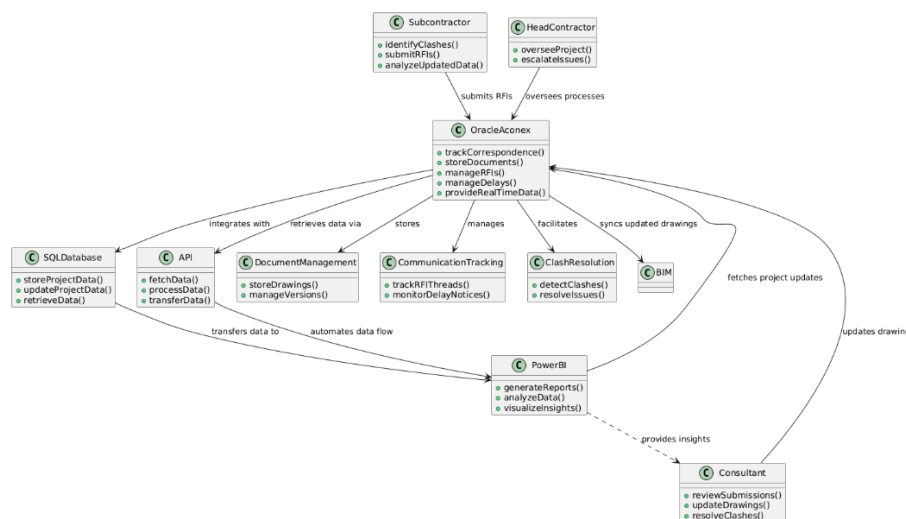


Figure 4.14: Oracle_Aconex Mapping

4.5.7. **Power BI (Project Analytical Platform)**

Power BI is the analytical core of the RealCONs framework, serving as a unified, scalable, data-driven platform. It connects, visualises, and analyses data from multiple project components, including Oracle-P6 (Primavera), Oracle-Aconex, Construction Area Progress, and BIM (Consultant). Power BI integrates centralised, cleaned, and analysed data into management dashboards through APIs and direct SQL database links. Project stakeholders use these dashboards daily to monitor progress, identify risks, and make informed decisions. Power BI

consolidates data from multiple sources into a single platform: Oracle-P6 supplies drawing data, Aconex provides updates on RFIs and delays, BIM updates 3D models, and SQL holds progress data. The data model in Power BI is built around the "Project ID," which connects all data through the "Analytic" table, linking to BIM, Aconex, Primavera, and SQL. This integration ensures that accurate, up-to-date project data is readily available for analysis and decision-making.

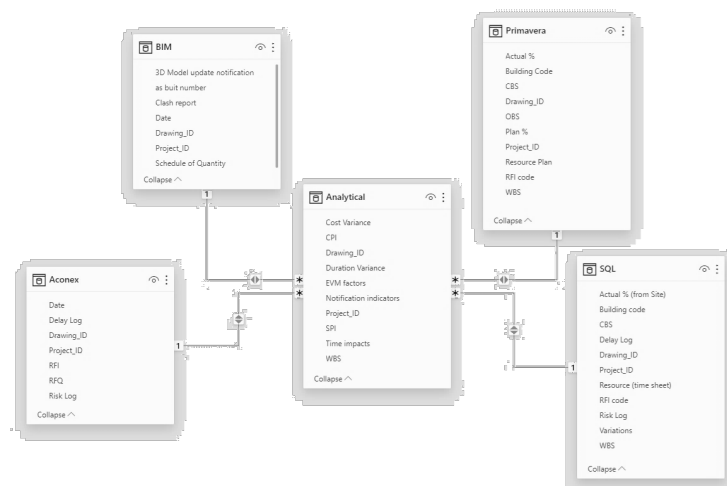


Figure 4.15: Power BI Modelling Cutoff View

By integrating these diverse data sources, Power BI creates a holistic view of the project, enabling stakeholders to a) Visualise Project Progress Through interactive dashboards that display real-time updates on tasks, schedules, and milestones; b) Identify Risks and Delays By analysing delay logs, time impacts, and risk registers; and c) Make Data-Driven Decisions: Using insights derived from centralised and cleaned data. Figure 4.16 illustrates the RealCONs Power BI component mapping approach.



Figure 4.16: Power BI Mapping

4.6 EXISTING PROCESS IMPROVEMENT WITH THE PROPOSED REALCONS FRAMEWORK

This section is divided into three subsections: Overview of the Existing Process – a brief explanation of the current workflow and its key steps; Introduction to RealCONS: The proposed process – a concise description of the RealCONS framework and its intended functionality; and Improving the Existing Process Using the RealCONS Framework – an analysis of how the RealCONS framework addresses current process gaps and enhances overall performance.

4.6.1. Overview of the Existing Process

Figures 4.4 and 4.5 present the activity and sequence diagrams that outline a project's end-to-end data collection, analysis, and reporting process. This workflow involves four key roles: Supervisor, Project Admin, Project Analyst, and Project Manager, ensuring accurate data handling and effective project monitoring. The process starts with the Supervisor collecting actual site data, such as progress percentages, which is then transferred to the Project Admin to be entered into the platform. This data is then sent to the Project Analyst for further analysis. The Analyst cleanses the data, eliminating errors or inconsistencies, and performs analysis, including calculating Earned Value (EV) indexes to assess performance against timelines and budgets. After analysis, detailed reports are prepared and submitted to the Project Manager for review. A key decision point in this process occurs when assessing if delays exist. If no delays are detected, the report moves directly to approval. However, if delays are found, the Analyst measures their impact, updating the report with delay analysis before sending it back to the Project Manager. This ensures deviations are documented, enabling proactive mitigation measures. The Project Manager reviews, edits, and approves the reports before forwarding them to the head contractor and project team, ensuring all stakeholders are informed. The process emphasizes collaboration, with each step ensuring data integrity, early identification of issues, and effective communication with stakeholders, enabling informed decision-making and timely

action.

4.6.2. Overview of RealCONs Framework Process

Figure 4.17 provides a technical overview of RealCONs' component interactions, demonstrating how the framework addresses gaps in existing systems and research questions. It outlines three interconnected steps: 1) Data Acquisition, 2) Data Analysis and Visualisation, and 3) Data-Driven Real-Time Decision-Making, illustrating their interdependence. Section 5 will present quantitative data showcasing RealCONs' ability to alert project managers to potential delays and highlight cost savings and improved project performance achieved through early identification and mitigation. The “Construction Area” collects data on progress, resource usage, and delays. “BIM (Consultant)” provides 3D model clash detection and ensures compliance. “Oracle-P6” manages scheduling resource planning and monitors critical paths, tracking progress and delays. “Oracle-Aconex” facilitates communication and document management, handling RFIs, RFCs, delay notices, and updated drawings to keep stakeholders informed. Lastly, “Analytical (Power BI)” consolidates data from all sources and provides insights through dashboards, including Productivity Tracking, Earned Value (EV) / Schedule Variance (SV) analysis, and Actual vs Planned progress tracking. This integration enables project managers to make data-driven, real-time decisions, enhancing project oversight and ensuring timely action against delays.

In Figure 4.17, red arrows into Power BI represent data flow from: 1) Construction Area (real-time installation, resource, and delay data); 2) BIM (3D model data, clash detection, compliance); 3) Oracle-P6 (project schedules, resource plans, WBS, CBS, critical path updates); and 4) Oracle-Aconex (RFI/RFC updates, delay notices, risk changes). Key processes include “Push-Acquisition” for data transfer, “Data Cleansing” for error-free data, “EV/SV Analysis” for project performance tracking, and “Productivity Tracking” for resource efficiency.

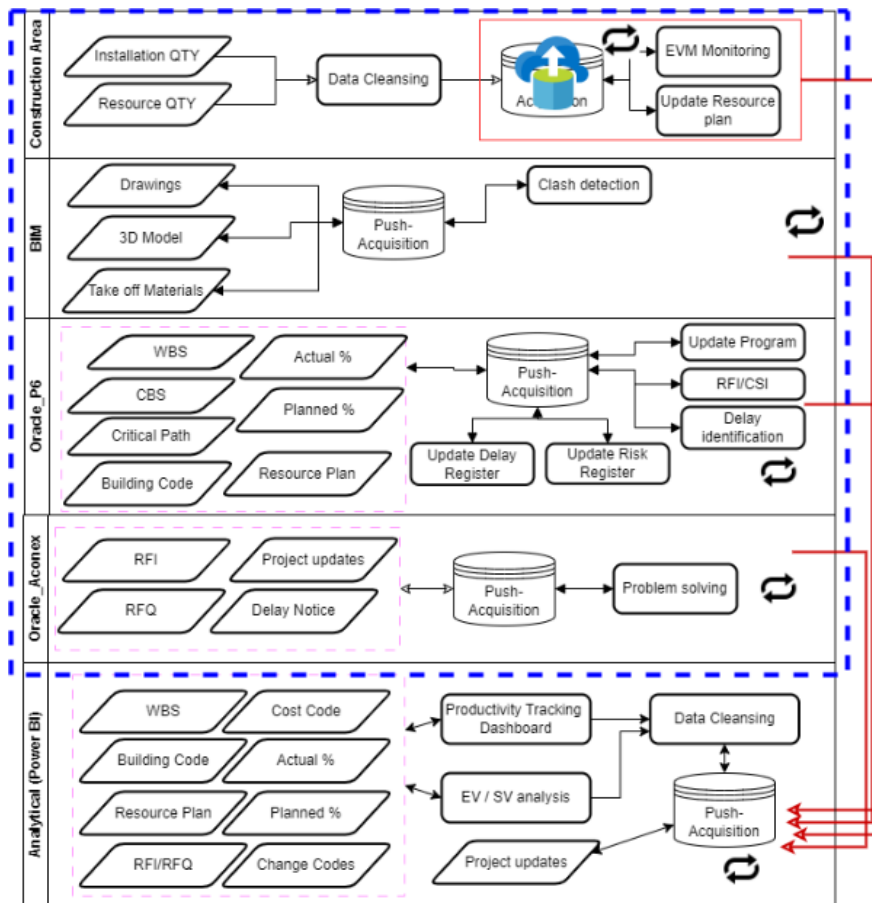


Figure 4.17: Technical View of RealCONs

Figure 4.18 outlines three steps: Data Acquisition, Analysis & Visualisation, and Data-driven Real-Time Decision-Making.

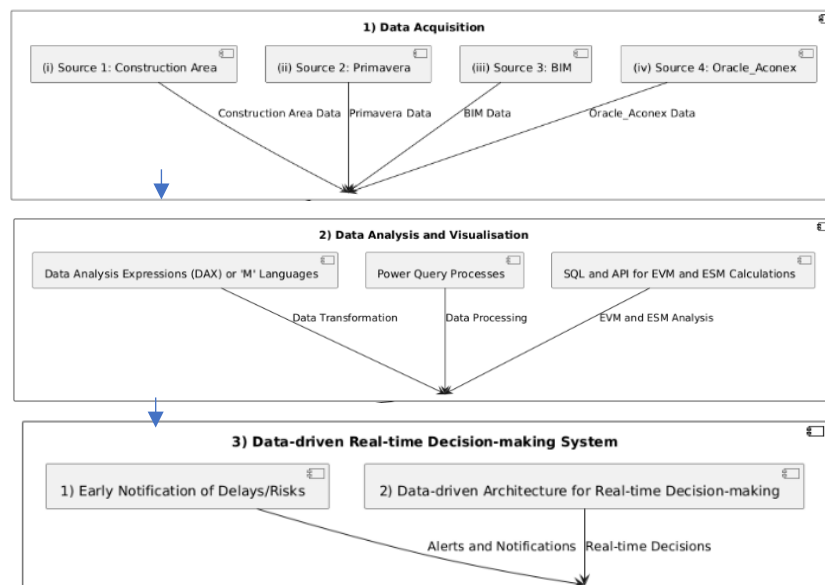


Figure 4.18: Steps of RealCONs framework process

Furthermore, section 5 will provide quantitative data illustrating the capacity of RealCONs to

alert project managers to potential delays. It will also highlight the possible cost savings and overall project performance that can be realised when these delays are identified, acted on and mitigated early:

Step 1) Data Acquisition

Construction management relies on a steady, reliable data flow to ensure effective and efficient activities [43]. As shown in Figure 4.3, RealCONs uses Power BI to integrate data from multiple sources: engineering/consultant (BIM), planning (Oracle P6), clients (Oracle Aconex), and construction areas. This integration provides a real-time project tracking and analysis system that supports timely decisions when delays occur, preventing escalation. This section addresses key research gaps by detailing four essential data sources (i, ii, iii, iv), explaining the processes, participant roles, tools, and RealCONs components, with subsections outlining data flow, capturing methods, and used tools:

- (i). **Source 1 from construction area:** The system combines smartphones with QR codes and an SQL server database. Supervisors collect data on cable pulled, cable tray installed, and labour hours using smartphones. Figures 8-10 show continuous communication between the construction area and a cloud-based SQL database via QR code scanning. Supervisors log into the app, and login time, date, and supervisor code are automatically recorded. QR codes for drawings and materials, such as cables and cable containment, enable supervisors to capture installation data, with associated codes displayed for each scan (Figure S1/1).

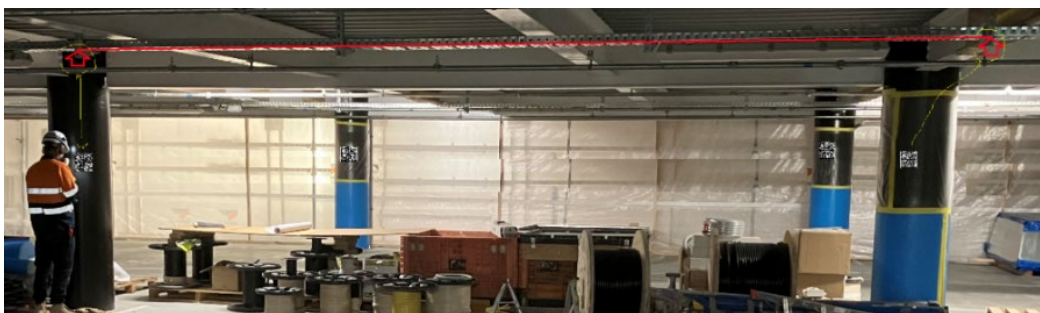


Figure S1/1- point to point

For example, if the installed containment precedes or follows the threshold QR code, the final

point is scanned, and an agreed-upon allowance is applied (Figure S1/2). In other words, if the containment from point A to point B is fully installed, but the section from point B to point C (threshold) is incomplete, the installed containment is calculated as the sum of point A (start), point B, and the allowance. From Figures S1/1 and S1/2, all acquired data on the actual installed length is automatically input under the drawing code and sent to an integrated SQL cloud-based database. The received data, processed through programmed SQL queries, undergoes data cleansing, quarantine of noisy data (e.g., data compromised due to poor internet coverage), and adjustment of WBS actual progress.



Figure S1/2- point to the threshold

(ii). **Source 2 from Primavera:** Connecting Primavera P6 to Power BI enhances project management by enabling real-time data tracking, management, and visualization, optimising decision-making and resource allocation [44]. To achieve this, the Microsoft Open Database Connectivity (ODBC) interface must be installed, allowing applications to access data from various database management systems (DBMSs). The SQLite ODBC driver is necessary to establish the connection between P6 and Power BI (Figure S2/1). This setup is called the 'Primavera Server' for better recognition.

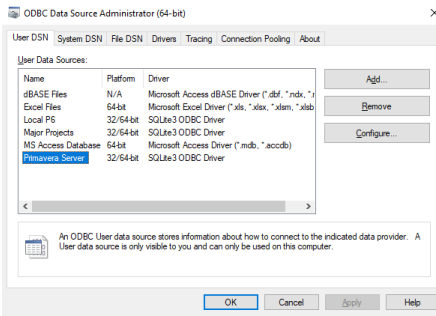


Figure S2/1 - SQLite ODBC driver

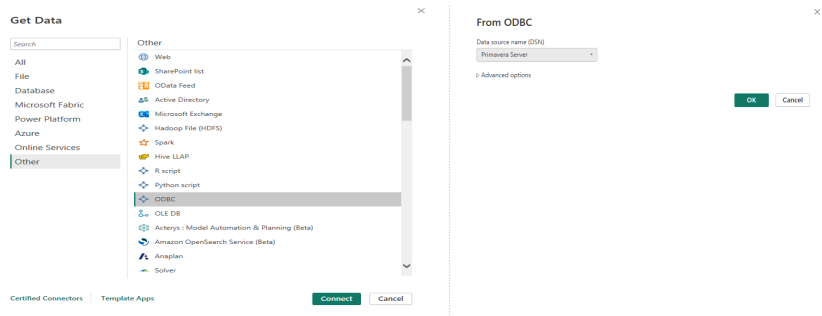


Figure S2/2 - ODBC on Power BI

Figure S2/2 demonstrates the configuration and setup of the ODBC data source on the Power BI side. From the ODBC page, select "Primavera Server", then choose the relevant tables and utilise Power BI's query editor to import data through the configured ODBC data source.

(iii). **Source 3 from BIM:** To fetch data from BIM using web queries so an API GET Request can be made. A third-party platform was used to retrieve all the BIM data stored in a model or through other API requests to obtain metadata with minimal interruption. For example, the following script demonstrates a "GET" request to retrieve all objects in the tree and their metadata. In this case, three variables must be provided as the "project" name, to which a model belongs; the "3D_Model_ID", a unique identifier used to retrieve the correct model; and the "API_ID", which authenticates the API request on the third-party server.

```

{"data": [
  {
    "_id": "2f641fff-4bc4-412a-bb84-ffdb345e563c",
    "metadata": {
      "IFC Type": "IfcBuilding",
      "IFC GUID": "11tM97QqytWdIGvc4sMN3E",
      "BuildingID": "n/a",
      "IsPermanentID": "True",
      "OccupancyType": "Project1",
      "IsLand marked": "True",
      "NumberOfStoreys": 2
    },
    "parents": ["9ccddb2-750d-654b-988f-bcf9ec2ecf91"]
  },
  {
    "_id": "34cb29bd-fb99-4472-a92f-86266b05t53v",
    "metadata": {
      "IFC Type": "IfcSite",
      "IFC GUID": "30FqTZVqJy2nhVdYtjtIcb"
    },
    "parents": ["96852ac3-9b6d-44ed-dv28-47e2ec89ac88"]
  },
  {
    "_id": "c4dr5dcf-tr43c-4b1e-c45g-bdc2bb101943",
    "metadata": {
      "IFC Type": "IfcBuildingElements",
      "IFC GUID": "2VkhAO4fr5ZQAS1ExSzcvm",
      "Reference": "LegoRoundTree"
    },
    "parents": ["4gf2f465-3f0r-41ba-43r4-c2rtyt3d4re3"]
  },
  {
    "_id": "t54r2cf2-7vr4-417c-8fe2-c3df4512de59",
    "metadata": {
      "IFC Type": "IfcBuildingStorey",
      "IFC GUID":

```

```

"4rS0eTs_PR8BFCPd4bID3D",
  "AboveGround": "False"
},
"parents": [
  "423r9900-ebtr-4845-34r0-ec4r45c7kr45"
]
}
}
}

```

Select "Transform Data" from the Home tab to transfer data into Power BI, as shown in Figure S3/1. Also, parameters need to be added in Power BI, so navigate to the Queries tab, select "New Parameter", and assign names to them such as "API Key", "Project", and "3D-Model ID" (Figure S3/2). The third party will also provide the "current value" for these parameters. Once all required data is entered into the parameter fields, Power BI will use these values to complete the API call. All in all, the relevant tables can be selected using Power BI's query editor.

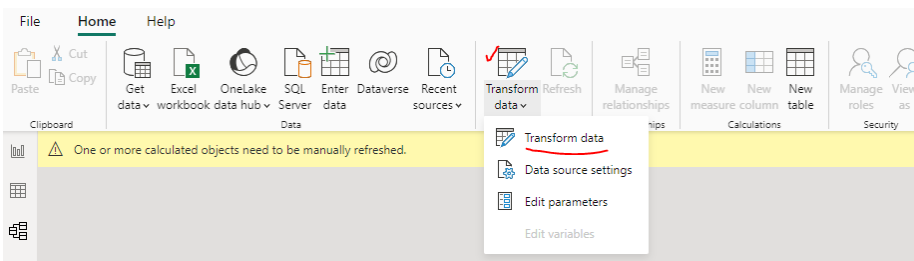


Figure S3/1- Transform data to Power BI

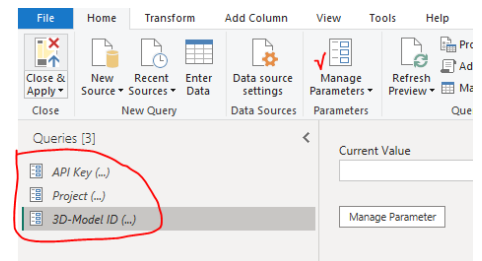


Figure S3/2- Parameters Managing

(iv). **Source 4 from oracle_Aconex:** From Figure 14, different API endpoints allow RealCONs to connect Aconex to Power BI to create interactive reports and dashboards. Therefore, Figure S4/1 illustrates connecting Power BI to "Aconex Connected Cost data". On this page, "Web" from the "New Source" tab should be selected, and the URL for the desired API endpoint needs to be entered. This URL includes the "Organisation" and "Project" fields, which can be converted into parameters in Power BI. Additionally, the Power Query Editor will display a data file. Finally, by clicking the "Expand Record" button next to the "Column1" heading, the query will show data from the Connected Cost module (Figure S4/2). This data can then be used to create reports and dashboards in Power BI.

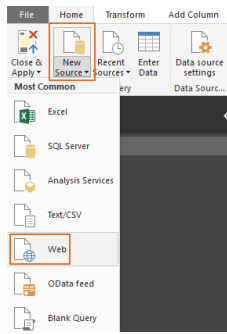


Figure S4/1- New Source and WEB and URL Views

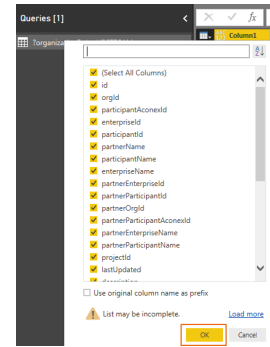
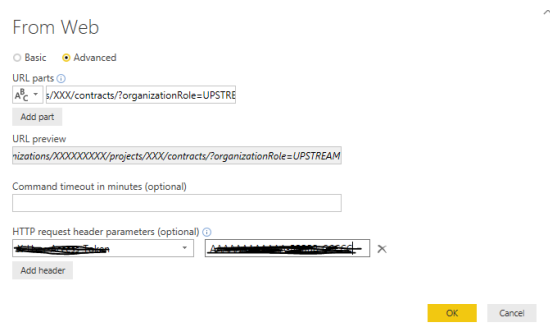


Figure S4/2- Expand Record

In summary, compared to the existing system (Figures 4.4 and 4.5), RealCONs offers a significant advantage with real-time data access and circulation (Figure 4.7). Subcontractors use QR codes for high accuracy in data collection, enabling project managers to receive real-time updates. While other parties focus on tasks like RFIs and model updates, RealCONs continuously fetches and consolidates data through Power BI, updating project status daily, unlike the existing system, which updates every five days or weekly.

Step 2) Data analysis and Visualisation

RealCONs provides real-time project management dashboards via Power BI. Data fetched through APIs or SQL connections from various components (as detailed in Section 4.1) is cleansed using Data Analysis Expressions (DAX) and 'M' languages. Power Query processes correct noisy data, such as typographical errors from BIM, Aconex, Primavera, or SQL servers. Cleaned data is stored with the received data for analysis. Tracking project status, including identifying delays, is crucial. Figure 4.19 shows how Power BI integrates with SQL Server to update the EVM and ESM indexes through data fetched via APIs.

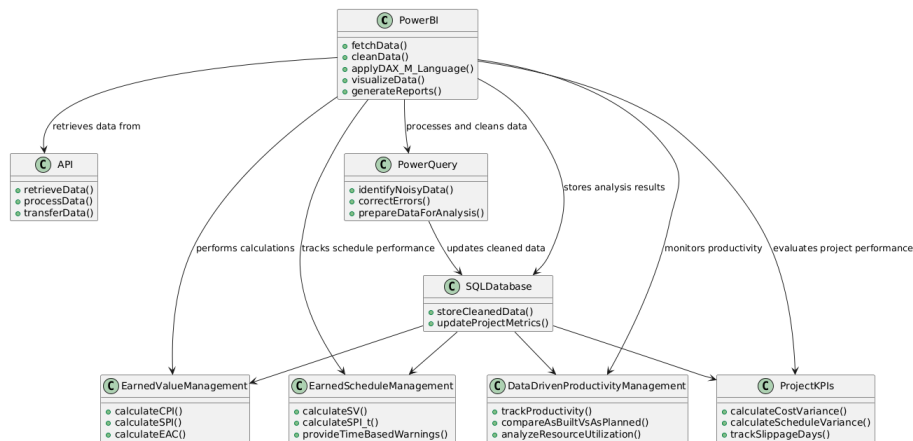


Figure 4.19: Data Analysis and Visualisation Mapping

However, RealCONs uses Power BI queries to analyze integrated data with KPI factors from Earned Value Management (EVM) and Earned Schedule Management (ESM). Table 4.2 shows key KPIs, including CPI, SPI, SVC, SPIC, EAC, CV, ES, SV, ETC, slippage impacts, and DDPM, with definitions for each as follows:

- Earned Value Management (EVM):** A project management technique integrating scope, time, and cost data to assess project performance. It uses metrics such as the Cost Performance Index (CPI) and Schedule Performance Index (SPI) to evaluate budget and schedule adherence.
- Earned Schedule Management (ESM):** An EVM extension focusing on schedule performance, measuring variance in time units with metrics like SV and SPI(t). ESM benefits: 1) Early time-based alerts, 2) Justifies schedule reserves, and 3) Highlights schedule issues for prompt action.
- Data-Driven Productivity Management (DDPM):** This approach monitors productivity by tracking efficiency and effectiveness, adjusting resource planning, and analyzing variances. BIM and Oracle-P6 reduce rework costs and track metrics. DDPM enables real-time As-Built vs As-Planned comparisons, while RealCONs and Power BI provide real-time updates, addressing monitoring and communication limitations.

Table 4.2: Key Factors of ESM and EVM [45]

	Term	Formula	Warning Indexes
EVM	SV: Deviation between the actual time and the planned to complete the project	$SV = EV - PV$	If $SV < 0$ means $PV > EV$
	CV: Deviation between actual cost and the planned cost	$CV = EV - AC$	If $CV < 0$ means $AC > EV$
	CPI: Actual cost of completing the project based on the performance to date	$CPI = EV / AC$	CPI =1: on budget CPI >1: Under budget CPI <1: Over budget
	SPI: Estimated the projected time to complete the project	$SPI = EV / PV$	SPI =1: on schedule SPI >1: ahead of schedule SPI <1: Behind schedule
	Estimate At Completion (EAC): PV of whole project/CPI	$EAC = PV / CPI$	NA
	Estimated time To Complete (ETC)	$ETC = \text{Original time} / SPI$	NA
	Planned Value (PV): Budgeted Cost of Work Scheduled (BCWS) Actual Cost (AC): Actual Cost of Work Performed (ACWP) Earned Value (EV): Budgeted Cost of Work Performed (BCWP)		

ESM	Earned Schedule (ES)	$ES = C + I$	NA
	Actual Time (C): is the number of periods completion for $BCWP \geq BCWS$ I: is increment index and uses PV and EV from EVM	$I = (EV - PV_C) / (PV_{C+1} - PV_C)$	
	Earned Schedule Variance (SV_C): Earned Schedule – Actual Time	$SV_C = ES - C$	NA
	Earned Schedule Performance Index SPI_C: Earned Schedule/Actual Time	$SPI_C = ES / C$	NA

Step 3) The Data-Driven, Real-Time Decision-Making System

RealCONs integrates data from multiple sources to support decision-making processes. This integration enables project decision-makers, such as project managers, to make real-time strategic and operational decisions in response to project status abnormalities, such as out-of-sequence jobs, clashes, and delays affecting materials and labour. This subsection will discuss the decision support system for construction projects, focusing on two key aspects: 1) early notification of delays/risks and 2) the data-driven architecture of real-time decision-making through the proposed framework.

- **Early Notification of Delays and Risks**

The risk of delays involves uncertainties impacting project tasks, including design, procurement, and construction [46, 47]. Early notification mechanisms for delays and risks help decision-makers mitigate losses by enabling timely actions and reducing inaccurate or delayed reporting. The RealCONs framework introduces a system covering six key aspects: Schedule, Design, Procurement, Construction, Financial, and Environmental Risks/Delays. Power BI uses a data model based on Key Performance Indicators (KPIs), Earned Value Management (EVM), and Earned Schedule Management (ESM) metrics to provide insights for informed decision-making [48-53].

Table 4.3: Risk and Delay Early-Notification Factors

Risk Factors					
Schedule Risk	Design Risk	Procurement Risk	Construction Risk	Financial Risk	Environment Risk
Bad estimate	Frequently changes	Contract risk	Management fault risk	Investment risk	Pandemic risk
Resource levelling	Material approval delay	Supplier chosen delay	Liability risk	Labour cost	Scope changes
Extension of Time/Acceleration	Change/Variation	Delivery delay	unproductivity	Payment claims	Shipping delay
Schedule Delay	Design Delay	Procurement Delay	Construction Delay	Financial Delay	Environmental Delay

Delay Factors

- **The Data-Driven Architecture of Real-Time Decision-Making**

Figure 4.20 illustrates the real-time decision-making aspect of RealCONs. Its data-driven architecture is a key component of the intelligent decision support system, transforming large data volumes into dynamic Key Performance Indicators (KPIs) displayed via visualizations like dashboards, bar graphs, and radar charts [45, 54]. This ensures data authenticity and timeliness, reflecting the project's real-time status and supporting decision-making. The system also delivers early notifications of potential delays or risks by analyzing historical data from BIM and SQL server databases, helping stakeholders identify emerging issues and enabling in-depth analysis to trace the source of problems.

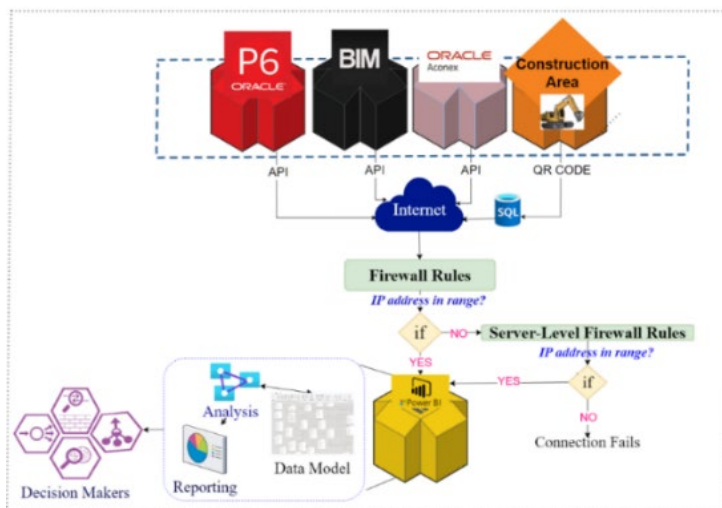


Figure 4.20: Data-Driven Architecture of Real-Time Decision-Making

a) Data Model: Data modelling in Power BI involves structuring data into a coherent and efficient format, enabling meaningful analysis and visualisation. This process includes defining relationships between data tables, creating calculated columns, and establishing data hierarchies. Data modelling is crucial in real-time decision-making as it allows for the seamless integration and analysis of dynamic data sources. This ensures decision-makers can access accurate, up-to-date information, enabling timely and informed decisions based on current project metrics and KPIs.

b) Data Analysis: Data analysis in Power BI, based on a well-structured data model, is essential for real-time decision-making. This analysis leverages Data Analysis Expressions (DAX) and Power Query M language to calculate key metrics such as Cost Performance Index (CPI), Schedule Performance Index (SPI), and Earned Schedule Variance (ESV) from data sources (Table 2). These calculations allow project managers to assess project health and performance in real time, providing insights into cost efficiency, schedule adherence, and potential delays. Using advanced

data analytics capabilities, Power BI enables decision-makers to react swiftly to changes and optimise project outcomes.

c) Reporting and Visualisation: Reporting and visualisation are crucial in real-time decision-making by providing precise and actionable insights from the data. In Power BI, once crucial performance indicators (KPIs) such as CPI and SPI are calculated, they can be visualised in dashboards and reports. For example, suppose the CPI exceeds 1, and the SPI falls below 1. In that case, it signals to the project manager that there is cost efficiency but schedule inefficiency, indicating potential issues in the project. The project manager can then be promptly notified of these discrepancies. By cross-referencing design documents and delay notifications in Aconex and aligning these insights with the Primavera program, the project manager can identify the root causes and take corrective actions before the situation escalates. This proactive approach helps maintain project schedules, control costs, and ensure project success.

4.6.3. Improving the Existing Process Using the RealCONs Framework

In comparison with the RealCONs approach (via Figure 4.17) and existing approach (via Figures 4.4 and 4.5), Figure 4.17 (technical cutaway view of RealCONs) presents a comprehensive, integrated system that enhances construction project management by addressing process gaps and improving performance, mainly focusing on early-stage delay identification. RealCONs integrates multiple data sources and platforms, including construction area data, Building Information Modelling (BIM), Oracle P6, Oracle Aconex, and analytical dashboards (Power BI). RealCONs facilitate real-time monitoring, data accuracy, and early identification of project risks and delays by connecting these systems through automated data acquisition and processing. One significant improvement RealCONs provides is data collection and cleansing automation across various domains. In the construction area, RealCONs collects data related to installation and resource quantities, which undergo a data cleansing process to ensure accuracy before being pushed to a central acquisition system. This refined data feeds into Earned Value Management (EVM) monitoring, allowing for continuous tracking of project performance and resource plan updates. RealCONs reduces manual errors, increases data accuracy, and ensures project managers have up-to-date information for proactive decision-making by automating these processes. In the BIM domain, RealCONs processes data from drawings, 3D models, and

material take-offs, which are integrated into the system through push-acquisition. A key feature is clash detection, which helps identify potential design conflicts early in the project lifecycle. This proactive identification minimises the risk of construction rework and delays by resolving design conflicts before physical work commences.

Furthermore, by integrating BIM data with other platforms, RealCONs improves interdisciplinary coordination and reduces communication gaps. The integration with Oracle P6 enhances scheduling accuracy and delay identification. RealCONs captures critical project data such as the Work Breakdown Structure (WBS), Cost Breakdown Structure (CBS), critical path, and resource plans, which are pushed to the central system. This allows the automatic update of delay and risk registers, supporting programme updates and identifying potential delays through Requests for Information (RFI) and Change Status Information (CSI). This automated process ensures delays are identified early, their impacts are assessed, and the project schedule is adjusted promptly. By reducing manual tracking and increasing the visibility of critical path changes, RealCONs enables more accurate forecasting and timely intervention. Similarly, RealCONs integrates with Oracle Aconex to capture RFI, RFQ, project updates, and delay notices. This information is fed into the central system to facilitate problem-solving and the resolution of project bottlenecks. The automated tracking and synchronisation of project communications ensure all stakeholders can access the latest project data, improving collaboration and response times to emerging issues. The Power BI analytical platform enhances RealCONs' performance by providing real-time dashboards for productivity tracking and Earned Value (EV) / Schedule Variance (SV) analysis. This platform integrates various data inputs, including WBS, cost codes, actual and planned percentages, and change codes, allowing for detailed performance analysis and early detection of deviations. Data cleansing is applied to ensure the reliability of inputs before they are pushed into the acquisition system. The dashboard provides project managers with visual insights and predictive analytics, enabling them to anticipate delays, assess their

impact, and implement corrective actions swiftly. RealCONs significantly enhances project performance by integrating disparate data sources, automating critical processes, and improving data accuracy. It addresses existing process gaps by providing real-time monitoring, clash detection, and automated delay identification, ensuring that delays are recognised and mitigated at the early stage. This integrated approach improves decision-making, enhances collaboration between project stakeholders, and reduces the risk of costly rework and delays. RealCONs optimises project outcomes and increases efficiency throughout the project lifecycle by providing accurate, timely, and actionable insights.

4.7 Results: Analysis and Discussion

Framework verification is critical for validating the accuracy and relationships of multi-source data [55]. This study quantitatively assesses the RealCONs framework, focusing on its capacity to deliver early delay alerts and its potential to generate cost and time savings through timely interventions. The verification process centred on two core dimensions: (1) the reliability of data collection and (2) the project-level impact of early notifications. A total of 90 workdays were analysed across eight construction projects, four employing traditional methods (Projects A–D) and four adopting the RealCONs framework (Projects E–H). As illustrated in Figure 4.21, a traceable workflow comparison demonstrates the operational differences between the two approaches using real-world scenarios.

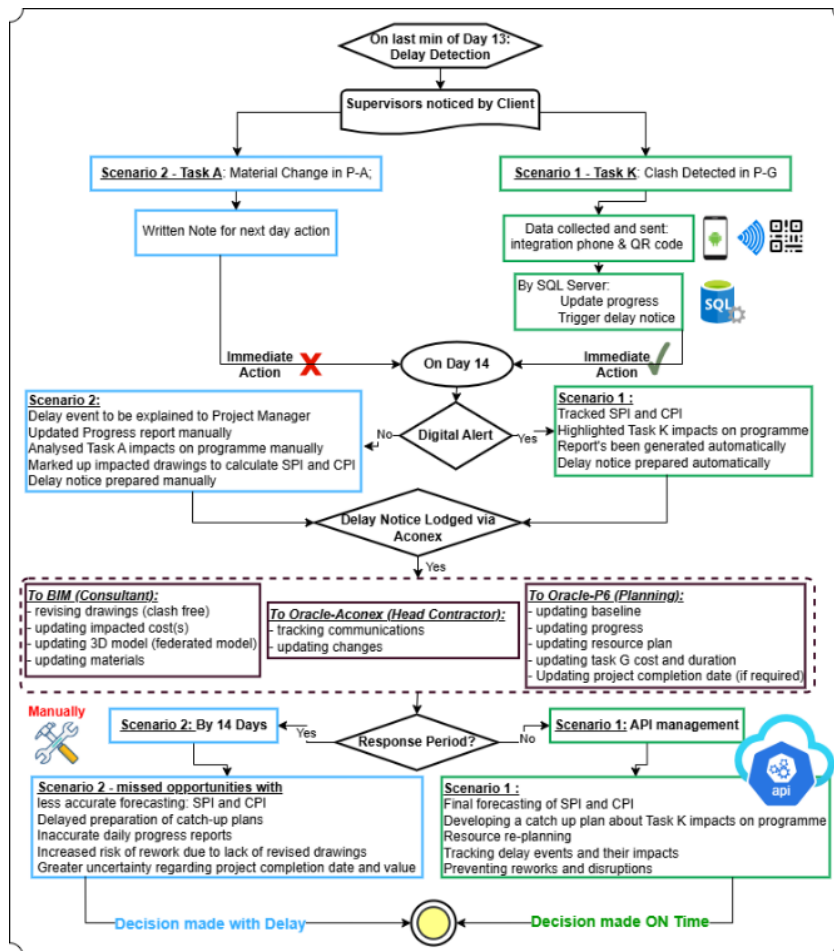


Figure 4.21: A Simple View of Data Flow Via Existing and RealCONs Approaches

In Scenario 1 (RealCONs), a conflict in Task K triggers immediate SPI and CPI tracking, automated reporting, and synchronised updates across platforms such as BIM and Oracle-Aconex/Primavera P6. This seamless integration, enabled through smartphone-based data entry and API-driven transfer, eliminates the contractual 14-day response lag. The system supports accurate forecasting and proactive resource reallocation. By contrast, Scenario 2 (Traditional Approach) reveals the inefficiencies of manual processes. A material change in Task A requires separate notice submission via Aconex, with over 24 hours needed for initial analysis—still subject to the 14-day contractual response window. Although both approaches rely on daily data inputs, the traditional method is hindered by delays in updating key systems such as P6 and BIM, leading to data gaps, compounded delays, and distorted forecasting. Figure 21 highlights these differences, showing that RealCONs significantly reduces decision latency—from weeks to

minutes—prevents delay propagation through early delay alerts and render contractual buffers increasingly redundant. Its automated workflows support real-time control, replacing reactive crisis management with targeted, data-driven interventions. Overall, the comparative findings confirm the RealCONs framework’s dual strengths in (a) reliable and integrated data collection and (b) delivering timely delay notifications that enhance project responsiveness and performance predictability:

4.7.1. Data Collection: Existing Approach Vs RealCONs Approach

Both approaches receive four daily reports (P-A/B/C/D for existing; P-E/F/G/H for RealCONs), totalling 360 reports over 90 days (120/month). Tables display 30-day snapshots. Table 4 uses 'Y' (received) and 'N' (not received) - e.g., on D1, existing showed two 'N's (P-A/C), scoring 2 (red line), while RealCONs had four 'Y's (P-B/D/G/H), scoring 4 (green line). Thus, existing received 2/4 reports versus RealCONs' 4/4 on D1. This pattern continues daily, demonstrating RealCONs' consistent reporting reliability versus the existing system's gaps.

Table 4.4: Daily Data Collection Status: A Snapshot of 30 Days Received Reports

Day		Project																														
		D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15	D16	D17	D18	D19	D20	D21	D22	D23	D24	D25	D26	D27	D28	D29	D30	
Planned		4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	
Existing		2	1	4	3	3	2	4	2	4	3	2	3	4	0	2	0	2	4	3	2	3	4	2	2	2	1	1	1	1	0	
RealCONs		4	4	4	4	3	4	4	4	4	4	4	3	4	4	4	4	3	4	4	4	4	4	3	4	4	4	4	4	4		
Existing	P-A	N	N	Y	N	Y	N	Y	Y	Y	Y	Y	N	Y	N	N	N	N	N	Y	Y	Y	N	Y	N	Y	N	N	N	Y	N	N
	P-B	N	Y	Y	Y	N	Y	Y	N	Y	Y	N	Y	Y	N	Y	N	Y	Y	Y	Y	N	Y	Y	Y	Y	N	N	Y	N	N	N
	P-C	Y	N	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y	N	Y	N	N	Y	N	Y	Y	Y	Y	Y	N	Y	Y	N	N	N	N
	P-F	Y	N	Y	Y	Y	N	Y	Y	Y	Y	N	Y	Y	N	N	N	Y	Y	Y	N	Y	Y	Y	N	N	N	Y	N	N	N	Y
RealCON	P-B	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	
	P-D	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	
	P-G	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	
	P-H	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Additionally, Figure 22 presents a bar chart based on Table 4.4, comparing the planned received data (in dark blue bars) with the data received for the existing approach in green and the proposed approach in red bars. Additionally, the horizontal axis represents the days (over 30 days), while the vertical axis shows the number of collected reports, ranging from 0 to 4.

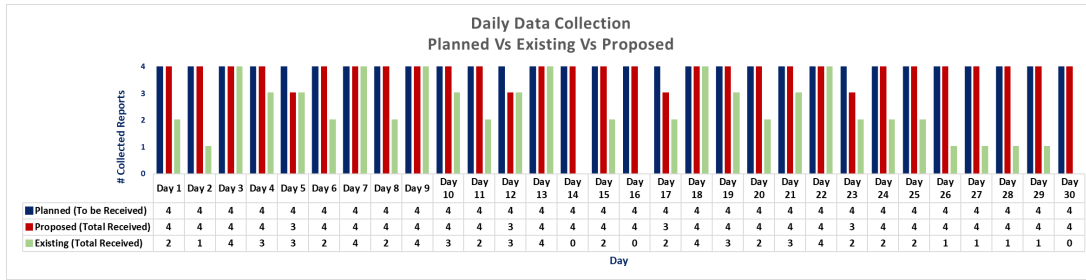


Figure 4.22: Daily Data Collection: Planned Vs Existing Vs Proposed

Figure 4.22 reveals that the proposed framework missed one report on days 5,12,17, and 23 due to internet issues, not data noise. Figure 23 plots 30-day variance percentages in data collection accuracy. On Day 1, both 'Planned' and 'Proposed' show 3% (4/120 reports), while 'Existing' shows 1.7% (2/120). This comparative analysis demonstrates RealCONs' superior reporting consistency despite occasional connectivity challenges, with its cumulative percentage closely tracking planned targets versus the existing system's significant deviations.

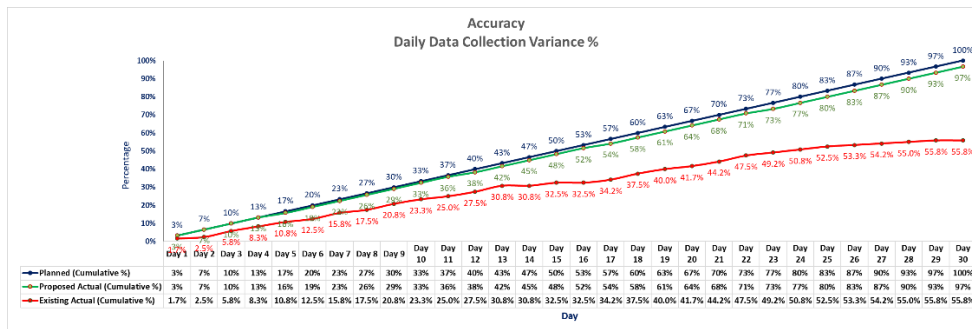


Figure 4.23: Daily Variance Percentage in Data Collection

Figure 4.23 highlights a substantial discrepancy between the existing approach (red line) and the planned target (dark blue line), whereas the RealCONs framework (green line) closely follows the planned trajectory. This visual alignment suggests RealCONs enables more accurate and timely data collection, improving day-to-day performance tracking. The current study applied the Shapiro-Wilk test to assess the normality of performance data distributions for both systems, thereby statistically validating these observations [56]. The test confirmed non-normal distributions, which justified the use of the Wilcoxon Signed-Rank analysis [57]—a non-parametric method appropriate for paired samples without normality:

Dataset	W Statistic	p-value	Description
Existing Actual	0.758	4.46×10^{-11}	The p-values for both datasets are far below 0.05, which means we reject the null hypothesis of normality. So, neither existing actual nor proposed actual is usually distributed.
Proposed Actual	0.290	3.95×10^{-19}	

$$W = \frac{(\sum_{i=1}^n a_i x_i)^2}{\sum_{i=1}^n (x_i - \bar{x})^2}$$

Where: x_i is the ordered sample values (sorted from smallest to largest), \bar{x} is

the mean of the sample, a_i constants derived from the expected values of ordered statistics of a normal distribution and their covariance matrix (pre-calculated via simulations or lookup tables), and n is the number of observations in the sample. The Wilcoxon test compares two related variances: V1) The difference between the planned target and existing actuals, and V2) the difference between the planned target and proposed (RealCONs) actuals. The hypotheses tested were:

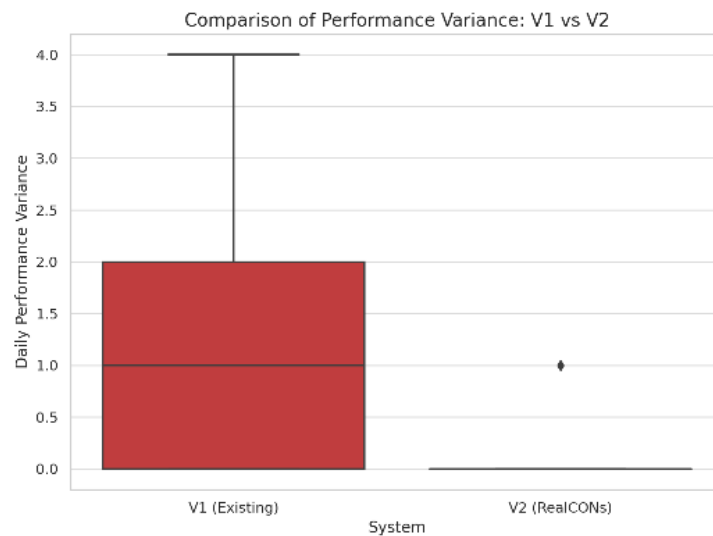
- Null Hypothesis (H_0): Median(V1) = Median(V2)
- Alternative Hypothesis (H_1): Median(V1) \neq Median(V2)

The test results strongly reject the null hypothesis, with a test statistic $W = 4095.0$, $Z = 7.624$, $p < 0.001$, and an effect size $r = 0.57$. These outcomes are interpreted as follows:

1. **Statistical Significance:** The p-value (< 0.001) confirms a significant difference between V1 and V2. The large Z-score indicates strong evidence against the null hypothesis, affirming that RealCONs significantly reduces variance.
2. **Effect Size:** With $r = 0.57$, the result indicates a moderate-to-large effect according to Cohen's thresholds (0.1 = small, 0.3 = medium, 0.5 = large). This suggests that the observed improvements are statistically significant and practically meaningful.
3. **Directionality:** The ranking distribution reveals 78 positive ranks ($V1 > V2$), six negative ranks, and six ties, meaning that on 86.7% of the days (78 out of 90), variance under the existing system exceeded that under RealCONs.

As seen below, Variance summaries further support these findings. Under the existing system,

75% of days had variance ≤ 2 , but outliers skewed the mean to 1.033. In contrast, RealCONs achieved zero deviation on 75% of days, with only 5% showing minor variance. The graph demonstrates the robustness and reliability of RealCONs in daily performance monitoring.



V1 (red) shows greater spread and outliers (up to 4), indicating inconsistency. V2 (green) maintains a stable variance close to zero, confirming more reliable and accurate reporting.

This section wraps up with practical implementation views derived from the statistical results. The statistical analysis confirms that the RealCONs framework significantly outperforms the existing approach by reducing data collection delays and decision-making, particularly in early-stage delay detection. So, project managers can adopt more proactive mitigation strategies for any delay events. The results highlight RealCONs’ potential to enhance project efficiency, lower costs, and optimise real-time construction management. RealCONs consistently maintains performance levels close to planned targets, with substantially reduced performance variance. These improvements are statistically significant and not due to random variation, indicating a systematic advantage. As such, the findings strongly support the adoption of RealCONs in operational contexts—particularly in environments where reliability and predictability are critical. The existing system (V1) demonstrates persistent underperformance, with a median performance variance of 1 and occasional severe underreporting (maximum variance = 4). These anomalies suggest the need for further investigation into specific outlier days (e.g., Days 14, 16, 30, 31, and 44). In contrast, the proposed system (V2) shows a stable alignment with project

plans, with a median variance of 0 and minimal fluctuations. Therefore, RealCONs effectively mitigates reporting inefficiencies, enhancing progress tracking, cost control, and mitigation planning accuracy and timeliness. Overall, the results provide strong empirical evidence favouring adopting RealCONs in real-world construction settings.

4.7.2. Early Delay Notification and Analysis Impact on Cost and Time

From an early notification standpoint, the existing approach (Scenario 2) is demonstrably slow in collecting and reporting data, resulting in missed opportunities for timely forecasting of cost and schedule impacts (Figure 21). This delay leaves project managers without the necessary information to respond effectively to emerging issues. In contrast, the RealCONs framework (Scenario 1) enables continuous daily reporting and early-stage delay alerts, supporting informed, real-time decision-making. As illustrated in Figure 22, when the reporting target was adjusted to 120 reports over 30 days, RealCONs achieved 116 submissions (97% of the target). In contrast, the existing method recorded only 67 (69%), indicating a 44% shortfall in early warning provision. To illustrate the practical implications, two comparable projects—P-A (Scenario 2) and P-G (Scenario 1)—were analysed. Both encountered delays at the end of Day 13. However, with poor reporting practices and frequent management complaints, P-A failed to support timely interventions. By contrast, P-G, monitored through RealCONs, maintained a near-complete reporting record, allowing for accurate cost and time adjustments. Table 4.1 highlights the difference in data trends, underscoring how early delay notifications significantly enhance managerial responsiveness and predictive reliability.

Table 4.5: A Snapshot of Table 4.4

Day \ Project		D13	D14	D15	D16	D17	D18	D19	D20
		Project							
Planned		4	4	4	4	4	4	4	4
Existing		4	0	2	0	2	4	3	2
RealCONs		4	4	4	4	3	4	4	4
Existing	P-A	Y	N	N	N	N	Y	Y	Y
	P-C	Y	N	Y	N	Y	Y	Y	N
	P-E	Y	N	Y	N	N	Y	N	Y
	P-F	Y	N	N	N	Y	Y	Y	N
RealCON	P-B	Y	Y	Y	Y	N	Y	Y	Y
	P-D	Y	Y	Y	Y	Y	Y	Y	Y
	P-G	Y	Y	Y	Y	Y	Y	Y	Y
	P-H	Y	Y	Y	Y	Y	Y	Y	Y

Between Days 14 and 17, Table 4.1 shows that Scenario 1 (RealCONs) successfully collected all daily reports for Project P-G, while Scenario 2 (Existing) recorded none for Project P-A. As illustrated in Figure 21, at the end of Day 13, supervisors on both projects identified a delay of approximately three days. The P-G supervisor immediately logged the delay and progress via a smartphone, triggering an early alert. In contrast, the P-A supervisor relied on handwritten notes, delaying the update until the following day. As a result, the P-G project manager received an automated early-stage delay notification and analysis from the SQL server via Power BI, including task duration, dependencies, and critical path details.

Meanwhile, the P-A manager remained unaware, potentially until Day 18, when the first report might be submitted. An investigation revealed several causes for the data reporting lag in Scenario 2: missing site updates, typographical errors, incomplete forms, manual data transfer delays, poor BIM-planning-reporting integration, and communication breakdowns—particularly regarding resource changes such as sick leave. A quantitative analysis using Figure 4.21 and Table 6 assessed the benefits of early-stage delay detection, employing Earned Value Management (EVM) and Earned Schedule Management (ESM) methodologies between Days 14 and 26. Four key EVM goals were evaluated: 1) impact on the \$20K Day-18 payment milestone; 2) trends in CPI and SPI; 3) variance comparisons (SV and CV); and 4) maintaining performance thresholds. Table 4.6 presents these metrics for both scenarios. Contractual

obligations governing delay notice responses informed our selection of this timeframe, as they allow consultants, planners, and the head contractor 14 days to respond. Our analysis demonstrates how timely alerts are critical in maintaining cost and schedule control.

Table 4.6: Earned Value Management (EVM) Matrix

Day	Planned Value PV	Earned Value EV		Actual Cost AC		Cost Variance CV=EV-AC		Schedule Variance SV=EV-PV		Cost Performance CPI=EV/AC		Schedule Performance SPI=EV/PV	
	S1:P-G & S2:P-A	(S1:P-G)	(S2:P-A)	(S1:P-G)	(S2:P-A)	CV (S1)	CV (S2)	SV (S1)	SV (S2)	CPI (S1)	CPI (S2)	SPI (S1)	SPI (S2)
1	\$1,111.11	\$1,166.67	\$1,222.22	\$1,060.90	\$1,164.03	\$105.77	\$58.19	\$55.56	\$111.11	1.10	1.05	1.05	1.10
2	\$2,222.22	\$2,450.20	\$2,762.20	\$2,334.48	\$2,652.85	\$115.72	\$109.35	\$227.98	\$539.98	1.05	1.04	1.10	1.24
3	\$3,333.33	\$3,500.00	\$3,166.67	\$3,300.25	\$3,500.00	\$199.75	-\$333.33	\$166.67	-\$166.66	1.06	0.90	1.05	0.95
4	\$4,444.44	\$4,666.67	\$4,222.22	\$4,222.22	\$4,666.67	\$444.45	-\$444.45	\$222.23	-\$222.22	1.11	0.90	1.05	0.95
5	\$5,555.56	\$5,300.00	\$4,222.22	\$4,222.22	\$4,666.67	\$1,077.78	-\$444.45	-\$255.56	-\$1,333.34	1.26	0.90	0.95	0.76
6	\$6,666.67	\$6,667.10	\$5,277.78	\$5,277.78	\$5,833.33	\$1,389.32	-\$555.55	\$0.45	-\$1,388.89	1.26	0.90	1.00	0.79
7	\$7,777.78	\$7,000.00	\$6,333.33	\$6,333.33	\$7,000.00	\$666.67	-\$666.67	-\$777.78	-\$1,444.45	1.11	0.90	0.90	0.81
8	\$8,888.89	\$9,100.00	\$9,000.50	\$7,388.89	\$8,166.67	\$1,711.11	\$833.83	\$211.11	-\$111.61	1.23	1.10	1.02	1.01
9	\$10,000.00	\$9,333.33	\$8,444.44	\$8,444.44	\$9,333.33	\$888.89	-\$888.89	-\$666.67	-\$1,555.56	1.11	0.90	0.93	0.84
10	\$11,111.11	\$11,300.50	\$9,555.56	\$9,555.56	\$10,500.00	\$1,744.94	-\$944.44	\$189.39	-\$1,555.55	1.18	0.91	1.02	0.86
11	\$12,222.22	\$12,200.36	\$10,266.66	\$10,611.11	\$11,666.67	\$1,589.25	-\$1,400.01	-\$21.86	-\$1,955.56	1.15	0.88	1.00	0.84
12	\$13,333.33	\$12,833.33	\$11,333.33	\$11,666.67	\$12,833.33	\$1,166.66	-\$1,500.00	-\$500.00	-\$2,000.00	1.10	0.88	0.96	0.85
13	\$14,444.44	\$14,000.00	\$12,277.77	\$12,722.22	\$14,000.00	\$1,277.78	-\$1,722.23	-\$444.44	-\$2,166.67	1.10	0.88	0.97	0.85
14	\$15,555.56	\$14,666.67	\$14,400.00	\$15,264.37	\$13,680.00	-\$597.70	\$720.00	-\$888.89	-\$1,155.56	0.96	1.05	0.94	0.93
15	\$16,666.67	\$15,833.33	\$14,400.00	\$16,100.30	\$13,680.00	-\$266.97	\$720.00	-\$833.34	-\$2,266.67	0.98	1.05	0.95	0.86
16	\$17,777.78	\$16,833.33	\$14,400.00	\$16,921.35	\$13,680.00	-\$88.02	\$720.00	-\$944.45	-\$3,377.78	0.99	1.05	0.95	0.81
17	\$18,888.89	\$17,833.33	\$14,400.00	\$18,374.05	\$13,680.00	-\$540.70	\$720.00	-\$1,055.56	-\$4,488.89	0.97	1.05	0.94	0.76
18	\$20,000.00	\$18,833.33	\$15,600.00	\$18,998.35	\$14,820.00	-\$165.02	\$780.00	-\$1,166.67	-\$4,400.00	0.99	1.05	0.94	0.78
19	\$21,111.11	\$19,833.33	\$16,800.00	\$20,001.36	\$15,960.00	-\$168.03	\$840.00	-\$1,277.78	-\$4,311.11	0.99	1.05	0.94	0.80
20	\$22,222.22	\$20,833.33	\$18,000.00	\$21,523.80	\$17,100.00	-\$690.47	\$900.00	-\$1,388.89	-\$4,222.22	0.97	1.05	0.94	0.81
21	\$23,333.33	\$21,833.33	\$16,235.25	\$21,833.40	\$23,560.00	-\$90.07	-\$7,324.75	-\$1,500.00	-\$7,098.08	1.00	0.69	0.94	0.70
22	\$24,444.44	\$24,100.25	\$17,268.98	\$22,166.67	\$24,536.35	\$1,933.58	-\$7,267.37	-\$344.19	-\$7,175.46	1.09	0.70	0.99	0.71
23	\$25,555.56	\$25,325.75	\$18,021.56	\$22,166.67	\$22,356.30	\$3,159.08	-\$4,334.74	-\$229.81	-\$7,534.00	1.14	0.81	0.99	0.71
24	\$26,666.67	\$26,012.50	\$19,125.23	\$23,222.22	\$21,500.00	\$2,790.28	-\$2,374.77	-\$654.17	-\$7,541.44	1.12	0.89	0.98	0.72
25	\$27,777.78	\$27,120.30	\$20,156.23	\$24,002.30	\$22,103.20	\$3,118.00	-\$1,946.97	-\$657.48	-\$7,621.55	1.13	0.91	0.98	0.73
26	\$28,888.89	\$28,080.85	\$20,831.45	\$25,333.33	\$24,120.32	\$2,747.52	-\$3,288.87	-\$808.04	-\$8,057.44	1.11	0.86	0.97	0.72
27	\$30,000.00	\$29,680.23	\$22,365.36	\$26,388.89	\$25,250.65	\$3,291.34	-\$2,885.29	-\$319.77	-\$7,634.64	1.12	0.89	0.99	0.75
28	\$31,111.11	\$30,921.20	\$25,270.00	\$27,444.44	\$27,300.00	\$3,476.76	-\$2,030.00	-\$189.91	-\$5,841.11	1.13	0.93	0.99	0.81
29	\$32,222.22	\$31,258.36	\$26,410.00	\$28,500.00	\$30,520.36	\$2,758.36	-\$4,110.36	-\$963.86	-\$5,812.22	1.10	0.87	0.97	0.82
30	\$33,333.33	\$32,142.30	\$27,550.00	\$29,555.56	\$31,569.65	\$2,586.74	-\$4,019.65	-\$1,191.05	-\$5,783.33	1.09	0.87	0.96	0.83

- **Goal-1) Impacts analysis on contract payment milestone:** From Table 6, analysis reveals that by Day 18, S1 (P-G) achieved an EV of \$18,833.33, just \$1,166.67 below the \$20K milestone, reaching it by Day 20; S2 (P-A) reached only \$15,600.00, falling short by \$4,400.00 and hitting the target on Day 25. So, loss values and days by day 18 are:

	Loss value	Loos day
S1 (RealCONs)	\$20,000.00 - \$18,833.33 = \$1,166.67	20-18=2 days
S2 (Existing)	\$20,000.00 - \$15,600.00 = \$4,400.00	25-18=7 days

As a result, S1 (P-G) is closer to the milestone and recovers faster, while S2 (P-A) faces significant delays and lags behind the planned value for several days.

- **Goal-2) monitoring EVM index trends (CPI, SPI):** Figures 4.24 and 4.25 reveal that while both scenarios faced schedule delays (SPI < 1), S1 (RealCONs) showed slight improvement,

and S2 deteriorated significantly. S1’s cost performance (CPI) steadily improved from 0.96 (Day 14) to 1.11 (Day 26), becoming cost-efficient (CPI ≥ 1) from Day 22 onward. In contrast, S2’s CPI, though initially strong (1.05), fell sharply to 0.86 by Day 26, indicating rising cost overruns. S1’s SPI rose from 0.94 to 0.97, suggesting steady progress; S2’s SPI plummeted from 0.92 to 0.72, highlighting severe schedule slippage.

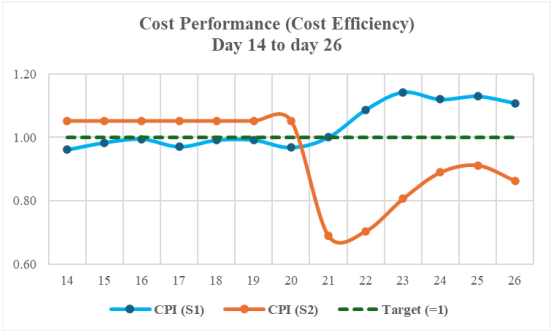


Figure 4.24: Cost Efficiency

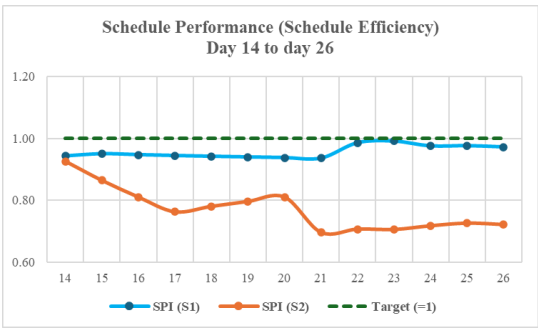


Figure 4.25: Schedule Efficiency

As a result, S1 (P-G) shows better schedule stability and cost efficiency after Day 22. S2 (P-A) experiences a significant performance breakdown post-Day 20 in cost and schedule.

- Goal-3) Comparing variances (SV, CV) Between Days 14 and 26:** Using RealCONs, the P-G team (S1) managed to stay closer to the planned value (PV), though slightly behind, while P-A (S2) lagged further, reflecting weaker schedule adherence despite early cost efficiency. Figures 4.26 and 4.27 show that S1’s cost variance (CV) fluctuated around zero but turned positive from Day 22, indicating improved cost efficiency. Conversely, S2’s CV dropped sharply from Day 21, signalling rising costs. Both scenarios showed negative schedule variance (SV), but S2’s decline was steeper, highlighting severe schedule delays.

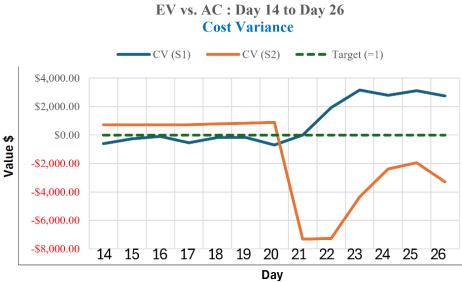


Figure 4.26: Cost Variance

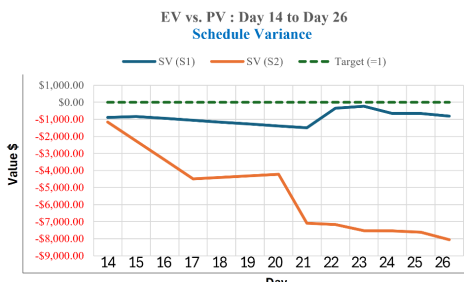


Figure 4.27: Schedule Variance

As a result, S1 (P-G) is performing better with controlled costs and minor delays. In contrast, S2 (P-A) faces significant cost overruns and is far behind schedule, indicating major performance issues.

- Goal-4) Performance Analysis (Day 14 to Day 26):** The performance analysis of S1 (P-G) shows that Cost Variance (CV) turns positive from Day 22, indicating the project is under budget. At the same time, Schedule Variance (SV) remains negative but gradually improves. The Cost Performance Index (CPI) exceeds one from Day 22, reflecting effective cost control, and the Schedule Performance Index (SPI) stays below 1, suggesting delays but with near-target progress. In contrast, S2 (P-A) experiences persistent negative CV, steep cost overruns around Days 21–22, and worsening SV. CPI drops to 0.69 by Day 21, and SPI remains low, highlighting poor performance. This contrast reinforces the value of early delay detection.

In addition, Figure 4.21 and Table 4.7 present an Earned Schedule Management (ESM) analysis to assess the impact of early-stage delay identification between Days 14–26. Table 4.7 includes key metrics—Earned Schedule (ES), Schedule Variance (SVc), and Schedule Performance Index (SPIc)—offering insights into project progress. Column "I" denotes the increment index, and "C" indicates the actual time (day).

Table 4.7: Earned Schedule Management (ESM) Matrix

	Planned Value	Earned Value		Earned Schedule		Increment (I)		Schedule Variance		Schedule Performance	
Day (C)	PV-S1 & S2	EV-S1	EV-S2	ES-S1	ES-S2	I-S1	I-S2	SVc-S1	SVc-S2	SPIc-S1	SPIc-S2
1	\$1,111.11	\$1,166.67	\$1,222.22	1.05	1.10	0.050	0.10	0.05	0.10	1.05	1.10
2	\$2,222.22	\$2,450.20	\$2,762.20	2.21	2.49	0.205	0.49	0.21	0.49	1.10	1.24
3	\$3,333.33	\$3,500.00	\$3,166.67	3.15	2.85	0.150	-0.15	0.15	-0.15	1.05	0.95
4	\$4,444.44	\$4,666.67	\$4,222.22	4.20	3.80	0.200	-0.20	0.20	-0.20	1.05	0.95
5	\$5,555.56	\$5,300.00	\$4,222.22	4.77	3.80	-0.230	-1.20	-0.23	-1.20	0.95	0.76
6	\$6,666.67	\$6,667.10	\$5,277.78	6.00	4.75	0.000	-1.25	0.00	-1.25	1.00	0.79
7	\$7,777.78	\$7,000.00	\$6,333.33	6.30	5.70	-0.700	-1.30	-0.70	-1.30	0.90	0.81
8	\$8,888.89	\$9,100.00	\$9,000.50	8.19	8.10	0.190	0.10	0.19	0.10	1.02	1.01
9	\$10,000.00	\$9,333.33	\$8,444.44	8.40	7.60	-0.600	-1.40	-0.60	-1.40	0.93	0.84
10	\$11,111.11	\$11,300.50	\$9,555.56	10.17	8.60	0.170	-1.40	0.17	-1.40	1.02	0.86
11	\$12,222.22	\$12,200.36	\$10,266.66	10.98	9.24	-0.020	-1.76	-0.02	-1.76	1.00	0.84
12	\$13,333.33	\$12,833.33	\$11,333.33	11.55	10.20	-0.450	-1.80	-0.45	-1.80	0.96	0.85
13	\$14,444.44	\$14,000.00	\$12,277.77	12.60	11.05	-0.400	-1.95	-0.40	-1.95	0.97	0.85
14	\$15,555.56	\$14,666.67	\$14,400.00	13.20	12.96	-0.800	-1.04	-0.80	-1.04	0.94	0.93
15	\$16,666.67	\$15,833.33	\$14,400.00	14.25	12.96	-0.750	-2.04	-0.75	-2.04	0.95	0.86
16	\$17,777.78	\$16,833.33	\$14,400.00	15.15	12.96	-0.850	-3.04	-0.85	-3.04	0.95	0.81
17	\$18,888.89	\$17,833.33	\$14,400.00	16.05	12.96	-0.950	-4.04	-0.95	-4.04	0.94	0.76
18	\$20,000.00	\$18,833.33	\$15,600.00	16.95	14.04	-1.050	-3.96	-1.05	-3.96	0.94	0.78
19	\$21,111.11	\$19,833.33	\$16,800.00	17.85	15.12	-1.150	-3.88	-1.15	-3.88	0.94	0.80
20	\$22,222.22	\$20,833.33	\$18,000.00	18.75	16.20	-1.250	-3.80	-1.25	-3.80	0.94	0.81
21	\$23,333.33	\$21,833.33	\$16,235.25	19.65	14.61	-1.350	-6.39	-1.35	-6.39	0.94	0.70
22	\$24,444.44	\$24,100.25	\$17,268.98	21.69	15.54	-0.310	-6.46	-0.31	-6.46	0.99	0.71
23	\$25,555.56	\$25,325.75	\$18,021.56	22.79	16.22	-0.207	-6.78	-0.21	-6.78	0.99	0.71
24	\$26,666.67	\$26,012.50	\$19,125.23	23.41	17.21	-0.589	-6.79	-0.59	-6.79	0.98	0.72
25	\$27,777.78	\$27,120.30	\$20,156.23	24.41	18.14	-0.592	-6.86	-0.59	-6.86	0.98	0.73

26	\$28,888.89	\$28,080.85	\$20,831.45	25.27	18.75	-0.727	-7.25	-0.73	-7.25	0.97	0.72
27	\$30,000.00	\$29,680.23	\$22,365.36	26.71	20.13	-0.288	-6.87	-0.29	-6.87	0.99	0.75
28	\$31,111.11	\$30,921.20	\$25,270.00	27.83	22.74	-0.171	-5.26	-0.17	-5.26	0.99	0.81
29	\$32,222.22	\$31,258.36	\$26,410.00	28.13	23.77	-0.867	-5.23	-0.87	-5.23	0.97	0.82
30	\$33,333.33	\$32,142.30	\$27,550.00	30.04	30.17	0.036	0.17	0.04	0.17	1.00	1.01

To understand the behaviours of S1 and S2 in Table 7, Table 8 provides an analysis of the progress and trends of S1:P-G and S2:P-A across three stages: Early Stages (Days 1–10), Mid-Stages (Days 11–20), and Late Stages (Days 21–30).

Table 4.8: Behaviors of P-A and P-G through ESM analysis

	Early Stages (Days 1-10)	Mid-Stages (Days 11-20)	Late Stages (Days 21-30)
Planned vs. Actual (S1: P-G)	The project is ahead of schedule ($ES > C$, positive SVc) with high efficiency ($SPIc > 1$), indicating accelerated progress.	$ES \approx C$ ($SVc \approx 0$): indicates stable schedule performance with minor slowdowns emerging.	$ES < C$ (Negative SVc shows project delays, while $SPIc < 1$ confirms declining efficiency and progress slippage.
Planned vs. Actual (S2: P-A)	$ES > C$ (Positive SVc) shows an on-schedule start but slower progress than S1.	ES stabilizes below S1 levels, showing rapid momentum loss and mid-phase bottlenecks emerging.	$ES < C$ (Negative SVc) shows severe late-stage delays, with $SPIc$ dropping faster than S1, indicating critical final-phase performance issues.

Behaviour analysis across three phases reveals distinct patterns (Table 4.8). S1 shows strong initial efficiency (fast start) but experiences gradual slowdowns, with delays accumulating toward project completion. S2 demonstrates slower overall progress than S1, with early efficiency declining rapidly, resulting in significant second-half delays. The Schedule Variance (SVc) metric quantifies these patterns: Positive SVc ($ES > C$) = ahead of schedule, Zero SVc ($ES \approx C$) = on schedule, and Negative SVc ($ES < C$) = behind schedule. Figure 4.28's daily SVc trends show S1 (P-G) beginning slightly ahead ($SVc > 0$) before stabilizing near zero, indicating a consistent pace with minor variations. Conversely, S2 (P-A) develops increasingly negative SVc after Day 14, reflecting growing schedule slippage. The comparative analysis demonstrates how early efficiency losses in S2 compound into substantially larger delays than S1's more gradual slowdown.

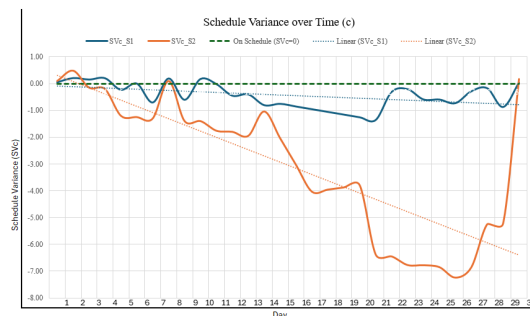


Figure 4.28: Schedule Variance (SVc)

Analysing EVM and ESM indicators (SPI and ES) is critical for quantifying the Day 13 delay's impact on project duration. These metrics assess how cost and schedule efficiency affect remaining work. The Schedule Performance Index (SPI) method, presented in Table 4.9 using the time extension (TS) formula, provides one approach for calculating additional days required:

$$\text{Time Extension (TE)} = \frac{\text{Planned Remaining Duration (Total planned days - Current day)}}{\text{SPI}}$$

Table 4.9: Time Extension Using SPI Method

On Day 13	Remaining Day: Day 13 to 30	SPI	TS (Day)	Additional Delay (Day)	Result
S1- RealCONs Approach	17 days	0.97(slight delay)	17/0.97=17.53	17.53-17=0.53 (≈1 day)	Adds ~1 day to the overall project duration
S2 - Existing Approach	17 days	0.88(larger delay)	17/0.88=19.32	19.32-17=2.32 (≈3 days)	add ~3 days to the overall project duration

Additionally, Table 4.10 presents the results of applying the ES method to calculate the time extension for Project P-A (S2) and Project P-G (S1). The Time Extension (TE) formula used in this method is:

$$\text{New Project Duration} = \text{Original Duration} + \text{Actual Time} - \text{ES}$$

Table 4.10: Time Extension Using ES Method

On Day 13	Planned ES	Actual ES (Day)	TS (Day)	Additional Delay (Day)	Result
S1- RealCONs Approach	Day 13	12.65	13-12.65=0.35	≈1 day	Adds ~1 day to the overall project duration
S2 - Existing Approach	Day 13	11.50	13-11.50=1.5	≈2 days	add ~2 days to the overall project duration

Figure 4.29 demonstrates that without intervention, the Day 13 delay extends completion to Day 31 for S1 (RealCONs) and adds three days for S2 (Existing). The orange trend reveals worsening delays in P-A (Existing). In contrast, RealCONs-enabled P-G implemented prompt corrective actions: immediate delay notices, team relocation, resource levelling, and direct data acquisition - bypassing contractual response periods. These measures yielded substantial time and cost efficiencies, minimising delay impacts. The dark bar trends illustrate how RealCONs facilitates smoother project adjustments, maintaining schedule adherence despite disruptions. The comparison highlights RealCONs' superiority in proactive delay mitigation through integrated data workflows and rapid response protocols.

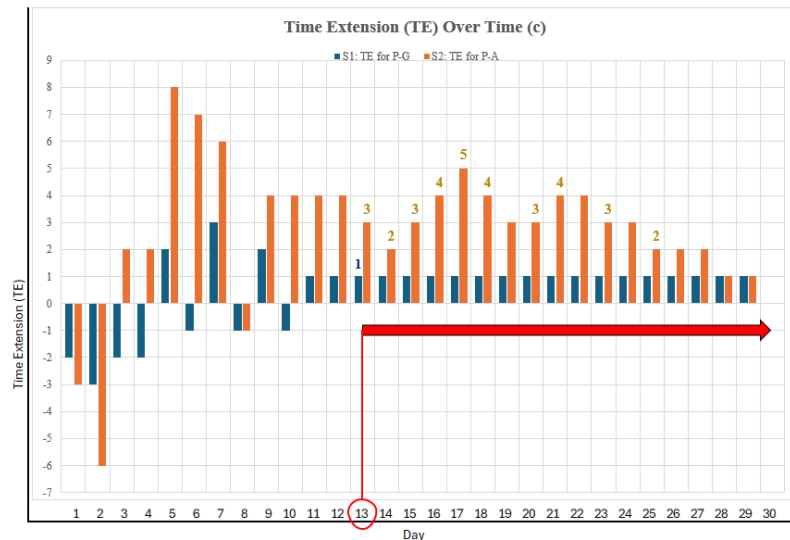


Figure 4.29: Time Extension: RealCONs Vs Existing Approach

4.8 Discussion

The comparison between RealCONs (S1) and the existing approach (S2) reveals significant cost and schedule performance differences, particularly in scalability, flexibility, and early delay identification. Analytical findings demonstrate RealCONs' broader applicability and potential benefits for construction stakeholders. While integrated tracking tools have proven successful in manufacturing and construction [42], construction projects present unique challenges: distinct project phases, decentralised work areas, and mobile resources (labour, materials, equipment). These complexities necessitate real-time data communication between stakeholders to monitor progress, respond to delays, and make timely decisions. Conventional tools often fail to cover the entire project lifecycle or effectively track delay-related cash flow impacts. The data-driven RealCONs framework addresses these limitations by incorporating advanced technologies for real-time data acquisition, early delay notifications, and dynamic project analysis. The framework enables proactive decision-making, offering superior scalability and flexibility across project types and sizes compared to traditional methods. Both approaches perform comparably in the initial stages (Days 1–4), but RealCONs maintains better cost and schedule control until Day 14, after which a moderate decline occurs. In contrast, S2 consistently underperforms, with escalating cost overruns and delays, highlighting its inability to adapt to project complexities.

RealCONs demonstrates notable resilience, recovering towards project completion (Day 30), as evidenced by improvements in Schedule Performance Index (SPIc) and Schedule Variance (SVc). This adaptability is critical for large-scale projects facing unforeseen disruptions. S2, however, lacks effective recovery mechanisms, exacerbating mid-project inefficiencies.

RealCONs' integration of advanced technologies supports real-time communication, which is essential for managing construction's decentralised nature. A key advantage of RealCONs is its generalisability across construction sectors (infrastructure, commercial, residential). Unlike conventional tools tailored to specific project types, RealCONs' flexible, data-driven approach adapts seamlessly to varied contractual arrangements and delivery models. It maintains accuracy in delay analysis and performance tracking regardless of project scale or complexity. Between Days 14–26, RealCONs identifies delays early, enabling timely interventions. Although performance declines gradually during this period, integrated monitoring mitigates impacts. For instance, slippage from the Day 18 payment milestone is less severe in S1, reflecting stronger schedule adherence. It underscores RealCONs' capacity to enhance predictability and control, making it a robust solution for improving efficiency across diverse construction applications.

The RealCONs framework outperforms existing methods by enabling real-time monitoring, predictive analytics, and integrated cost/schedule control. It delivers faster delay detection, mobile resource visibility, and data-driven decisions, addressing fragmented communication and late risk identification—ideal for complex, large-scale projects. Although various digital tools such as Last Planner System (LPS) [58], 4D/5D Building Information Modelling (BIM) [41, 59], Digital Twin technologies [60, 61], and the project management methods like Critical Path Method (CPM) [62, 63], have contributed to planning, coordination, and visualisation, they tend to operate in silos or lack real-time responsiveness. Table 4.11 provides a comparative evaluation of RealCONs and these established frameworks across key project management attributes.

Table 4.11: Comparative Evaluation of RealCONs with Existing Digital Tools/Frameworks

Digital Tool/Framework	Real-Time Monitoring	Early Delay Detection	Lifecycle Integration	Cost-Schedule Linkage	Adaptability	Limitations
RealCONs	✓ High	✓ Proactive	✓ Full lifecycle	✓ Direct, automated	✓ High	Requires connection authentications, site internet coverage
LPS	✗ Manual	✗ Reactive	✗ Execution-focused	✗ Weak	✓ Moderate	Relies on team discipline and facilitator input
4D/5D BIM	✓ Visual	✗ Limited	✓ Design–Execution	✓ Static, visual	✓ Moderate	Requires regular manual updating
Digital Twin	✓ Dynamic	✓ Conditional	✓ Strong	✓ High fidelity	✗ Low	High setup cost and technical complexity
CPM	✗ Static	✗ Post-facto	✗ Planning-only	✗ Indirect	✗ Low	Inflexible, lacks adaptability to changing site conditions

In contrast to these frameworks, RealCONs integrates real-time data from on-site sources via QR scanning through mobile technologies, enabling early delay warning systems and automatic deviation tracking. Reducing subjectivity in performance assessments supports pre-emptive corrective measures such as task resequencing or resource reallocation. Notably, RealCONs facilitates timely responses to issues emerging between Day 14 and Day 26—during which Scenario 1 shows moderate decline but remains significantly more resilient than Scenario 2. As shown in Table 4.12, Scenario 1 consistently outperforms Scenario 2 across key Earned Value Management (EVM) and Earned Schedule Management (ESM) metrics, particularly during early project stages where early intervention has the most significant effect. While some late-stage performance deterioration occurs, Scenario 1 demonstrates stronger resilience and partial recovery, underscoring the long-term value of early delay detection and response. While other systems focus narrowly on planning (e.g. CPM) or visual coordination (e.g. 4D/5D BIM), RealCONs bridges these gaps by enabling full lifecycle integration and financial foresight. Its cloud-based platform connects real-time data with predictive indicators of labour and material costs, facilitating advanced cash flow forecasting and early risk mitigation.

Table 4.12: Analytical Table for S1 Vs S2 Through ESM and EVM

Metric	Scenario 1 (S1-RealCONs)	Scenario 2 (S2-Existing)	Insights/Comments
EVM - CPI	Strong start, then CPI < 1 after Day 14	Consistently poor (CPI < 1)	S1 initially controls cost better; S2 lacks cost efficiency
EVM - SPI	Declines after Day 5 (SPI < 1)	Sharper decline post-Day 5	S2 faces more severe schedule delays
ESM - SVc	Positive early (Days 1–4), then negative	Similar trend, but a sharper drop	S2's delays are more complex to recover from
ESM - SPIc	Recovery visible by Day 30	Minimal and inconsistent recovery	S1 shows signs of resilience; S2 struggles throughout

Metric	Scenario 1 (S1-RealCONs)	Scenario 2 (S2-Existing)	Insights/Comments
Cost Efficiency	Good initially, worsens later	Poor throughout	RealCONs supports cost control in the early phases
Schedule Efficiency	Better adherence early, mid-project decline	Poor adherence from the start	RealCONs offers initial performance

From an implementation perspective, RealCONs supports a phased rollout. The Planning phase ensures that data pathways, monitoring goals, and stakeholder roles are well established. In the Execution phase, real-time alerts flag deviations before they escalate. In the Review phase, feedback loops refine analytics and decision-making protocols for future projects. The practical benefits of RealCONs extend across all key stakeholder groups: Project owners benefit from improved budget and timeline predictability, while contractors face fewer disruptions to on-site workflows. Project managers gain enhanced operational clarity through automated updates and visual analytics. End-users, in turn, are more likely to receive completed assets on schedule and within budget. RealCONs fosters a cultural shift from reactive problem-solving to proactive delay risk mitigation by enabling early delay notification-informed interventions rather than delayed responses. This shift is significant in dynamic site environments, where timely decisions yield the highest cumulative benefit. Moreover, by systematically identifying early-stage delay identification and deviations, RealCONs empowers teams to adopt a forward-planning ethos that transcends the traditional mindset of damage control. As such, it not only strengthens site-level execution but also bridges theoretical, data-driven project management strategies and the complex, fluid realities of construction practice. In doing so, RealCONs sets a new benchmark for real-time control, stakeholder collaboration, and digitally enabled project governance. While the framework offers significant advancements, its effectiveness relies on robust digital infrastructure, secure access protocols, stakeholder engagement, and appropriate workforce training.

Nevertheless, it remains user-friendly and accessible for end users, such as site supervisors. Integration may require adaptation to suit varying contractual conditions and regional practices.

Despite these considerations, by consolidating predictive analytics, financial oversight, and delay response into a single platform, RealCONs emerges as a strategic enabler for more resilient and intelligent construction project delivery.

4.9 Conclusions

Advanced tools and technologies are increasingly applied to construction projects to enhance project management [33]. However, the current construction project tracking standalone or semi-automated systems with less real-time interaction, for example, between MS Project and BIM, creates significant challenges in real-time data collection, delay notifications, and analysis among project stakeholders, including main contractors, subcontractors, and design consultants [42, 64]. Key shortcomings, such as difficulties in traceability, fragmented data interactions, inaccuracies in data collection, and inconsistent project updates, hinder real-time decision-making. To address these challenges, this study examines the generalizability of the RealCONs framework by comparing two distinct project management approaches: S1 (RealCONs), which leverages real-time data and automated processes, and S2 (Existing Approach), which relies on traditional, manual project management methods. The findings demonstrate that RealCONs significantly outperforms the Existing Approach in key dimensions such as cost control, schedule adherence, and decision-making efficiency. The automated real-time data collection process in RealCONs enables timely updates and analysis, improving project monitoring and responsiveness. RealCONs employs smartphone-based QR code scanning to capture site data, which is then transferred to an SQL server for real-time updates on delay-affected items. This automated system ensures that all stakeholders receive prompt delay notifications through platforms such as Aconex.

In contrast, the Existing Approach (S2) relies on traditional response mechanisms, such as manual updates via email, paper documentation, or Excel spreadsheets, leading to delays and inefficiencies. The superior data handling and communication mechanisms within RealCONs


underpin its enhanced performance in managing delays, costs, and schedules. A critical strength of RealCONs is its generalisability across a wide range of construction projects and project types, including infrastructure, commercial, and residential developments. Unlike existing tracking tools designed for specific project structures, RealCONs offers a scalable and adaptable framework that integrates seamlessly with different contractual arrangements, project delivery models, and stakeholder environments. Its flexibility ensures its applicability across projects of varying complexity, from small-scale developments to large-scale infrastructure works, maintaining accuracy in delay analysis, performance tracking, and real-time decision-making. The scalability and adaptability of RealCONs further enhance its suitability for diverse construction environments. Whether applied to small-scale residential projects or large-scale infrastructure developments, RealCONs provides a consistent and reliable project management solution. Its automated tracking capabilities and dynamic processes enable it to adjust to different project complexities, reducing administrative burdens and improving overall efficiency. This scalability makes it a valuable tool for organisations seeking to enhance project predictability, control, and performance. Despite its strengths, RealCONs have certain limitations that should be addressed to improve their broader applicability. Challenges like internet connectivity issues in remote locations, QR code durability during installation, and data source authentication may impact its effectiveness. Technological adoption resistance, integration complexities, and high implementation costs could also limit its feasibility, particularly for smaller projects. Furthermore, data privacy concerns, dependency on accurate historical data, and the need for scalability adjustments for small-scale projects pose additional challenges. Addressing these issues through enhanced connectivity, robust tracking solutions, stakeholder training, and strengthened data security measures will further improve the applicability and effectiveness of the RealCONs framework.

As a result, the findings underscore the importance of adopting real-time, data-driven project

management frameworks to enhance construction project performance. RealCONs provides multiple advantages, including enhanced accuracy in Earned Value Management (EVM) and Earned Schedule Management (ESM) calculations, faster decision-making, improved delay recovery, and legal protection through accurate documentation. Its scalability and flexibility ensure consistent performance across various construction environments, making it an asset for organisations managing complex, high-stakes projects. To fully realise the benefits of RealCONs, future research should explore its long-term impact on multi-project portfolios and further refine its automation and predictive analytics capabilities. By addressing its current limitations and continuously enhancing its functionalities, RealCONs has the potential to become an industry-standard framework for real-time construction project management.

STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

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In which chapter is the manuscript/published work?	Chapter 5		
Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work: ¹ Ratio of student to supervisory team 90:10, Student: Brought and Structured idea, Captured data, created model, Analysed, Drafted and Finilised Text Supervisory team: Conducted Study, Improved conceptual model, Reviewed and Finilised Text			
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Chapter 5: RealCONs: A Digital Framework for Construction Reporting Accuracy and Early Delay Detection

The current chapter is based on the following article:

Radman K, Babaeian Jelodar M, Lovreglio R (2025). RealCONs: A Digital Framework for Construction Reporting Accuracy and Early Delay Detection, *Journal of Information Technology in Construction: ITcon*, Vol. 30, pg. 745-777, <https://doi.org/10.36680/j.itcon.2025.031>

Published in Journal of Information Technology in Construction (ITcon)



Objective should be covered:

OBJ_5: Evaluate the Proposed Framework

5.1 SUMMARY

Accurate and timely reporting is essential for effective construction project management. However, existing progress tracking systems often face challenges such as delayed reporting, data inconsistencies, and inefficient documentation processes, compromising report accuracy and prolonging preparation times. This study introduces RealCONs, a digital framework for on-site project reporting management designed to enhance construction site real-time data acquisition, project tracking and reporting. The framework integrates the Rational Unified Process (RUP) methodology and Unified Modelling Language (UML) to streamline workflows. A comparative analysis was conducted using case studies from the Electrical and

Instrumentation (E&I) trade dataset to evaluate RealCONs' effectiveness in 1) improving daily reports generation speed, 2) Reducing reporting errors, and 3) Improving project performance via early delay identification. A mixed-methods approach was employed to validate RealCONs' objectives, analysing daily reports and their preparation times while utilising Earned Value Management (EVM) metrics to assess the impact of early delay identification on project performance (CPI, SPI). The results demonstrate that RealCONs significantly outperforms traditional methods, increasing total report generation by 32.2%, reducing reporting errors by 84%, and enabling earlier delay notifications. Although developed for the E&I trade, the framework offers scalable applications for broader construction and infrastructure projects facing similar reporting inefficiencies.

5.2 INTRODUCTION

Project management techniques act as a critical bridge, aligning the infrastructure needs of construction projects with the practical responsibilities of project managers and site teams to ensure timely delivery and effective management (Abdelhafiz & Mostafa, 2020; Amirtash, Jalal, & Jelodar, 2021; Correa, Castañeda, Quintero, & Giraldo, 2018; Johnson, Boucher, Connors, & Robinson, 2001). A core element of this alignment is communication, which underpins project success and demands robust execution and reporting systems to keep decision-makers and stakeholders in sync (Jelodar, Yiu, & Wilkinson, 2016; Kamalirad & Kermanshachi, 2018; Safapour, Kermanshachi, Habibi, & Shane, 2018). Despite this, discrepancies between baseline plans, actual progress, and persistent schedule delays remain widespread in construction projects (Radman, Babaeian Jelodar, Ghazizadeh, & Wilkinson, 2021). Although current productivity and progress tracking systems aim to mitigate these issues by collecting site data and generating digital reports, the speed of daily report generation and reporting accuracy remain critical

concerns. Existing models, such as labour output or time per unit of activity, can measure productivity, but their effectiveness is undermined by the reliability and timeliness of the underlying data (Arif & Khan, 2020; Ham, Moon, Kim, & Kim, 2020). Manual data collection still dominates the industry, often resulting in inefficient workflows, delayed reporting, and significant human error. Supervisors typically record progress manually, contributing to slow and inaccurate daily reports, which limit managers' ability to make timely decisions (H. Eliwa, Jelodar, & Poshdar, 2018; Zou et al., 2019). In contrast, real-time monitoring systems offer the potential to detect delays early, improve decision-making, and enhance overall project performance by enabling timely interventions. However, integrating effective information systems (IS) into construction management has proven challenging. Striking a balance between accuracy, reliability, and speed remains a major hurdle, particularly when digital solutions are not adequately tailored to construction-specific needs (Jelodar, Yiu, & Wilkinson, 2014; Jelodar et al., 2016).

As the construction sector continues to support national development, it faces rising pressure to deliver large-scale and complex projects. It has accelerated the adoption of advanced technologies such as Building Information Modelling (BIM), Artificial Intelligence (AI), Virtual Reality (VR), and data science to maintain competitiveness (Berdik, Otoum, Schmidt, Porter, & Jararweh, 2021; Kurbonovich, 2019). Automation and digitalisation are now widely recognised as essential for reducing manual errors, accelerating report generation, and enhancing decision-making processes (Babaeian Jelodar, Yiu, & Wilkinson, 2022; Kerzner, 2017). Nevertheless, many organisations rely on outdated systems for managing vast and interconnected project data, resulting in prolonged reporting cycles and low accuracy levels. These inefficiencies hinder real-time responsiveness and directly impact project outcomes (Berdik et al., 2021; H. K. Eliwa, Jelodar, Poshdar, & Yi, 2023; Kaur & Bhatia, 2024; Kurbonovich, 2019). This study introduces RealCONs, a digital reporting framework designed to address these issues by improving daily

reporting speed, reducing reporting errors, and boosting project performance through early delay identification. This research is structured as follows: Section 1 introduces the study, followed by an overview of current digital tools and systems in Section 2. Section 3 defines the research problem, while Section 4 outlines the objectives. Section 5 details the methodology, and Section 6 examines the application of RUP/UML for efficient data handling. The proposed RealCONs framework is presented in Section 7, with the case study approach described in Section 8. Section 9 presents the results, subdivided into 9.1 (Site Data Collection Approach): Improvements in daily report generation speed and error reduction; and 9.2 (Implications of Early Delay Detection): Performance enhancements through EV-based delay identification. Finally, Section 10 concludes with key findings and recommendations for future work.

5.3 BACKGROUND

Project documentation and status reporting systems are fundamental components of construction management, acting as the backbone for decision-making and progress tracking (Lamprey & Fayek, 2012; Mena, López, Framiñan, Flores, & Gallego, 2010). These systems manage a wide range of interconnected data, including cost breakdown structures (CBS), work breakdown structures (WBS), schedules, and resource plans. When maintained effectively, documentation enables project managers to monitor progress accurately and make informed decisions, particularly regarding delays (Babaeian Jelodar et al., 2022). Advanced tools such as Building Information Modelling (BIM) and database management systems (DBMS) enhance documentation processes by integrating historical data and supporting life-cycle cost analysis (Kerzner, 2017, 2022; Parisi, Fanti, & Mangini, 2021). However, implementing efficient documentation and reporting systems in construction projects remains challenging. Existing methods are often manual, time-consuming, error-prone, and lack integration. This fragmented

approach hinders the ability to correlate delays with key project metrics such as CBS and WBS, resulting in inefficiencies and inaccurate reporting (Radman, Jelodar, Lovreglio, Ghazizadeh, & Wilkinson, 2022a). The complexity of large-scale projects and the volume of data involved further complicate real-time decision-making. Relational databases and internet-enabled systems have been proposed to solve these issues (Goonetillake, Ren, & Li, 2023). By linking historical and real-time data, these tools provide comprehensive insights and improve project status tracking (H. Eliwa et al., 2018). However, their adoption often requires significant technical expertise and investment, which can be prohibitive for smaller firms (Likita, Jelodar, Vishnupriya, & Rotimi, 2024). Database management systems are crucial in construction and other industries because they facilitate structured data's efficient storage, retrieval, and long-term management. They support activities ranging from document control to complex data queries (Khan et al., 2023). DBMS technologies allow for creating schemas, managing large datasets, and controlling user access, typically implemented through programming languages like SQL or modelling tools like UML (Goonetillake et al., 2023).

In construction projects, documentation spans many interconnected data, including project costs, site progress reports, S-curves, resource plans, and payment records (Davis, Ledbetter, & Burati Jr, 1989). Traditionally, such datasets have been managed using fragmented methods, often leading to inefficiencies and inaccuracies. This lack of integration affects contractors' ability to assess the impact of delay events on critical project performance indicators such as CPI and SPI (Lopez & Love, 2012). Research indicates that aligning CBS and WBS through data analytics improves the ability to assess and manage delays (Radman, Jelodar, Lovreglio, Wilkinson, & Ghazizadeh, 2022). Progress curves have also been shown to support real-time tracking and improve project control (Cerezo-Narváez, Pastor-Fernández, Otero-Mateo, & Ballesteros-Pérez, 2020; Park & Cai, 2017). Moreover, combining relational databases with BIM offers the potential to resolve historical data challenges (Huang, Liu, Huang, Onstein, &

Merschbrock, 2023). While this enables more accurate cost tracking and budget forecasting, access to reliable historical data remains limited (Le, Likhitrungsilp, & Yabuki, 2020; Newman et al., 2021; Solihin, Eastman, Lee, & Yang, 2017). Adu-Amankwa, Rahimian, Dawood, and Park (2023) proposed a reporting framework tailored for AECO applications, demonstrating its value in streamlining reporting processes and enhancing project efficiency. Studies on major UK construction firms further explored the opportunities and challenges associated with Industry 4.0 implementation, offering insights into the future of project management (Adu-Amankwa et al., 2023; Newman et al., 2021). The incorporation of lean construction and Industry 4.0 technologies has been refined through further research, proposing improved methods for optimising documentation (Maqbool, Saiba, & Ashfaq, 2023; Newman et al., 2021). Emerging frameworks, such as the blockchain-based digital twin model for Construction 4.0, aim to integrate sustainability goals with digital innovation in reporting systems, thereby improving tracking processes and enabling broader impact analysis (Sepasgozar et al., 2023; Tanko, Zakka, & Heng, 2024; Teisserenc & Sepasgozar, 2021). Alongside these developments, advanced DBMS continue to evolve to meet the complex data needs of modern construction reporting systems (Zou et al., 2019). Through integration with the Internet, these systems consolidate inputs from various stakeholders—including site teams, engineers, contractors, and suppliers—along with historical data and analytical models to create dynamic project dashboards and reporting platforms (Radman et al., 2021). These tools provide real-time insights, allowing contractors to monitor projects more accurately and efficiently. Relational databases, in particular, offer a structured and reliable framework for data management, enabling better access and accuracy while helping stakeholders detect delay patterns and formulate mitigation strategies (Ghosh et al., 2020; Wellings, Bollella, Dibble, & Holmes, 2004). The integration of UML with databases has further strengthened data management practices (Huang et al., 2023), reinforcing the transformative role of digital technologies in modernising construction reporting and tracking

systems(Maqbool et al., 2023; Newman et al., 2021; Tanko et al., 2024).

5.4 PROBLEM STATEMENT

Despite advancements in construction reporting systems, a significant gap remains in implementing integrated, real-time, data-driven solutions to optimise multi-source data (e.g., engineering, planning, site operations, and contractor activities) across major projects. Existing systems often fail to leverage centralised approaches, which is critical for managing construction's dynamic complexity (Arif & Khan, 2020). Key challenges associated with current projects tracking approaches include: (1) High Costs: Prohibitive expenses limit adoption (Braun, Tuttas, Stilla, & Borrmann, 2014; Freimuth & König, 2018; Meredith, Shafer, Mantel Jr, & Sutton, 2020); (2) Inefficiency: Time-consuming implementation reduces on-site utility (Alizadehsalehi & Yitmen, 2019; Hwang, Zhao, & Ng, 2013); (3) Poor Communication: Collaboration tools inadequately support project-wide coordination (Gamil & Abd Rahman, 2023; Kerzner, 2017); (4) Data Management Challenges: Disorganised historical data impedes productivity and progress comparison (Azhar, Nadeem, Mok, & Leung, 2008; Eastman, Eastman, Teicholz, Sacks, & Liston, 2011; Jung & Kang, 2007; Kazemi, Beheshti, & Nobari, 2020; Ngcobo, Bhengu, Mudau, Thango, & Lerato, 2024; Vestin, Säfsten, & Popovic, 2023); (5) Integration Complexity: Projects struggle to address interdisciplinary requirements (Jiang & Messner, 2023; Wu, Li, & AbouRizk, 2022; Zhong et al., 2019). (6) Accuracy: Persistent reporting inaccuracies despite BIM/P6/Aconex use, exacerbated by flawed data flow among stakeholders (contractors, designers, engineers, and project teams) (Radman et al., 2021; Radman, Jelodar, Lovreglio, Ghazizadeh, & Wilkinson, 2022b). Furthermore, reliance on manual or semi-automated systems (e.g., paper-based data collection, photo documentation, and retrospective spreadsheet analysis) significantly increases the risk of delayed decision-making

for critical delay events (Sanni-Anibire, Mohamad Zin, & Olatunji, 2022). These outdated approaches impair accurate time and cost forecasting, leading to compounded schedule disruptions and budget overruns (Figure 5.1). Standalone project management tools exacerbate these inefficiencies by creating data silos rather than enabling real-time analysis (Radman, Jelodar, et al., 2022b).

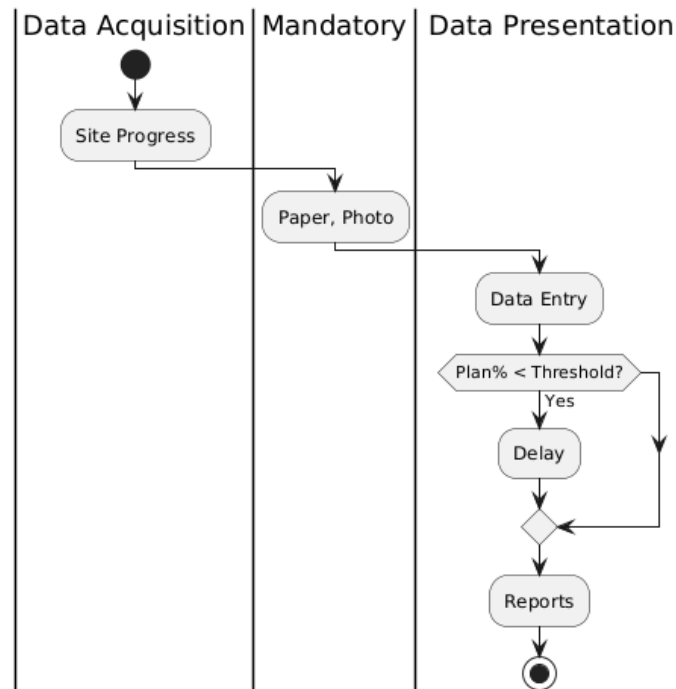


Figure 5.1: Overview: existing data collection process for data presentation

To This research proposes RealCONs, a digital framework for real-time construction reporting designed to address these challenges by capturing on-site data to enhance reporting accuracy, accelerate report preparation, improve data integrity, reduce reporting errors, and minimise delay-related costs and time impacts through early-stage delay management.

5.5 RESEARCH GOALS AND OBJECTIVES

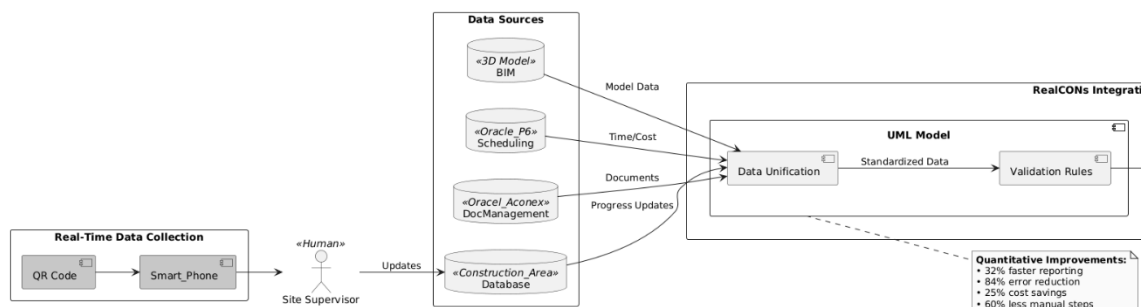
This study aims to develop and validate RealCONs, a digital reporting framework to streamline construction site reporting. The core goals and objectives are to:

- Accelerate daily report generation through real-time data integration.
- Enhance reporting accuracy by reducing manual errors via standardised validation rules.
- Improve project performance by enabling earlier identification of delays using EVM metrics.

The research also benchmarks RealCONs against key digital tools, addressing existing inefficiencies and promoting more innovative data-driven construction practices.

5.6 RESEARCH METHODOLOGY

This study employs the Rational Unified Process (RUP) framework to guide the development of RealCONs, a digital construction reporting system aimed at (1) improving daily report generation speed, (2) reducing reporting errors, and (3) enhancing project performance through early delay identification. The RUP phases, such as Inception, Elaboration, Construction, and Transition, were adapted to structure RealCONs' development, from scoping and stakeholder analysis to system architecture definition, data integration, and report delivery. As seen in Figure 5.2, the system integrates real-time field data captured via QR codes and smartphones by site supervisors, synchronised with data from BIM (3D model), Oracle P6 (time/cost), Aconex (documents), and site databases (progress updates). A UML-based model standardises data through unification and validation workflows, minimising manual interventions and aligning reporting outputs.



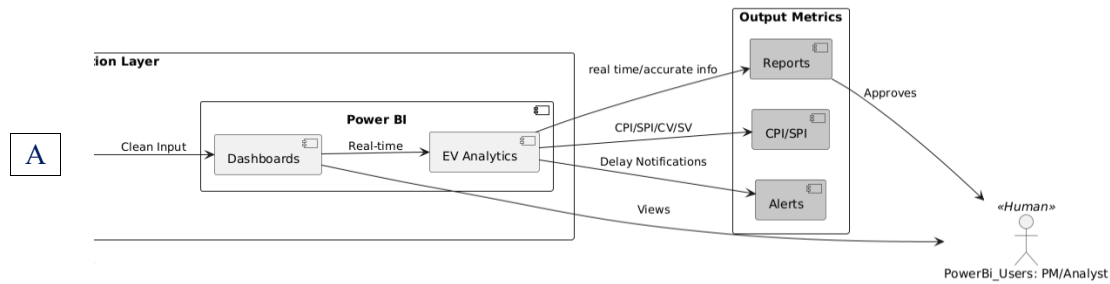


Figure 5.2: Research Methodology

5.6.1. Research Design and Data Collection: A mixed-methods approach validated the RealCONs framework. Quantitative data were sourced from an active Electrical & Instrumentation (E&I) construction project. Daily report preparation times, error frequencies, and Earned Value Management (EVM) indicators were collected and analysed.

5.6.2. Evaluation Metrics: RealCONs' performance was assessed using the following metrics:

- Report Generation Speed: Average daily report preparation times before and after implementation.
- Reporting Accuracy: Frequency and errors recorded in error logs.
- Project Performance Impact: Impact of early delay identification measured using CPI and SPI.

5.7 MODELLING: RATIONAL UNIFIED PROCESS (RUP)

Designing a real-time progress tracking and reporting system requires seamless hardware and software components integration. The Rational Unified Process (RUP), an iterative development methodology, and the Unified Modelling Language (UML), a widely used graphical language for data modelling, provide a structured approach to simplifying this task. In other words, UML is a static diagram defining a system's structure and how its components interact. Data modelling is fundamental in visualising and organising collaboration among system components, ensuring efficient tracking and reporting. This process involves three key stages: (i) Requirement Identification, where project needs are defined; (ii) Conceptual Modelling, which establishes the

relationships between stakeholders and system components; and (iii) Implementation, where suitable technologies are selected and integrated into a cohesive system. This approach is illustrated by examining a dynamic on-site tracking and reporting system for railcar monitoring, which highlights the nonlinear and intricate nature of project tracking. RUP is a standard methodology that simplifies the modelling process by focusing on system architecture and relevant use cases, ensuring that only essential elements are included. RUP consists of four iterative phases: Inception, Elaboration, Construction, and Transition, each with clearly defined disciplines, activities, roles, and outputs such as documentation, models, and system components. Therefore, Figure 5.3 presents the RUP view as follows:

- Phase 1- Inception Phase: It establishes project feasibility by identifying the project scope, defining stakeholders, assessing data collection needs, developing a business case, and drafting an initial reporting framework.
- Phase 2- Elaboration Phase: It refines the system architecture, establishes data processing workflows, and enhances approval and delay assessment rules, laying the groundwork for subsequent phases.
- Phase 3- Construction Phase: It involves data collection by supervisors, project administrators, and analysts, with project administrators entering data into the system. The project analyst then cleans and analyses the data, generating comprehensive reports.
- Phase 4- Transition Phase: It focuses on finalising reports, delivering them to stakeholders, improving workflow efficiency, ensuring enhanced decision-making and streamlined project execution.

UML is applied to support this structured approach due to its versatility in graphical data modelling. UML comprehensively represents the four RUP phases through class and use-case diagrams, enabling effective process monitoring and optimisation. The proposed framework ensures dynamic project tracking and reporting, with experimental results validating its effectiveness in improving accuracy, efficiency, and decision-making in project management.

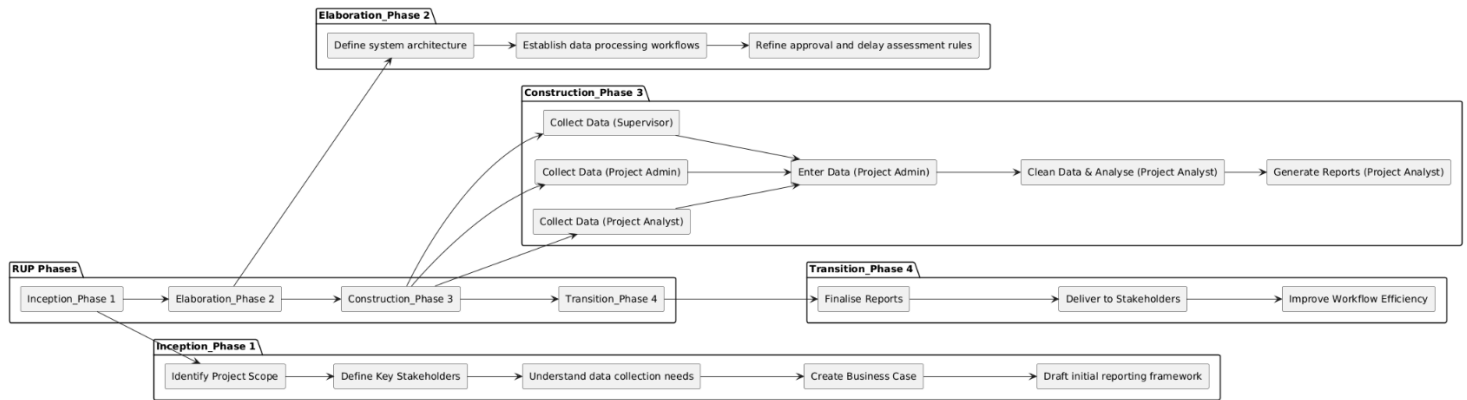


Figure 5.3: Research RUP Structure

5.8 RealCONs FRAMEWORK IN DETAIL

This work presents a new process-based digital framework for on-site project reporting management (RealCONs) designed to address the limitations identified in the problem statements. The RealCONs framework integrates various tools and systems to improve project management, tracking, and reporting in large-scale construction projects. It connects essential tools such as Building Information Modelling (BIM), Aconex (a document management system), Primavera (P6) (planning and scheduling software), Power BI (an analytical dashboard), and SQL (a server that stores real-time construction site data) to enable seamless data flow and support real-time decision-making. The RealCONs framework employs security rules and protocols using Application Programming Interfaces (APIs), which allow multiple resources to communicate securely. Technically, APIs facilitate system integration by enabling applications to exchange data and perform tasks without requiring detailed knowledge of each application's internal workings. Within the RealCONs framework, APIs ensure efficient data exchange between BIM, Aconex, P6, and Power BI, allowing real-time data to be updated and analysed. Additionally, the Construction Site component collects real-time data using smartphones to scan QR codes. The collected data is stored in an SQL database, which connects to Power BI for advanced reporting and visualisation.

This integrated structure centralises data from multiple sources, providing a comprehensive solution for managing and reporting processes throughout major construction projects. Figure 5.4 depicts a use case diagram outlining the operational workflow. Authorised site supervisors employ smartphones to scan QR codes, with captured data transmitted to a centralised SQL Server repository. Concurrently, integrated tools such as BIM software, Oracle Primavera P6, and Oracle Aconex interface with Power BI via API connections, enabling cross-platform data interoperability. The analytical dashboard (Power BI) subsequently processes this aggregated data, generating visualised reports for stakeholder review.

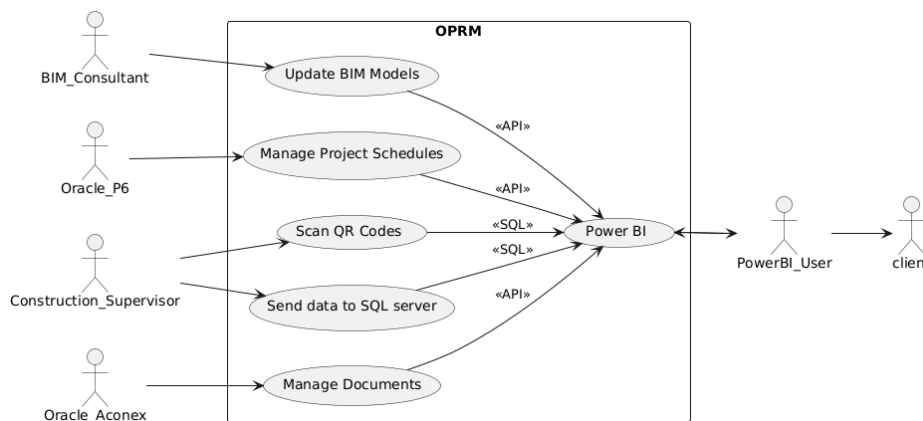


Figure 5.4: RealCONs framework's use case diagram between different users

Structurally, Figure 5.4 encompasses five defined actors (A1–A5) and two core components (C1 and C2), as detailed in the preceding sections. This diagrammatically encapsulates the systemic integration of data collection, storage, and analytical visualisation within the project framework, as described below:

- Actors**
- A1. **Construction Supervisor:** Authorised site supervisors can employ smartphones for on-site data collection. These devices scan QR codes, systematically gathering real-time operational data directly from construction sites.
 - A2. **BIM_Consultant:** Members of the engineering and design team, including BIM consultants, utilise specialised software (e.g., Revit, Navisworks) to access, review, and collaborate on BIM. It facilitates the integration of technical designs and project documentation.
 - A3. **Project Scheduler (Oracle_P6):** Project planners, schedulers or analysts oversee the development, management, and monitoring of project timelines using Oracle Primavera (P6). This role involves critical path analysis, resource allocation, and progress tracking to ensure adherence to scheduled milestones.
 - A4. **Document Manager (Oracle_Aconex):** The head contractor grants subcontractors access to a centralised platform (Oracle Aconex) for document submission. The document manager oversees the coordination, storage, and maintenance of all project-related documentation to ensure compliance and accessibility.

System Components

A5. **Power BI User:** Authorised stakeholders, such as project managers and senior decision-makers, are granted read-only access to visual dashboards displaying analytical reports. For security purposes, editing privileges are restricted to designated project schedulers and analysts, who may develop, modify, and disseminate reports via Power BI.

C1) **SQL Server:** Microsoft SQL Server functions as a centralised data repository, aggregating operational information captured via QR code scans conducted on-site. This data is subsequently channelled to Power BI to support real-time analytical processing, ensuring stakeholders can access up-to-date insights for informed decision-making.

C2) **API Connections:** Application Programming Interfaces (APIs) facilitate bidirectional data integration between Power BI and external third-party platforms, such as Oracle Primavera P6, Oracle Aconex, and BIM software. These connections ensure interoperability, enabling automated data synchronisation across systems while maintaining consistency and operational coherence.

Figure 5.5 presents a cross-sectional view of the RealCONs framework's sequence diagram, methodically delineating the chronological interactions and systemic data flow from initial on-site data collection (via QR code scanning) to the final presentation of analytical reports. In this process, construction supervisors use smartphones to scan on-site QR codes, collecting data on tasks to be completed, ongoing tasks, delays encountered, and resource utilisation. The collected data is simultaneously sent to a cloud-based central SQL Server (called construction_area as a virtual actor). The SQL Server then transfers this real-time data to Power BI for analysis and reporting. As a result, project managers, analysts, planners, and key stakeholders can monitor real-time project status and progress through Power BI dashboards. Additionally, in Figure 5.5, API_Systmes is representative of other actors contribute updates to Power BI via APIs as follows:

- **BIM (Consultant):** Provides 3D model data, which is transmitted through an API for visualisation in Power BI.
- **Oracle_P6:** Sends scheduling information, such as actual progress compared to planned timelines, via API for comparative analysis.
- **Oracle_Aconex:** Delivers document management data (e.g., version history and approvals) to Power BI through API integration, enabling efficient document tracking.

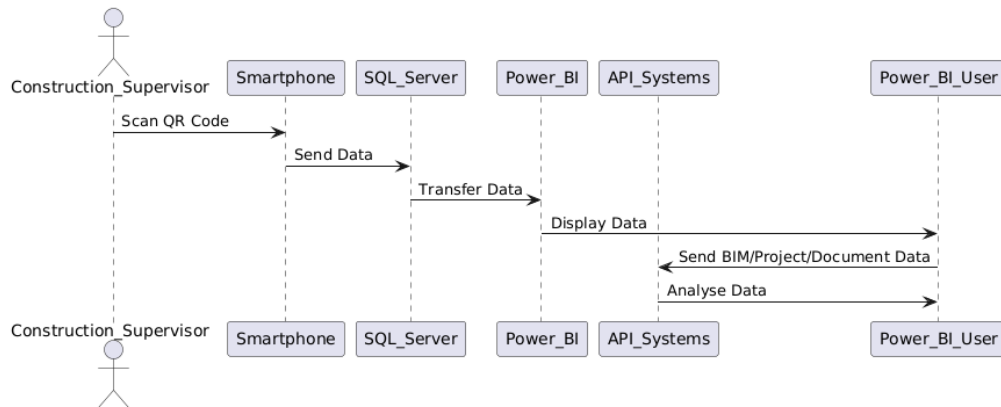


Figure 5.5: RealCONs framework' sequence diagram: Collected site data stage to reporting stage

By integrating multiple data sources such as SQL Server, BIM, Oracle P6, and Oracle Aconex, Power BI creates a holistic view of the project, enabling stakeholders i) To visualise project status through interactive dashboards that display real-time reports; ii) To identify delays and analysis their impacts using EV metrics (Table 5.1); and iii) To make Data-Driven Decisions.

Figure 6 illustrates the RealCONs integrated mapping approach.



Figure 5.6: RealCONs integrated mapping approach

Table 5.1: Earned Value Metrics (PMI, 2021)

Parameters	Formula	Warning Indexes
Schedule Variance (SV): The difference between planned and actual progress in time units.	$SV = EV - PV$	If $SV < 0$ means $PV > EV$
Cost Variance (CV): Deviation between actual and planned costs.	$CV = EV - AC$	If $CV < 0$ means $AC > EV$
Cost Performance Index (CPI): The ratio of EV to actual cost, measuring cost efficiency.	$CPI = EV / AC$	CPI =1: on budget CPI >1: Under budget CPI <1: Over budget
Schedule Performance Index (SPI): Estimated the projected time to complete the project	$SPI = EV / PV$	SPI =1: on schedule SPI >1: ahead of schedule SPI <1: Behind schedule
Estimate At Completion (EAC): PV of whole project/CPI	$EAC = PV / CPI$	
Estimated time To Complete (ETC)	$ETC = \text{Original time} / SPI$	

Planned Value (PV) is Budgeted Cost of Work Scheduled (called BCWS)
Actual Cost (AC) is Actual Cost of Work Performed (called ACWP)
Earned Value (EV) is Budgeted Cost of Work Performed (called BCWP)

The class diagram explains the data flow within each component and actor in Figure 5.5. Consequently, Figure 5.7 (a–e) presents individual class diagrams of the RealCONs framework components, illustrating data transfer from Oracle P6, Oracle Aconex, the construction area, and BIM to Power BI via APIs and SQL. The process starts when a smartphone scans a QR code, connects to the SQL Server, and transmits data to the construction site. A key advantage of the RealCONs system is its ability to provide early delay notifications. By continuously comparing actual progress with planned schedules (using tools such as Oracle P6), the system alerts project managers to potential delays as they arise. This early warning mechanism helps mitigate risks, enhances decision-making, and improves overall project efficiency. The following sections of this article will examine how the RealCONs system achieves its research objectives through comparative case studies.

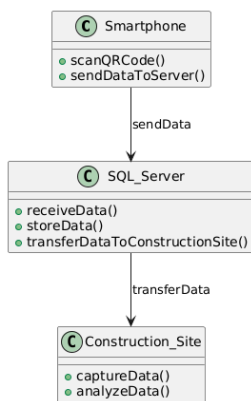


Figure 5.7(a)- Site Actual Data from Smartphone to Construction_Area

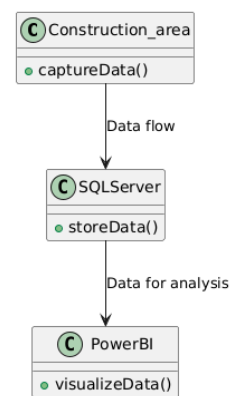


Figure 5.7 (b)- Construction_Area (captured data) to Power BI

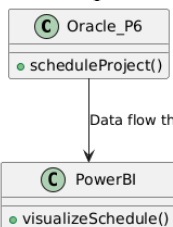


Figure 5.7 (c)- Oracle_P6 (Scheduling) to Power BI

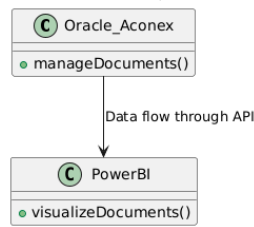


Figure 5.7 (d)- Oracle_Aconex (Document Management) to Power BI

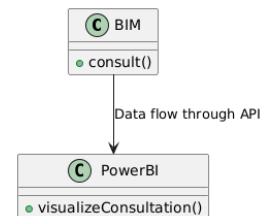


Figure 5.7 (e)- BIM (Consultant) to Power BI

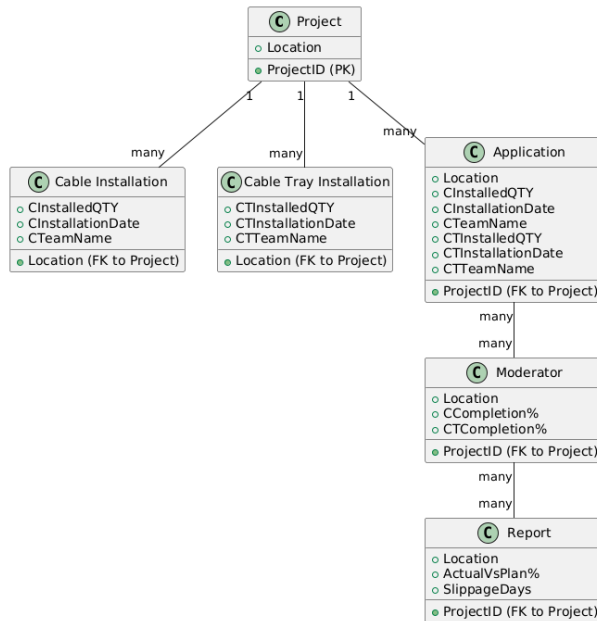


Figure 5.8: UML's classes and attributes

Figure 5.5 illustrates the SQL Server component's role as a critical mechanism for collecting real-time site data, processing it, and transferring it to Power BI. While this workflow appears streamlined, it incorporates layered technologies and applications to facilitate efficient data acquisition, analysis, and visualisation. An object-oriented model, depicted in Figure 8 through UML class and use-case diagrams, is developed to formalise this structure. The class diagram acts as a foundational blueprint, defining system components, their attributes, and interrelationships. This abstract framework clarifies the responsibilities and services of each object within the system. For example, the "data acquisition" application class specifies parameters such as measurable items, data recording locations (e.g., building ID), timings, and personnel involved (e.g., on-site supervisors). Subsequent processing is managed through interconnected classes, including the project, cable installation, and cable tray installation classes, ensuring structured data flow and operational coherence. From a database management perspective, the processes illustrated in Figure 8 are implemented into a project database. It involves developing SQL scripts to create six relational tables: Project, Cable_Installation, Cable_Tray_Installation, Application, Moderator, and Report. The SQL script used to build this

relational database is detailed in Table 5.2.

Table 5.2: Research database SQL script

Create the Project table

```
CREATE TABLE Project (  
ProjectID INT PRIMARY KEY,  
Location VARCHAR(255) NOT NULL  
);
```

Create the Cable Installation table

```
CREATE TABLE CableInstallation (  
CableInstallationID INT PRIMARY KEY AUTO_INCREMENT,  
ProjectID INT NOT NULL,  
Location VARCHAR(255) NOT NULL,  
CInstalledQTY INT NOT NULL,  
CInstallationDate DATE NOT NULL,  
CTeamName VARCHAR(255),  
FOREIGN KEY (ProjectID) REFERENCES Project(ProjectID)  
);
```

Create the Cable Tray Installation table

```
CREATE TABLE CableTrayInstallation (  
CableTrayInstallationID INT PRIMARY KEY AUTO_INCREMENT,  
ProjectID INT NOT NULL,  
Location VARCHAR(255) NOT NULL,  
CTInstalledQTY INT NOT NULL,  
CTInstallationDate DATE NOT NULL,  
CTTeamName VARCHAR(255),  
FOREIGN KEY (ProjectID) REFERENCES Project(ProjectID)  
);
```

Create the Application table

```
CREATE TABLE Application (  
ApplicationID INT PRIMARY KEY AUTO_INCREMENT,  
ProjectID INT NOT NULL,  
Location VARCHAR(255) NOT NULL,  
CInstalledQTY INT NOT NULL,  
CInstallationDate DATE NOT NULL,  
CTeamName VARCHAR(255),  
CTInstalledQTY INT NOT NULL,  
CTInstallationDate DATE NOT NULL,  
CTTeamName VARCHAR(255),  
FOREIGN KEY (ProjectID) REFERENCES Project(ProjectID)  
);
```

Create the Moderator table

```
CREATE TABLE Moderator (  
ModeratorID INT PRIMARY KEY AUTO_INCREMENT,  
ProjectID INT NOT NULL,  
Location VARCHAR(255) NOT NULL,  
CCompletion DECIMAL(5, 2) NOT NULL,  
CTCompletion DECIMAL(5, 2) NOT NULL,  
FOREIGN KEY (ProjectID) REFERENCES Project(ProjectID)  
);
```

Create the Report table

```
CREATE TABLE Report (  
ReportID INT PRIMARY KEY AUTO_INCREMENT,  
ProjectID INT NOT NULL,
```

```

Location VARCHAR(255) NOT NULL,
ActualVsPlanPercentage DECIMAL(5, 2) NOT NULL,
SlippageDays INT NOT NULL,
FOREIGN KEY (ProjectID) REFERENCES Project(ProjectID)
);

```

This database system enables project managers to process construction documents more effectively using the six tables. Figure 8 illustrates that the relationships between the Application, Moderator, and Report are many-to-many (m:n). Thus, links between the Application and Moderator and the Report are essential to the database structure.

Link Application and Moderator	Link Moderator and Report
<pre> CREATE TABLE ApplicationModerator (ApplicationID INT NOT NULL, ModeratorID INT NOT NULL, PRIMARY KEY (ApplicationID, ModeratorID), FOREIGN KEY (ApplicationID) REFERENCES Application(ApplicationID), FOREIGN KEY (ModeratorID) REFERENCES Moderator(ModeratorID)); </pre>	<pre> CREATE TABLE ModeratorReport (ModeratorID INT NOT NULL, ReportID INT NOT NULL, PRIMARY KEY (ModeratorID, ReportID), FOREIGN KEY (ModeratorID) REFERENCES Moderator(ModeratorID), FOREIGN KEY (ReportID) REFERENCES Report(ReportID)); </pre>

In Table 5.2, the key points are as follows:

- Auto-Increment IDs: Auto-incrementing IDs (CableInstallationID, CableTrayInstallationID, etc.) ensure unique entries for each table.
- Foreign Keys: Maintain relationships between tables (e.g., ProjectID is a foreign key in dependent tables).
- Many-to-Many (m:n) Relationships: The ApplicationModerator and ModeratorReport junction tables manage the many-to-many relationships.

5.9 CASE STUDY

The case study methodology provides an in-depth understanding of specific contexts, processes, or issues within real-life settings, offering practical insights and actionable outcomes (Fellows & Liu, 2021). To establish RealCONs, two major construction projects, P-A and P-B, in double-storey buildings with a floor plan of approximately 900 m² are selected. These buildings are designed for healthcare purposes, necessitating close monitoring and reporting time, cost, and quality throughout the project life-cycle. Therefore, daily tracking of the project's

productivity is essential to maintain efficiency and ensure the project stays on budget and schedule. The selection of case studies was based on several key criteria to ensure that the projects effectively represent the challenges that the RealCONs framework aims to address, such as 1) Project Scale and Value – the project value averages \$120M, but E&I value between \$20M and \$35M; (i) Similarity- each project (building) having reached at least 85% structural completion before E&I access was granted to the site. It means buildings' roofs and walls have to be completed; (ii) Availability of data and reporting system- for example, the E&I team should report cabling (metre) and cable tray (meter) installation for all case studies. However, The projects use the exact reporting mechanism using Excel, photos, paper and MS Project; and (iii) Stakeholder Diversity- involvement of multidisciplinary trades, including Builders, E&I, Mechanical, Piping, and Structural involved multiple contractors, subcontractors, and consultants. However, the main reason for prioritising the Electrical and Instrumentation (E&I) trade is that E&I tasks must be completed earlier than other service trades, such as mechanical and security activities. This is because other trades require power for their equipment during commissioning and testing. Some overlapping tasks may be acceptable, but E&I work remains a high priority. As a result, progress is closely monitored, and early identification of issues is actively managed. The project brief specification expects the total metre of cabling and cable trays to be installed in each project, as seen in Table 5.3.

Table 5.3: Cabling and Cable Tray total quantity (must be installed)

Project	P-A	P-B	E&I Value \$
Cabling (m)	12,000	11,320	\$35 Million
Cable Tray(m)	12,800	12,800	\$ 21 Million

For more visibility, Figure 5.9 provides a use case diagram that illustrates the interactions among key roles within the project management process, particularly in data-driven decision-making and reporting approaches. The primary roles include the Supervisor, Project Admin,

Project Analyst, and Project Manager, each with distinct responsibilities to ensure an efficient workflow.

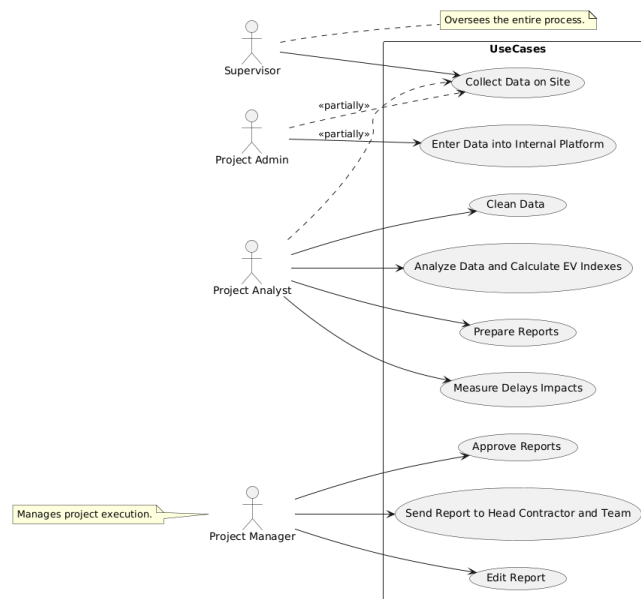


Figure 5.9: Use case: existing reporting approach

The Supervisor oversees the entire process, while the Project Admin supports data entry into the internal platform, albeit partially. The Project Analyst assumes a pivotal role, engaging in critical activities such as partially collecting site data, cleaning and analysing data, and calculating Earned Value (EV) indices. The Project Analyst is also responsible for preparing reports and assessing delay impacts. The Project Manager oversees project execution, including reviewing, editing, and approving reports before disseminating them to the head contractor and the wider project team. The collaborative nature of the process is reinforced by partial contributions from the Project Admin, ensuring data integrity and completeness. This use case diagram underscores the structured approach to project management, where systematic data collection, rigorous analysis, and effective communication among stakeholders contribute to the successful execution of projects. Integrating these roles ensures that all critical aspects, from data acquisition to final reporting, are meticulously addressed, enhancing project performance and decision-making accuracy. Moreover, the existing reporting approach is examined through the

reporting system structure of Project A.

For this purpose, a UML diagram is designed, as illustrated in Figure 5.3 – Research RUP Structure. In Project A, key stakeholders such as project managers, planners, and supervisors are represented as actors, with their relationships depicted as connections. UML is used as a tool to improve communication among these actors and to clarify project requirements. Additionally, the SIPOC (Suppliers, Inputs, Processes, Outputs, and Customers) model is applied to identify and analyse internal and external relationships within the project process, providing a structured understanding of the system. (Mishra & Kumar Sharma, 2014; Nshirim & Nwagwu, 2023). The SIPOC model is a structured framework for delineating key components within a construction project, facilitating stakeholder clarity and alignment. Suppliers encompass material providers, subcontractors, and regulatory authorities, who contribute resources or approvals essential to project initiation. Inputs include tangible and intangible elements, from construction materials, permits, and labour to technical specifications and financial capital. Processes, such as design development, site preparation, structural assembly, and quality inspections that constitute the activities Outputs are the resultant deliverables, such as completed infrastructure, compliance certifications, and project documentation, which fulfil contractual and regulatory requirements. Customers extend beyond the primary client to encompass end-users, local communities, and governing bodies, each with distinct expectations and criteria for project success. By mapping these interlinked elements, the SIPOC model enhances transparency, mitigates risks of miscommunication, and supports efficient resource allocation, thereby underpinning robust project governance in the inherently complex construction sector. Its systematic approach ensures stakeholders maintain a shared understanding of the project scope, fostering collaborative decision-making and adherence to predefined objectives.

Furthermore, SIPOC supports the Unified Modelling Language (UML) application by

providing a high-level conceptual foundation for visualising system interactions. The identified Suppliers, Inputs, and Customers within SIPOC align with UML's actor and stakeholder definitions in use case diagrams. At the same time, Processes and Outputs inform activity or sequence diagrams, enabling granular mapping of workflows and dependencies. This integration ensures UML models remain contextually anchored to real-world project parameters, enhancing their utility in analysing process efficiency, stakeholder roles, and system boundaries during construction planning and execution. Figure 5.10 illustrates the SIPOC model diagram for the P-A project.

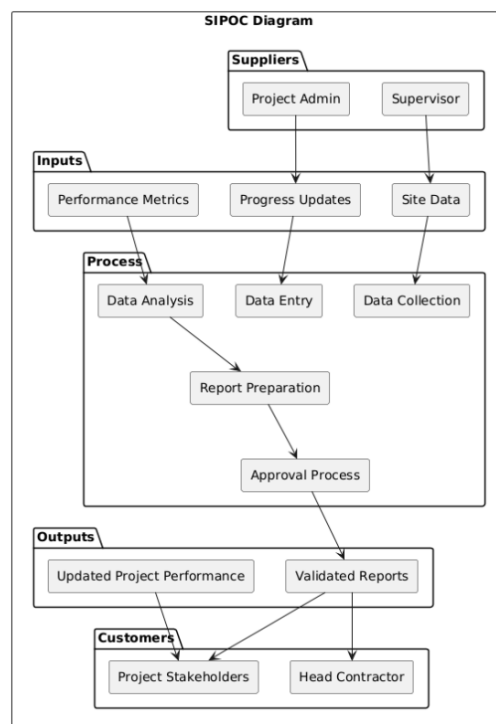


Figure 5.10: SIPOC model diagram for P-A Project

From Figure 5.10, the SIPOC breakdown aligned with the UML activity diagram (Figure 5.11) as follows:

- **Suppliers (S):** The **Supervisor** is the primary data supplier, collecting on-site information and forwarding it to the **Project Admin**. So, the **Project Admin** enters the collected data into an internal platform before sending it for further analysis.
- **Inputs (I):** The primary inputs include site data, project progress updates, and performance metrics. These inputs are transferred through a structured data collection and submission process.
- **Process (P):** it is followed by six steps:

- 1) **Data Processing & Cleansing:** The **Project Analyst** receives the data, cleans it, and ensures accuracy.
 - 2) **Data Analysis & EV Index Calculation:** Earned Value (EV) metrics are calculated to assess performance.
 - 3) **Report Preparation:** Findings are compiled into a structured report.
 - 4) **Approval Process:** The report is forwarded to the **Project Manager** for validation.
 - 5) **Conditional Assessment (Alternative Flow):** If delays are detected, their impact is measured, and an updated report is sent for review.
 - 6) **Final Approval & Submission:** The **Project Manager** edits, approves, and shares the final report with the Head Contractor and project team.
- **Outputs (O):** The final output is a validated project performance report incorporating potential delay impacts. Additionally, updated reports ensure real-time monitoring and proactive decision-making.
 - **Customers (C):** The Head Contractor and project stakeholders utilise the report for strategic planning and execution. Finally, the report aids in mitigating risks and optimising project performance.

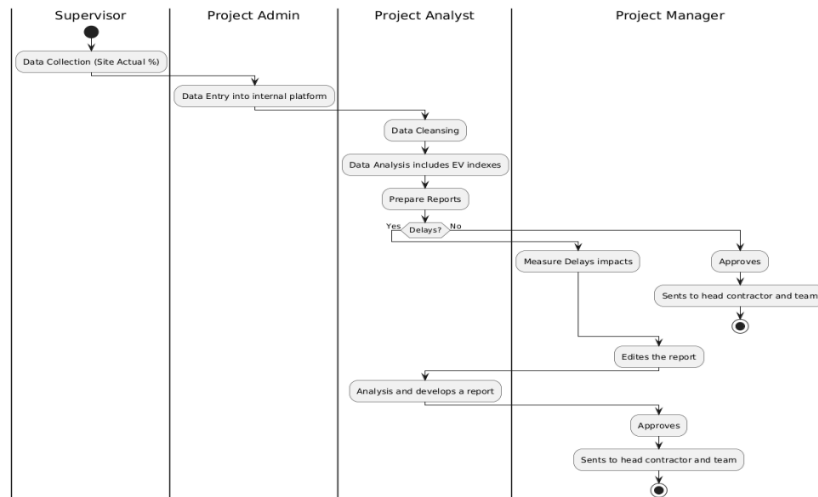


Figure 5.11: Project P-A (existing approach)' Activity Diagram

In Figure 5.11, the activity diagram presents a structured project management process involving multiple roles and sequential steps to ensure efficient project execution. Key roles include the Supervisor, who oversees the process; the Project Admin, who is responsible for administrative tasks; the Project Analyst, who analyses data and prepares reports; and the Project Manager, who coordinates tasks and ensures timely delivery. The workflow begins with data collection from the site, followed by data entry, cleansing, and analysis, including Earned Value (EV) index calculations. Reports are then prepared and reviewed, leading to a decision point where delays are assessed. If delays are identified, their impacts are analysed before proceeding. The reports undergo approval and submission, followed by possible editing and final analysis before final approval. Once approved, the report is shared with the head contractor and team for implementation. This structured approach ensures data accuracy, timely reporting, and informed

decision-making in project management.

Furthermore, the depicted sequence diagram in Figure 5.12 illustrates a structured workflow involving multiple roles in a project management process, focusing on data handling, analysis, and reporting. The process begins with the Project Manager collecting data on-site, which the Project Admin enters into an internal platform. This data is sent for analysis, where the Project Analyst performs data cleansing to ensure accuracy and calculates EV (Earned Value) indexes, which are critical for assessing project performance. Once the data is analysed, the Project Analyst prepares a report and sends it to the Supervisor for approval. A decision point arises to determine if there are any delays in the project. If delays exist, their impacts are measured, and the report is updated accordingly. The Supervisor may request edits to the report before approving it. Once approved, the final report is sent to the head contractor and the team for further action. This sequence highlights the collaborative effort between roles, emphasising the importance of accurate data processing, thorough analysis, and iterative approval processes to ensure effective project management and decision-making.

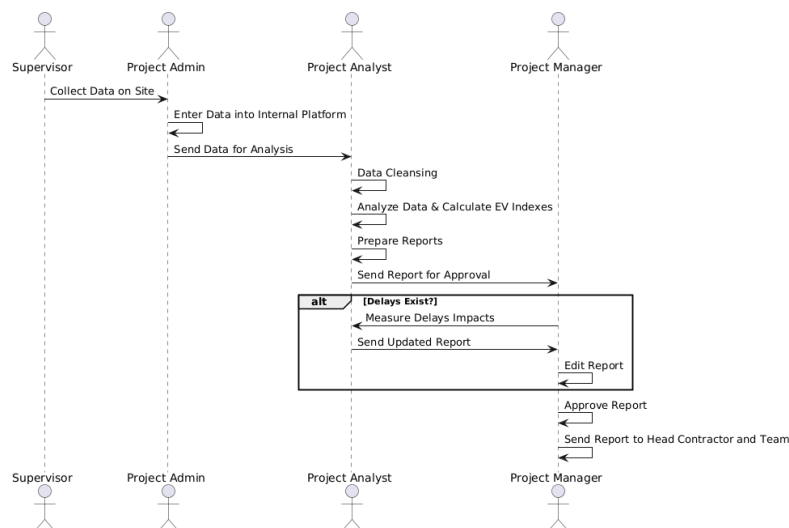


Figure 5.12: Project P-A (existing approach)' Sequence Diagram

The following section will focus on assessing the research's goals: 1) improving daily report generation speed, 2) Reducing reporting errors, and 3) Implementing early delay detection and

project performance analysis.

5.10 DISCUSSION AND RESULTS

The proposed RealCONs framework was validated through a comparative analysis between Project A (P-A), employing conventional reporting systems, and Project B (P-B), which implemented RealCONs. Two key qualitative metrics were examined: report accuracy, measured through data collection consistency rates, and report preparation time, calculated from initial data cleaning to final approval. The study further assessed RealCONs' effectiveness in early delay identification using earned value (EV) metrics and its subsequent impact on project performance. The analysis was structured into two sub_sections: Sub 9.1 (Site Data Collection Approach) focused on improving daily report generation speed and reducing reporting errors. At the same time, Sub 9.2 (Implications of Early Delay Detection) evaluated performance enhancements achieved through EV-based early delay identification.

5.10.1 Site Data Collection Approach

This section evaluates RealCONs' effectiveness in speeding up daily report generation and reducing errors through a three-month comparison between Project A (existing system) and Project B (RealCONs). The analysis measures report accuracy and preparation time under controlled conditions: simultaneous daily report collection, 90-report target (Table 5.5- three months), continuous operations, matched teams, and standardized methods (Figures 5 & 10). Project A relied on manual data collection by supervisors, requiring additional staff time for corrections, while Project B used QR code scanning. Results show Project B achieved 86/90 reports versus Project A's 65/90, with "N" indicating missing reports. Table 5.4 presents key

performance metrics, demonstrating RealCONs' superior completion and error reduction rate efficiency. The structured comparison identifies performance gaps between the systems, validating RealCONs' advantages in operational reporting:

$$\text{Improvement (\%)} = \frac{(\text{Project A "Existing"}) - (\text{Project "B" RealCONs})}{(\text{Project A "Existing"})} \times 100$$

For example, the total errors detected were 25 for Project A and 4 for Project B, resulting in an improvement percentage of 84%, calculated as (25-4)/25.

Table 5.4: Indexes analysis: Project A Vs Project B

Performance Metric	Project A (Existing)	Project B (RealCONs)	Improvement (%)
Total Reports Generated	65	86	32.31%
Total Errors Detected #	25	4	84.00%
Total Errors Detected Ratio	25/90=27.78%	4/90=4.44%	84.00%
Report Preparation Time Per Report	135 minutes	50 minutes	62.96%
Total Time Saved (Across 90 Days)	-	7310 minutes	-
Daily Time Saved	-	81.22 minutes/day	-

The evaluation of time savings involved tracking actual report preparation time using a daily timesheet, which recorded the time spent by various users, including supervisors, administrators, project analysts, and project managers, from data collection to reporting approval. This process was measured across multiple reports per day to account for variations. The average time per report was calculated using the formula:

$$\text{Actual Avg. Report Preparation Time} = \frac{\text{Total Time Spent on All Reports}}{\text{Total Number of Reports}}$$

For example, in Project A (Existing Approach)= $\frac{12180}{90} = 135 \text{ minutes per report}$

To compare the performance of the two projects in report preparation time, accuracy, and efficiency, Table 5.4 presents key metrics. The RealCONs system (Project B) significantly improved the existing system (Project A). Over 90 days, Project B produced 86 reports compared to Project A's 65, achieving a 32.3% increase in output. Error rates declined

sharply, with total errors reduced from 25 to 4 (an 84.0% improvement), while the error-to-report ratio fell from 27.8% to 4.4%. Additionally, report preparation time per submission decreased from 135 minutes to 50 minutes, yielding a 63.0% time saving and totalling 7,310 minutes saved over the 90 days as follows:

Total Time Saved

$$= (\text{Report Preparation Time in Project A} - \text{Report Preparation Time in Project B}) \times \text{Total Reports in Project B}$$

$$\text{Total Time Saved} - \text{Project B} = (135 - 50) \times 86 = 7310 \text{ minutes}$$

On a daily scale, this corresponds to a time saving of 81.22 minutes per day, determined by:

$$\text{Daily Time Saved} = \frac{\text{Total Time Saved}}{\text{Total Days}} = \frac{7310}{90} = 81.22 \text{ minutes/day}$$

Table 5.6 states the Actual Average Time per Report (Minutes) for projects A and B:

Table 5.5: Actual Average Time per Report (Minutes)

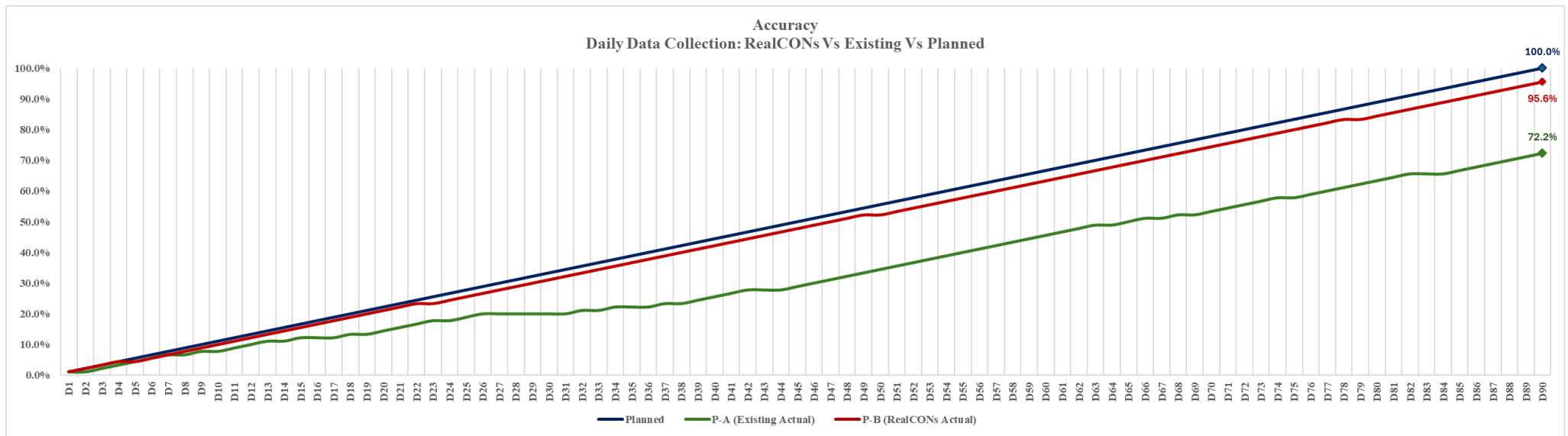
Project System	Total Reports in 90 Days	Total Time Spent (Minutes)	Actual Average Time per Report (Minutes)
Project A (Existing)	90 reports	12,180 min	135 min/report
Project B (RealCONs)	90 reports	4,530 min	50 min/report

The analysis showed clear improvements: (i) in reporting accuracy using RealCONs (Project B), which reached 95.6% compared to 72.2% in Project A (Figure 5.13), and (ii) in data slippage, which was significantly reduced from 27.8% to 4.4% (Figure 5.14). Table 5.6 outlines common reporting errors, including data entry mistakes, missing information, miscalculations, formatting issues, delays, misclassifications, and synchronisation problems. These issues often result in rework, financial discrepancies, and poor decision-making. Unlike the existing system (Project A), which depends on administrators to correct errors and fill data gaps—requiring additional time—RealCONs reduced the error rate by 84% through automated validation, real-time synchronisation, and standardised templates (Table 5.4). These findings demonstrate how RealCONs streamlines reporting, reduces errors, and improves operational efficiency in construction projects. While the system already outperforms manual processes, further refinement of its error detection mechanisms could enhance its reliability. Overall, this highlights

the potential of digital reporting tools like RealCONs to improve accuracy and productivity in project management.

Table 5.6: Three-month data collection: Project A Vs Project B

Total Received Daily Report	90	65	86
Day	Planned	P-A (Existing)	P-B (RealCONs)
D1	1	Y	Y
D2	1	N	Y
D3	1	Y	Y
D4	1	Y	Y
D5	1	Y	N
D6	1	Y	Y
D7	1	Y	Y
D8	1	N	Y
D9	1	Y	Y
D10	1	N	Y
D11	1	Y	Y
D12	1	Y	Y
D13	1	Y	Y
D14	1	N	Y
D15	1	Y	Y
D16	1	N	Y
D17	1	N	Y
D18	1	Y	Y
D19	1	N	Y
D20	1	Y	Y
D21	1	Y	Y
D22	1	Y	Y
D23	1	Y	N
D24	1	N	Y
D25	1	Y	Y
D26	1	Y	Y
D27	1	N	Y
D28	1	N	Y
D29	1	N	Y
D30	1	N	Y
D31	1	N	Y
D32	1	Y	Y
D33	1	N	Y
D34	1	Y	Y
D35	1	N	Y
D36	1	N	Y
D37	1	Y	Y
D38	1	N	Y
D39	1	Y	Y
D40	1	Y	Y
D41	1	Y	Y
D42	1	Y	Y
D43	1	N	Y
D44	1	N	Y
D45	1	Y	Y
Continued			
Day	Planned	P-A (Existing)	P-B (RealCONs)
D46	1	Y	Y
D47	1	Y	Y
D48	1	Y	Y
D49	1	Y	Y
D50	1	Y	N
D51	1	Y	Y
D52	1	Y	Y
D53	1	Y	Y
D54	1	Y	Y
D55	1	Y	Y
D56	1	Y	Y
D57	1	Y	Y
D58	1	Y	Y
D59	1	Y	Y
D60	1	Y	Y
D61	1	Y	Y
D62	1	Y	Y
D63	1	Y	Y
D64	1	N	Y
D65	1	Y	Y
D66	1	Y	Y
D67	1	N	Y
D68	1	Y	Y
D69	1	N	Y
D70	1	Y	Y
D71	1	Y	Y
D72	1	Y	Y
D73	1	Y	Y
D74	1	Y	Y
D75	1	N	Y
D76	1	Y	Y
D77	1	Y	Y
D78	1	Y	Y
D79	1	Y	N
D80	1	Y	Y
D81	1	Y	Y
D82	1	Y	Y
D83	1	N	Y
D84	1	N	Y
D85	1	Y	Y
D86	1	Y	Y
D87	1	Y	Y
D88	1	Y	Y
D89	1	Y	Y
D90	1	Y	Y



	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15	D16	D17	D18	D19	D20	D21	D22	D23	D24	D25	D26	D27	D28	D29	D30
Planned	1.1%	2.2%	3.3%	4.4%	5.6%	6.7%	7.8%	8.9%	10.0%	11.1%	12.2%	13.3%	14.4%	15.6%	16.7%	17.8%	18.9%	20.0%	21.1%	22.2%	23.3%	24.4%	25.6%	26.7%	27.8%	28.9%	30.0%	31.1%	32.2%	33.3%
P-A (Existing Actual)	1.1%	1.1%	2.2%	3.3%	4.4%	5.6%	6.7%	6.7%	7.8%	7.8%	8.9%	10.0%	11.1%	11.1%	12.2%	12.2%	12.2%	13.3%	13.3%	14.4%	15.6%	16.7%	17.8%	17.8%	18.9%	20.0%	20.0%	20.0%	20.0%	20.0%
P-B (RealCONs Actual)	1.1%	2.2%	3.3%	4.4%	4.4%	5.6%	6.7%	7.8%	8.9%	10.0%	11.1%	12.2%	13.3%	14.4%	15.6%	16.7%	17.8%	18.9%	20.0%	21.1%	22.2%	23.3%	23.3%	24.4%	25.6%	26.7%	27.8%	28.9%	30.0%	31.1%

	D31	D32	D33	D34	D35	D36	D37	D38	D39	D40	D41	D42	D43	D44	D45	D46	D47	D48	D49	D50	D51	D52	D53	D54	D55	D56	D57	D58	D59	D60
Planned	34.4%	35.6%	36.7%	37.8%	38.9%	40.0%	41.1%	42.2%	43.3%	44.4%	45.6%	46.7%	47.8%	48.9%	50.0%	51.1%	52.2%	53.3%	54.4%	55.6%	56.7%	57.8%	58.9%	60.0%	61.1%	62.2%	63.3%	64.4%	65.6%	66.7%
P-A (Existing Actual)	20.0%	21.1%	21.1%	22.2%	22.2%	22.2%	23.3%	23.3%	24.4%	25.6%	26.7%	27.8%	27.8%	27.8%	28.9%	30.0%	31.1%	32.2%	33.3%	34.4%	35.6%	36.7%	37.8%	38.9%	40.0%	41.1%	42.2%	43.3%	44.4%	45.6%
P-B (RealCONs Actual)	32.2%	33.3%	34.4%	35.6%	36.7%	37.8%	38.9%	40.0%	41.1%	42.2%	43.3%	44.4%	45.6%	46.7%	47.8%	48.9%	50.0%	51.1%	52.2%	52.2%	53.3%	54.4%	55.6%	56.7%	57.8%	58.9%	60.0%	61.1%	62.2%	63.3%

	D61	D62	D63	D64	D65	D66	D67	D68	D69	D70	D71	D72	D73	D74	D75	D76	D77	D78	D79	D80	D81	D82	D83	D84	D85	D86	D87	D88	D89	D90
Planned	67.8%	68.9%	70.0%	71.1%	72.2%	73.3%	74.4%	75.6%	76.7%	77.8%	78.9%	80.0%	81.1%	82.2%	83.3%	84.4%	85.6%	86.7%	87.8%	88.9%	90.0%	91.1%	92.2%	93.3%	94.4%	95.6%	96.7%	97.8%	98.9%	100.0%
P-A (Existing Actual)	46.7%	47.8%	48.9%	48.9%	50.0%	51.1%	51.1%	52.2%	52.2%	53.3%	54.4%	55.6%	56.7%	57.8%	57.8%	58.9%	60.0%	61.1%	62.2%	63.3%	64.4%	65.6%	65.6%	65.6%	66.7%	67.8%	68.9%	70.0%	71.1%	72.2%
P-B (RealCONs Actual)	64.4%	65.6%	66.7%	67.8%	68.9%	70.0%	71.1%	72.2%	73.3%	74.4%	75.6%	76.7%	77.8%	78.9%	80.0%	81.1%	82.2%	83.3%	83.3%	84.4%	85.6%	86.7%	87.8%	88.9%	90.0%	91.1%	92.2%	93.3%	94.4%	95.6%

All items highlighted in red indicate missing daily reports.

Figure 5.13: Data Accuracy: RealCONs Vs Existing Approach

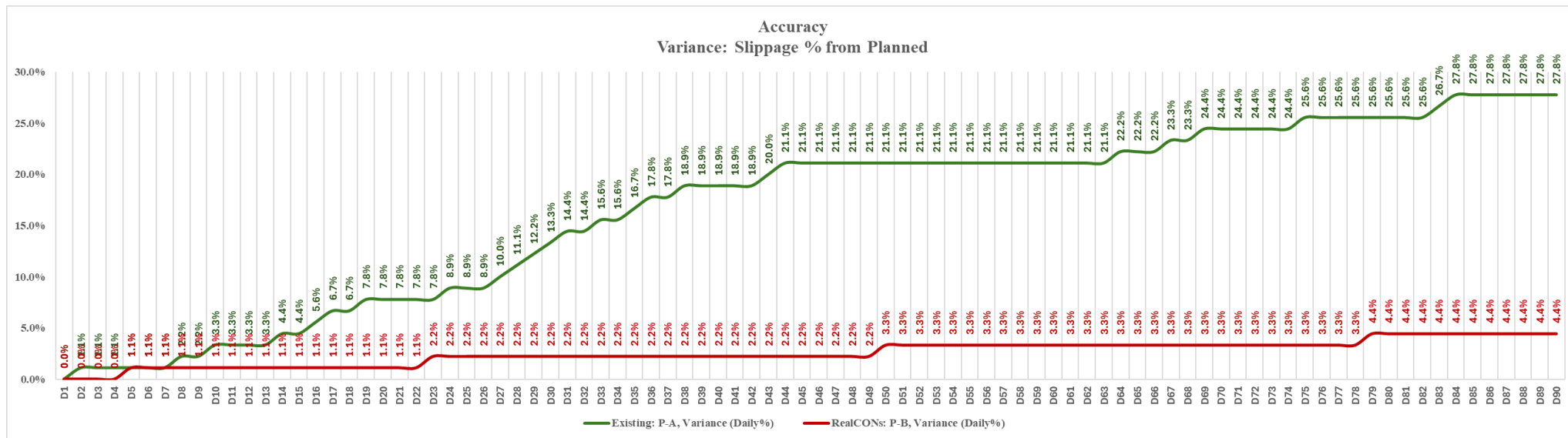


Figure 5.14: Data Accuracy variance: RealCONS Vs Existing approach

Table 5.7: Types of Errors in Report Accuracy Analysis: RealCONS vs. Existing System

Error Type	Common Issues	Impact on Reports	Existing System	RealCONS	Improvement
Data Entry Errors	Incorrect values, typos, misplaced decimals (e.g., 100.5 vs. 10.05). ^{*5}	Flawed decisions due to inaccurate records.	12 errors	2 errors ^{*1}	83.30%
Missing Data	Unrecorded measurements, skipped details.	Unreliable analysis, rework.	25 missing reports (65/90)	4 missing reports (86/90)	(25-4)/25= 84%
Calculation Errors	Wrong EV/CPI formulas summation mistakes.	Misrepresented project efficiency/financial status.	8 errors ^{*2}	1 error ^{*1}	(8-1)/8= 87.50%
Formatting Errors	Misaligned tables, unit inconsistencies, mismatched graphs.	Misinterpretation by stakeholders.	6 errors ^{*3}	1 error ^{*1}	83.30%
Time-Lag Errors	Delays in submission (e.g., 3-day lag).	Decisions are based on outdated data.	3-day	4-hour	88.9% ^{*4}

^{*1}- Internet connectivity problems caused system glitches.

^{*2}-Manual spreadsheet formulas prone to human error.

^{*3}-Lack of standardized templates; ad-hoc report creation

^{*4}-(3_days - 4_hours) / 3_days

^{*5}- Project Analysis of Project A (existing) recorded data entry errors during analysis of the 90 reports

5.10.2 Implications of early delay detection and project performance analysis

This section explains how RealCONs enhances project performance through earned value (EV) metrics (CPI/SPI). The framework enables real-time EV analysis by integrating actual site data—captured via smartphone QR code scanning—into a structured SQL Server database (see data model). The model links project activities (e.g., cable installation, cable tray installation, applications, moderator updates, and reports) to unique ProjectIDs across locations. Automated data transfers populate SQL tables with installed quantities, team names, and dates. Power Query Editor transforms this data using M-code scripts to clean and standardise inputs (handling nulls, converting data types, filtering dates) in Power BI. Concurrently, Power BI imports planned schedule data (task start dates, durations, status) from the planning system (Figure 6), enabling baseline-vs-actual progress alignment. Earned Value metrics are dynamically calculated: PV (Planned Value), the Budgeted cost of scheduled work; EV, the Budgeted cost of completed work (based on installed quantities); and AC (Actual Cost): Site records/cost logs. Daily SPI and CPI comparisons trigger automated alerts if thresholds are breached (e.g., significant schedule/cost deviations). The system then analyses delays, identifies affected tasks, quantifies impacts (days/cost), and visualises results in dashboards. Power BI automatically generates comprehensive progress reports that include (1) task-level schedule progress tracking, (2) time and cost variance analysis, (3) delay alerts with earned value (EV) matrix insights, and (4) impact forecasts projecting revised completion dates and potential budget overruns. All reported changes and delays must be systematically updated across the relevant connected components, Oracle_P6, BIM, and Oracle_Aconex, to maintain data integrity. For instance, Figure 5.15 demonstrates the practical implementation of real-time monitoring, presenting an integrated technical view of Oracle_P6 components (from Figure 6) and data flow processes (from Figure

5). It illustrates how real-time site data links to and informs the project plan/schedule through systematic analysis and Oracle_P6 updates relevant changes.

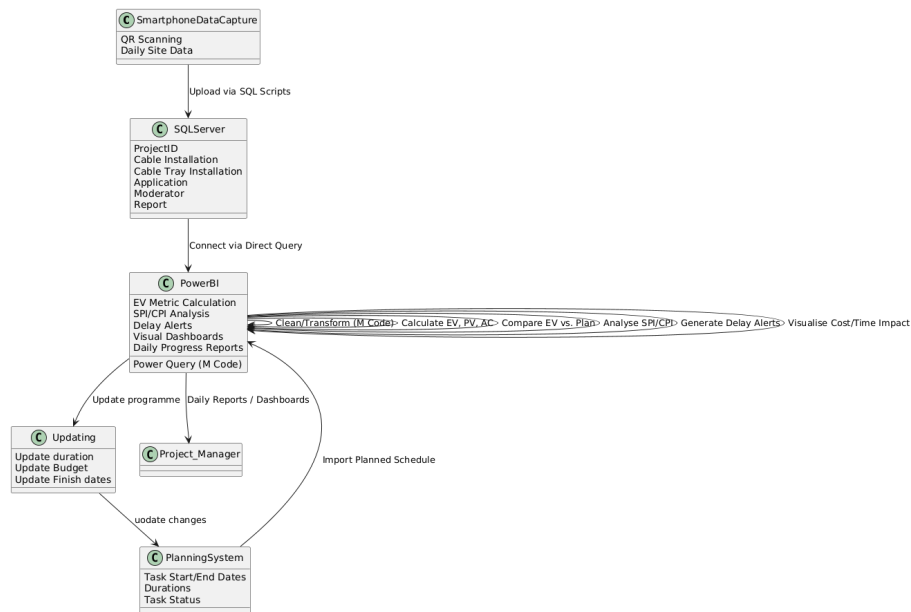


Figure 5.15: Technical view: earned value (EV) metrics analysis

As illustrated in Figure 5.15, when a delay was reported on Day 13, RealCONs immediately updated the project schedule, enabling the schedule key milestone (contract payment) to identify affected tasks and dependencies, revealing a two-day shift in project completion (refer to SG1 as bellow). This proactive adjustment gave the project manager accurate budget forecasts for delay impacts, resulting in a \$6.98M saving by Day 26 (refer to SG2 below). RealCONs achieved this through real-time integration of smartphone-captured site data (via QR codes) into SQL Server, which Power BI processed to compute Earned Value (EV) metrics, generate daily reports, and align actual progress with the planned schedule. Table 5.8 presents the first month of a 90-day project, quantifying the effects of the Day 13 delay. The contract included a \$20k payment milestone on Day 18 and a 14-day notice response period (in this case, Day 26). Upon identifying the delay, the P-B supervisor (using RealCONs) immediately logged the disruption via smartphone, triggering an automated alert.

In contrast, the P-A supervisor (using the existing system) relied on handwritten notes,

delaying the report until Day 15. As a result, P-B received real-time Power BI analysis of critical path and task dependencies, while P-A experienced a 48-hour lag, leaving the project manager unaware until Day 18. Post-analysis of P-A revealed systemic failures: missing updates, typographical errors, manual data transfer delays, and fragmented report integration—further exacerbated by poor communication regarding resource changes (e.g., sick leave). Table 5.8 displays the first month of the 90-day project schedule, quantifying the impact of a delay event occurring on Day 13. To evaluate the third research goal, Table 5.8 assesses two sub-goals: SG1) Contract Payment Milestone Impact Analysis and SG2) Project Performance Monitoring.

Table 5.8: A snippet of 90 Days early delay identification via EV metrics

Day	Planned Value PV	Earned Value EV		Actual Cost AC		Cost Variance CV=EV – AC		Schedule Variance SV= EV – PV		Cost Performance CPI=EV/AC		Schedule Performance SPI=EV/PV	
	P-A & P-B	(P-B)	(P-A)	(P-B)	(P-A)	CV (P-B)	CV (P-A)	SV (P-B)	SV (P-A)	CPI (P-B)	CPI (P-A)	SPI (P-B)	SPI (P-A)
1	\$1,111.11	\$1,166.67	\$1,222.22	\$1,060.90	\$1,164.03	\$105.77	\$58.19	\$55.56	\$111.11	1.10	1.05	1.05	1.10
2	\$2,222.22	\$2,450.20	\$2,762.20	\$2,334.48	\$2,652.85	\$115.72	\$109.35	\$227.98	\$539.98	1.05	1.04	1.10	1.24
3	\$3,333.33	\$3,500.00	\$3,166.67	\$3,300.25	\$3,500.00	\$199.75	-\$333.33	\$166.67	-\$166.66	1.06	0.90	1.05	0.95
4	\$4,444.44	\$4,666.67	\$4,222.22	\$4,222.22	\$4,666.67	\$444.45	-\$444.45	\$222.23	-\$222.22	1.11	0.90	1.05	0.95
5	\$5,555.56	\$5,300.00	\$4,222.22	\$4,222.22	\$4,666.67	\$1,077.78	-\$444.45	-\$255.56	-\$1,333.34	1.26	0.90	0.95	0.76
6	\$6,666.67	\$6,667.10	\$5,277.78	\$5,277.78	\$5,833.33	\$1,389.32	-\$555.55	\$0.43	-\$1,388.89	1.26	0.90	1.00	0.79
7	\$7,777.78	\$7,000.00	\$6,333.33	\$6,333.33	\$7,000.00	\$666.67	-\$666.67	-\$777.78	-\$1,444.45	1.11	0.90	0.90	0.81
8	\$8,888.89	\$9,100.00	\$9,000.50	\$7,388.89	\$8,166.67	\$1,711.11	\$833.83	\$211.11	\$111.61	1.23	1.10	1.02	1.01
9	\$10,000.00	\$9,333.33	\$8,444.44	\$8,444.44	\$9,333.33	\$888.89	-\$888.89	-\$666.67	-\$1,555.56	1.11	0.90	0.93	0.84
10	\$11,111.11	\$11,300.50	\$9,555.56	\$9,555.56	\$10,500.00	\$1,744.94	-\$944.44	\$189.39	-\$1,555.55	1.18	0.91	1.02	0.86
11	\$12,222.22	\$12,200.36	\$10,266.66	\$10,611.11	\$11,666.67	\$1,589.25	-\$1,400.01	-\$21.86	-\$1,955.56	1.15	0.88	1.00	0.84
12	\$13,333.33	\$12,833.33	\$11,333.33	\$11,666.67	\$12,833.33	\$1,166.66	-\$1,500.00	-\$500.00	-\$2,000.00	1.10	0.88	0.96	0.85
13	\$14,444.44	\$14,000.00	\$12,277.77	\$12,722.22	\$14,000.00	\$1,277.78	-\$1,722.23	-\$444.44	-\$2,166.67	1.10	0.88	0.97	0.85
14	\$15,555.56	\$14,666.67	\$14,400.00	\$15,264.37	\$13,680.00	-\$597.70	\$720.00	-\$888.89	-\$1,155.56	0.96	1.05	0.94	0.93
15	\$16,666.67	\$15,833.33	\$14,400.00	\$16,100.30	\$13,680.00	-\$266.97	\$720.00	-\$833.34	-\$2,266.67	0.98	1.05	0.95	0.86
16	\$17,777.78	\$16,833.33	\$14,400.00	\$16,921.35	\$13,680.00	-\$88.02	\$720.00	-\$944.45	-\$3,377.78	0.99	1.05	0.95	0.81
17	\$18,888.89	\$17,833.33	\$14,400.00	\$18,374.03	\$13,680.00	-\$540.70	\$720.00	-\$1,055.56	-\$4,488.89	0.97	1.05	0.94	0.76
18	\$20,000.00	\$18,833.33	\$15,600.00	\$18,998.35	\$14,820.00	-\$165.02	\$780.00	-\$1,166.67	-\$4,400.00	0.99	1.05	0.94	0.78
19	\$21,111.11	\$19,833.33	\$16,800.00	\$20,001.36	\$15,960.00	-\$168.03	\$840.00	-\$1,277.78	-\$4,311.11	0.99	1.05	0.94	0.80
20	\$22,222.22	\$20,833.33	\$18,000.00	\$21,523.80	\$17,100.00	-\$690.47	\$900.00	-\$1,388.89	-\$4,222.22	0.97	1.05	0.94	0.81
21	\$23,333.33	\$21,833.33	\$16,235.25	\$21,833.40	\$23,560.00	-\$0.07	-\$7,324.75	-\$1,500.00	-\$7,098.08	1.00	0.69	0.94	0.70
22	\$24,444.44	\$24,100.25	\$17,268.98	\$22,166.67	\$24,536.35	\$1,933.58	-\$7,267.37	-\$344.19	-\$7,175.46	1.09	0.70	0.99	0.71
23	\$25,555.56	\$25,325.75	\$18,021.56	\$22,166.67	\$22,356.30	\$3,159.08	-\$4,334.74	-\$229.81	-\$7,534.00	1.14	0.81	0.99	0.71
24	\$26,666.67	\$26,012.50	\$19,125.23	\$23,222.22	\$21,500.00	\$2,790.28	-\$2,374.77	-\$654.17	-\$7,541.44	1.12	0.89	0.98	0.72
25	\$27,777.78	\$27,120.30	\$20,156.23	\$24,002.30	\$22,103.20	\$3,118.00	-\$1,946.97	-\$657.48	-\$7,621.55	1.13	0.91	0.98	0.73
26	\$28,888.89	\$28,080.85	\$20,831.45	\$25,333.33	\$24,120.32	\$2,747.52	-\$3,288.87	-\$808.04	-\$8,057.44	1.11	0.86	0.97	0.72
27	\$30,000.00	\$29,680.23	\$22,365.36	\$26,388.89	\$25,250.65	\$3,291.34	-\$2,885.29	-\$319.77	-\$7,634.64	1.12	0.89	0.99	0.75
28	\$31,111.11	\$30,921.20	\$25,270.00	\$27,444.44	\$27,300.00	\$3,476.76	-\$2,030.00	-\$189.91	-\$5,841.11	1.13	0.93	0.99	0.81
29	\$32,222.22	\$31,258.36	\$26,410.00	\$28,500.00	\$30,520.36	\$2,758.36	-\$4,110.36	-\$963.86	-\$5,812.22	1.10	0.87	0.97	0.82
30	\$33,333.33	\$32,142.30	\$27,550.00	\$29,555.56	\$31,569.65	\$2,586.74	-\$4,019.65	-\$1,191.03	-\$5,783.33	1.09	0.87	0.96	0.83

- **SG1) Contract Payment Milestone Impact Analysis:** The analysis demonstrates significant divergence in milestone achievement: Project B (RealCONs) achieved \$18,833.33 EV by Day 18, nearing the \$20k payment milestone (shortfall: \$1,166.67) and almost reaching it by Day 20. while Project A (Existing) reached only \$15,600.00 by Day 18 (4,400 short), almost attaining the

milestone by Day 25 (Table 5.8). So, loss values and days by day 18 are:

	Loss value	Loss day
P-B (RealCONs)	\$20,000.00 - \$18,833.33 = \$1,166.67	20-18=2 days
P-A (Existing)	\$20,000.00 - \$15,600.00 = \$4,400.00	25-18=7 days

This 5-day acceleration in Project B reflects superior schedule adherence, while Project A's delay incurred cumulative losses.

- SG2) Project Performance Monitoring:** The performance analysis reveals stark contrasts between RealCONs and the Existing system. While projects B and A faced delays (SPI<1), Project B (RealCONs) showed improving trends: its CPI rose from 0.96 to 1.11 (Days 14-26), and SPI increased from 0.94 to 0.97, achieving cost-efficiency by Day 22. In contrast, Project A's performance deteriorated sharply, with CPI falling to 0.86 and SPI collapsing to 0.72 by Day 26, indicating severe cost overruns and schedule slippage (Figures 16 and 17):

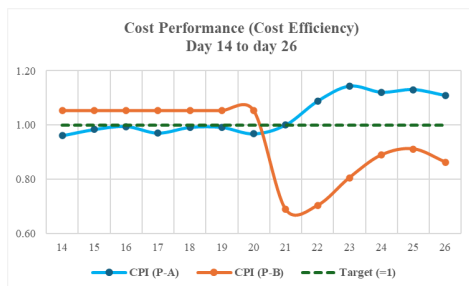


Figure 5.16: Cost Efficiency

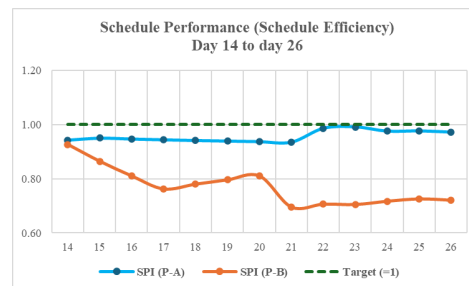


Figure 5.17: Schedule Efficiency

As a result, RealCONs demonstrated superior stability, particularly after Day 20, when the existing system began to show signs of failure. This section highlights how real-time early delay alerts enabled proactive recovery actions, helping reduce cost overruns (through CPI protection) and minimise schedule slippage (via SPI stabilisation) through timely interventions. Furthermore, from the Oracle P6 (planning and scheduling) perspective, the schedule variance observed between the day after the delay was reported (Day 14) and the end of the delay notice period (Day 26) indicates that RealCONs achieved a total cost-saving of \$6.98 million, as outlined below:

Project	SV _{Day 14} (Million)	SV _{Day 26} (Million)	Delta (Million)	Total Delta (Million)
P-B (via RealCONs)	\$888.89	\$808.04	-\$80.85 B	A-B = \$6,982.73
P-A (via Existing)	\$1,155.56	\$8,057.44	\$6,901.88 A	

Figure 5.18 illustrates the data flow sequence of Figure 6. It shows that regarding the reported delay (in this case, on day 13), similar to Figure 5.15, other components (Oracl_Aconex and BIM) are updated relevantly. For example, suppose a delay on Day 13 reported clash detection or material issue. In that case, BIM and Oracl_Aconex should be involved in updating the 3D federate model and publishing as-built drawings through oracle_Aconex for subcontractors. Otherwise, if a delay occurs because of disruption, only oracle_P6 and oracle_as should be updated.

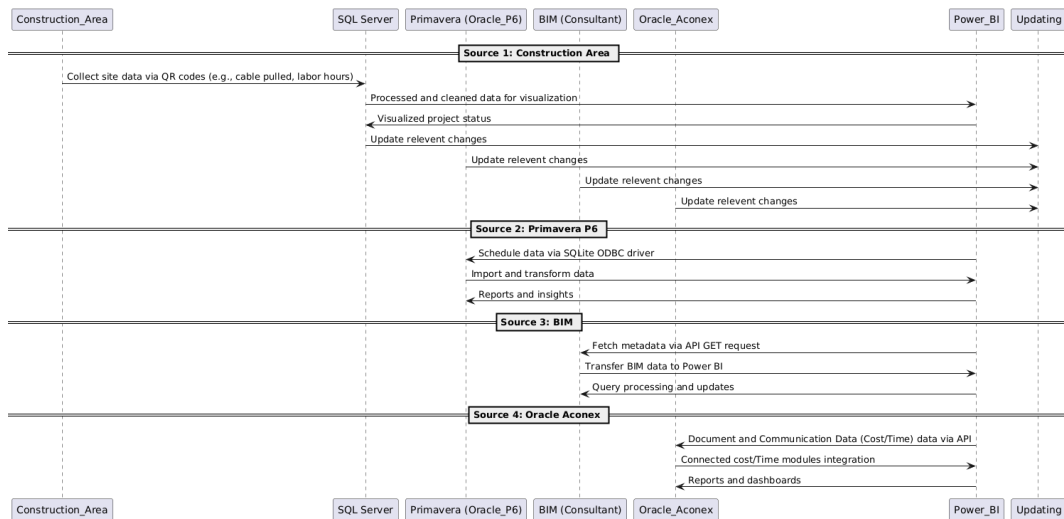


Figure 5.18: Data Flow Sequence of Figure 5.6

To conclude this section, Figures 5.19-5.24 present key digital and analytical reports generated by Power BI to support the research discussion. Figure 5.19 (the main dashboard) is an early warning system for SPI and CPI changes, triggering delay identification. Figure 5.20 enables project managers to review Earned Value trends by adjusting dates and building scopes. Figure 5.21 visualises activity breakdowns, combining cost data, actual vs. planned percentages, and cost variance for an at-a-glance project overview. Figures A4 and A5 provide dedicated views of project delays and cost trends, improving forecasting accuracy. Finally, Figure 5.24 displays a building sketch as a graphical progress report.

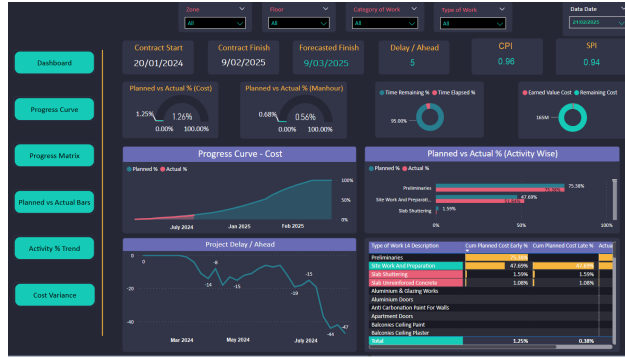


Figure 5.19: Project Main Dashboard (Digital Report)



Figure 5.20: Earned value tracking

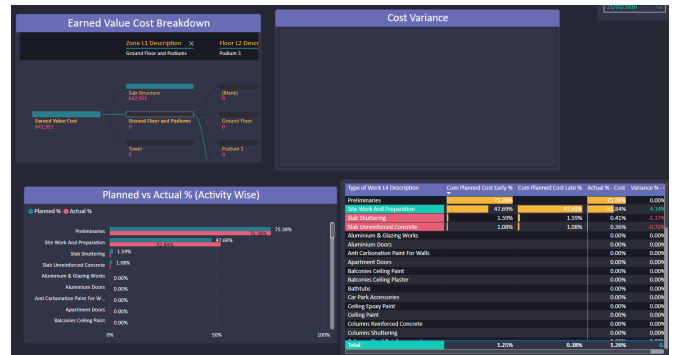


Figure 5.21: Breakdown Analysis

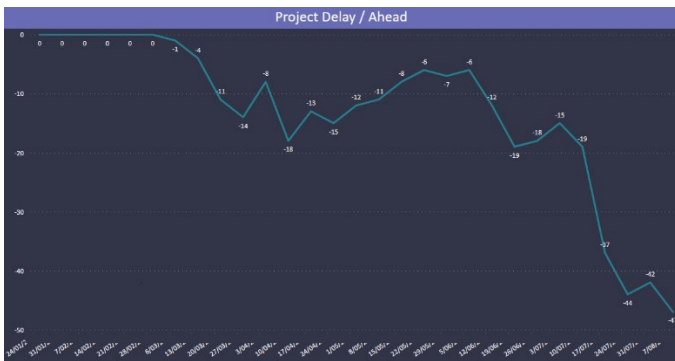


Figure 5.22: Delay trend

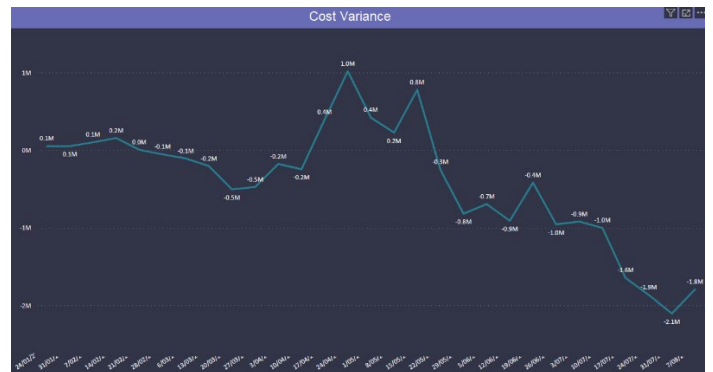


Figure 5.23: Cost variance trend



Figure 5.24: Building sketch monitoring

Compared with existing digital tools/frameworks and the proposed framework, the RealCONs framework demonstrates clear advantages by enabling real-time monitoring and analysis of project status. RealCONs facilitates faster delay detection and impact analysis to make project managers make informed decisions, directly addressing fragmented communication and late delay(s) identification. These features are particularly valuable in major construction projects. While various digital tools such as Last Planner System (LPS) (C. Liu et al., 2024), 4D/5D Building Information Modelling (BIM) (Likita et al., 2024; Sun, Sun, Zhang, & Li, 2024), Digital Twin technologies (Liu, Feng, Lu, & Zhou, 2024; Xu, Feng, Jelodar, & Guo, 2024), and the project management methods like Critical Path Method (CPM) (Mostofi, Tokdemir, & Toğan, 2024; Petroutsatou, 2022), have contributed to improved planning, coordination and visualisation, they often operate in isolation or lack responsiveness to real-time changes. In contrast, RealCONs enhances project accuracy and preparation efficiency by reducing manual errors and improving early-stage reporting performance. Table 5.9 compares RealCONs with other digital tools, focusing on core project management attributes.

Table 5.9: RealCONs Vs Existing Digital Tools/Frameworks

Digital Tool/Framework	Real-Time Monitoring	Early Delay Detection	Life-cycle Integration	Cost-Schedule Linkage	Adaptability	Limitations
RealCONs	✓ High	✓ Proactive	✓ Full life cycle	✓ Direct, automated	✓ High	Requires connection authentications, site internet coverage
LPS	✗ Manual	✗ Reactive	✗ Execution-focused	✗ Weak	✓ Moderate	Relies on team discipline and facilitator input
4D/5D BIM	✓ Visual	✗ Limited	✓ Design–Execution	✓ Static, visual	✓ Moderate	Requires regular manual updating
Digital Twin	✓ Dynamic	✓ Conditional	✓ Strong	✓ High fidelity	✗ Low	High setup cost and technical complexity
CPM	✗ Static	✗ post-facto	✗ Planning-only	✗ Indirect	✗ Low	Inflexible, lacks adaptability to changing site conditions

Table 5.9 shows RealCONs utilises real-time data collection through QR code scanning on mobile devices, enabling automated deviation tracking and early warning alerts for potential delays. This functionality reduces subjectivity in performance evaluation and facilitates timely corrective actions, such as task resequencing or resource reallocation. The system also enhances reporting accuracy by decreasing preparation time and minimising human error during data capture and analysis. Importantly, it remains user-friendly and accessible to end users, including site supervisors. While integration may require adjustments to accommodate different

contractual frameworks and regional practices, RealCONs consolidates predictive analytics, financial control, and delay management into a single platform. In doing so, it serves as a strategic enabler for more resilient, efficient, and data-driven construction project delivery.

5.11 CONCLUSION AND FUTURE RESEARCH



This research validates the RealCONs digital framework as an effective solution to six major limitations in more common construction tracking systems: high costs, inefficiency, poor communication, fragmented data handling, integration challenges, and inaccurate reporting. By aligning RealCONs with the Rational Unified Process (RUP) methodology, the system's development and deployment followed a structured, iterative approach, enhancing transparency and performance across the project life-cycle:

1) the project scope, key stakeholders, and data collection needs were clearly defined in the Inception Phase. It led to the draft of an initial reporting framework tailored for Electrical and Instrumentation (E&I) works, which was chosen due to their dependency-sensitive sequencing and cross-trade implications. To ensure meaningful comparison, both case study projects (A and B) had reached at least 85% structural completion, focusing analysis on internal trades with active dependencies rather than structural variability; 2) During the Elaboration Phase, RealCONs system architecture was established, and data workflows were modelled, enabling real-time validation and delay detection rules; 3) This phase created the foundation for automation and synchronisation features later deployed. The Construction Phase involved operational deployment. Supervisors and project administrators collected real-time data, entered it via mobile interfaces, analysed it by project analysts, and translated it into structured reports. This end-to-end process significantly reduced data errors, accelerated report generation, and improved daily insights; 4) In the Transition Phase, finalised reports were delivered to

stakeholders, driving more informed decisions. RealCONs reduced report preparation time from 135 to 50 minutes, increased reporting output by 32.31%, and improved report accuracy from 72.2% (Project A) to 95.6% (Project B). Data slippage was reduced from 27.78% to just 4.44%.

The framework also strengthened project control. Project B, supported by RealCONs, recovered from initial delays with a Cost Performance Index (CPI) improvement from 0.96 to 1.11 and Schedule Performance Index (SPI) stabilisation at 0.97 by Day 26. In contrast, the control project (A) declined to a CPI of 0.86 and SPI of 0.72. By enabling early delay alerts (as seen in UML Step: "Enter Data" to "Clean & Analyse" to "Generate Reports"), RealCONs helped avert a projected \$6.98 million deviation, proving the value of the proactive intervention. Despite its success, RealCONs faces limitations for wider adoption: connectivity issues in remote areas, QR code resilience, RFID-related privacy concerns, and data source authentication. However, it also bridges the longstanding gap between planned schedules and site realities, fostering a culture of real-time responsiveness. Beyond technical improvements, RealCONs fosters a proactive and transparent project culture by bridging the gap between theoretical planning and on-site realities. Future research should focus on integrating AI and big data warehousing to enhance RealCONs' scalability and intelligence further. Priorities include improving digital connectivity, developing resilient tracking tools, and establishing robust data governance practices to manage privacy, data reliability, and regulatory compliance on construction sites.

STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.			
Student name:	Kambiz Rdaman		
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In which chapter is the manuscript/published work?	Chapter 6		
Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work: ¹ Ratio of student to supervisory team 90:10, Student: Brought and Structured idea, Captured data, created model, Analysed, Drafted and Finilised Text Supervisory team: Conducted Study, Improved conceptual model, Reviewed and Finilised Text			
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Chapter 6: PRODUCTIVITY TRACKING IN CONSTRUCTION PROJECTS

The current chapter is based on the following article:

Radman, K., Jelodar, M. B., Lovreglio, R., Wilkinson, S., & Ghazizadeh, E. (2022). Real-time project productivity tracking system: Practical case in smart construction projects. In 7TH New Zealand built environment research symposium (p. 409)



Manuscript status: Conference Paper – Accepted/Presented

Objective should be covered:

OBJ_5: Evaluate the Proposed Framework

6.1 SUMMARY

The productivity and progress tracking systems currently employed in construction projects aim to acquire site data and convert it into various digital reports. However, existing methods for capturing and transferring data are often slow and inefficient, frequently leading to human error. This can result in the omission of critical information, preventing project managers from making timely decisions regarding delays and unproductivity. This paper proposes a real-time productivity tracking system to register data and manage delays for Electrical and Instrumentation services in smart construction projects in New Zealand. The research involved reviewing industry delay reports, leveraging expert judgement, and comparing the proposed method with existing practices. Preliminary findings indicate that integrating smartphone

technology with MS Project real-time monitoring software optimises site reporting procedures and productivity management workflows. The proposed method significantly enhances time and cost-effectiveness in decision-making, with data collection and program update hours reduced by 24%. This advancement is expected to support construction decision-makers in managing delays and improving project outcomes effectively.

6.2 INTRODUCTION

The project life cycle encompasses five distinct phases: initiation, planning, execution, monitoring, and closure, which collectively transform a project charter into a functional product (Aronés, Mendoza, Rodriguez, & Ramirez, 2019). Among these, the monitoring phase is crucial, requiring effective coordination of resources, materials, equipment, time, and costs across design, procurement, logistics, and installation activities. Traditional progress tracking methods, which rely on manual data collection through meetings and subsequent digital formatting into spreadsheets, are time-intensive and prone to inaccuracies. This often results in delays, rework, and reduced productivity, leaving project decision-makers with untimely and unreliable information that can hinder effective decision-making (Alizadehsalehi & Yitmen, 2021).

Recent advancements have introduced innovative solutions to address these inefficiencies. Techniques such as Building Information Modelling (BIM), video-grammetry, laser scanning, and photogrammetry, as well as hybrid approaches like RFID integrated with photogrammetry or laser scanning, have demonstrated significant improvements. These methods reduce data acquisition time by up to 50%, enhance accuracy across project phases, and support a more structured approach to decision-making (Radman, Babaeian Jelodar, Ghazizadeh, & Wilkinson, 2021; You & Wu, 2019). Furthermore, emerging technologies have been leveraged to optimise construction progress monitoring. Examples include high-definition video cameras for analysing

crew productivity and workplace safety, low-precision 3D scanning integrated into worker equipment for real-time site capture, and short-range photogrammetry for detecting schedule discrepancies through BIM comparisons (Salehi & Yitmen, 2018). Tools such as Autodesk BIM 360 Field allow daily progress reporting via mobile devices, centralising information for seamless communication between site and office teams. Collaborative systems incorporating smart sensors and telepresence technologies have also demonstrated potential for improving data collection, labour inspections, and decision-making efficiency (Khoshnava et al., 2020; Xu, Chong, & Liao, 2019).

While previous research highlights the transformative role of technology in construction project management, further investigation is needed to establish a comprehensive work procedure that reduces time and effort in data collection, report preparation, and information exchange. This study aims to address these challenges by exploring technological tools that enhance efficiency and enable project managers to focus on critical activities requiring greater attention (You & Feng, 2020; You & Wu, 2019).

6.3 RESEARCH AIM AND OBJECTIVES

This study aims to present a method for construction project decision-makers who will decide timely. Meanwhile, hours booked to collect data and update programmes and models dropped by 24%.

6.4 RESEARCH METHODOLOGY

The core objective of this research is to validate the proposed RealCONs framework for data collection, integration, analysis, and visualisation in managing delays and productivity in Electrical and Instrumentation services. The study adopts a mixed-methods research design,

combining qualitative and quantitative approaches to ensure both practical depth and analytical rigour.

6.4.1 Case Selection:

Data were collected from large-scale construction projects in New Zealand categorised as “major” (value exceeding NZD \$500 million) and “smart” (involving the integration of at least one IoT-based technology). These projects were selected because they represent complex environments where productivity tracking and delay management are particularly challenging. The Electrical and Instrumentation service trade was prioritised due to its critical role in project sequencing and its high dependency on coordination across multiple trades.

6.4.2 Data Collection:

The methodology was structured in three stages. First, documentary analysis of industry delay reports and project records was undertaken to identify recurring causes of delay and inefficiencies in progress reporting. Second, expert judgement was sought through structured interviews and workshops with project managers, planners, and site engineers to validate observed issues and refine the proposed workflow. Third, empirical data were captured directly from case study sites using smart thin devices (e.g., SiteDoc, WhatsApp, MS Teams) and integrated with MS Project real-time monitoring software. This enabled direct comparison between current manual processes and the proposed digital workflow.

6.4.3 Process Mapping and Workflow Evaluation:

A before-and-after data flow diagram (DFD) was developed (Table 9.1) to illustrate the current and proposed reporting procedures. The analytical framework assessed data acquisition speed, accuracy, and integration across workflow stages, with particular focus on the time consumed to collect, classify, and transfer progress data to planners and project managers. The proposed framework eliminated redundant steps, enabling planners to generate analytical reports

automatically and project managers to make earlier and better-informed decisions.

6.4.4 Data Analysis:

A comparative time–motion study was conducted to measure the efficiency of the current versus proposed methods. Quantitative analysis focused on average hours spent per reporting cycle, while qualitative feedback from practitioners was used to assess usability, reliability, and stakeholder acceptance. The evaluation matrix (Figure 6.1) provided a structured mechanism to measure improvements in accuracy, timeliness, and decision-making effectiveness.

6.4.5 Validation:

Triangulation was applied to strengthen validity by cross-verifying findings from documentary analysis, expert judgement, and field data. Comparative metrics (e.g., average hours saved, reporting frequency, decision-making speed) were benchmarked against international studies on digital construction management tools. Pilot implementation across selected projects allowed the proposed method to be tested iteratively, with refinements based on practitioner feedback. It is acknowledged that the case study scope—limited to Electrical and Instrumentation services in major New Zealand smart projects—may restrict the generalisability of findings. Furthermore, while the study quantifies time efficiency, broader impacts such as cost savings, labour productivity, and risk mitigation will require longitudinal evaluation in future research.

Table 6.1: Before and after DFD

Step	Before (current)			After (Proposed)	
1	Engineering team →	Create Drawings	⇨ Current By App ⇨	Engineering team →	Create Drawings
2	Supervisors →	Review Drawing for changes		Supervisors →	Review Drawing for changes
3	Site team →	Implementing drawings		Site team →	Implementing drawings
4	Planner →	Collecting progress % for each phase and tasks		Planner →	Collecting progress % with any changes and real-time critical issues
5	Planner →	Classify %		Planner →	Create the classified and analytical reports
6	Planner →	Create an analytical report		Project manager →	Make decision
7	Project manager →	Make decision		N/A	

6.5 PRELIMINARY FINDINGS

The finding shows the proposed method uses a combination of smart thin devices and Ms Project real-time monitoring software to optimise the current site reporting procedure and workflow of productivity managing. To achieve this goal, the current study has structured a simple process (Figure 1): a) identify the current process of data collection into case studies; b) classify the type of data and their importance; c) find gaps and re-structure the current one; d) create an evaluation matrix to measure accuracy and accurate timing of data acquisition tools used in this research.

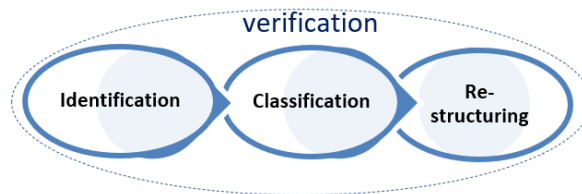


Figure 6.1: The proposed method process

6.6 RESEARCH SIGNIFICANCE

The proposed method demonstrates a substantial potential to enhance time and cost efficiency while improving delay management and facilitating more effective decision-making processes in construction projects. A detailed comparison of the time required for data collection and strategic report preparation under the current and proposed methods highlights these advantages (Table 2).

6.6.1 Time Efficiency and Cost-Effectiveness

The average time spent on data collection and report preparation under the current method is 5.5 hours per task, compared to 4.2 hours with the proposed method—representing a time

savings of 24% (Table 2). This reduction is particularly evident in two stages:

- **Data Collection:** Time reduced from 3.1 to 2.4 hours, reflecting a more efficient approach to acquiring real-time field information.
- **Report Preparation:** Time reduced from 2.4 to 1.8 hours, emphasising the method's capability to streamline the consolidation and analysis of data for decision-making.

Table 6.2: Average of Time Comparison between Current and proposed methods

Stage	Current method	Proposed method
Data collection	3.1	2.4
Preparing Strategic reports	2.4	1.8
Total (h)	5.5	4.2 (24% saved)

The improvements are attributed to the method's reliance on technological tools that enable automated data collection and standardised report templates, reducing manual intervention and associated inefficiencies.

6.6.2 Impact on Decision-Making

The method's time efficiency extends beyond operational savings. By reducing delays in data collection and analysis, project decision-makers can access critical insights more promptly, allowing for timely interventions and minimising the risk of prolonged delays. The quicker turnaround also promotes better communication and coordination among stakeholders, fostering a collaborative approach to issue resolution.

6.6.3 Strategic Advantages

The reduced time requirements directly influence project timelines and budgets. The cost

savings associated with decreased hours allocated to data management can be redirected towards other resource-intensive activities. Additionally, the more frequent and accurate updates provide stakeholders with enhanced visibility into project progress, improving overall project governance and risk management.

6.6.4 Visual Comparison of Time Allocation

Figure 2 illustrates the comparative analysis of time allocation between the current and proposed methods. It demonstrates the distinct reduction in hours across both stages, reinforcing the method’s operational and strategic benefits. In conclusion, the proposed method offers a robust framework for optimising time and cost management in construction projects. By improving data accuracy and enabling more effective decision-making, it addresses key challenges faced by construction professionals and contributes to the broader goal of efficient project delivery.

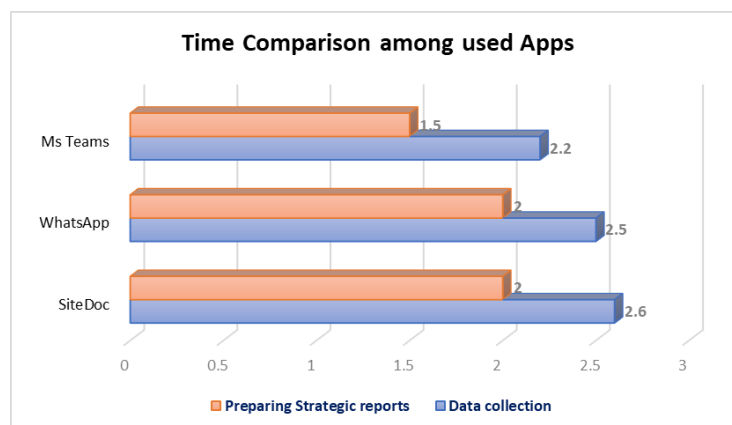


Figure 6.2: Time Comparison among used Apps

6.7 ANALYTICAL DISCUSSION

The findings of this study highlight significant advancements in productivity and delay

management for Electrical and Instrumentation services in smart construction projects. The proposed real-time tracking system effectively addresses the inefficiencies inherent in traditional methods, offering a comprehensive solution that integrates technology and streamlined processes.

6.7.1 Efficiency in Data Collection and Reporting

The comparative analysis of current and proposed methods (Table 2) demonstrates that the implementation of smart devices and MS Project real-time monitoring software reduces total time spent on data collection and strategic report preparation by 24%. This improvement is achieved by replacing manual, error-prone processes with automated systems that enable real-time updates and seamless data transfer. A closer look at the time allocation reveals significant improvements in both data collection and report preparation stages:

- **Data Collection:** The reduction from 3.1 to 2.4 hours underscores the effectiveness of integrating digital tools like SiteDoc, WhatsApp, and MS Teams for real-time data acquisition. These tools streamline communication and eliminate redundant steps in progress reporting.
- **Report Preparation:** The reduction from 2.4 to 1.8 hours demonstrates the value of automated report templates and real-time monitoring software in simplifying analytical workflows and reducing manual effort.

6.7.2 Enhanced Decision-Making

The proposed method improves decision-making efficiency by providing project managers

with accurate, real-time data. This capability reduces the lag between data collection and actionable insights, enabling timely interventions to mitigate delays and unproductivity. The revised process (Table 9.1) demonstrates a notable shift, where the planner's role transitions from extensive data compilation to real-time classification and analysis. As a result, project managers are equipped to make informed decisions earlier in the project timeline, minimising risks and enhancing productivity.

6.7.3 Strategic and Financial Implications

The streamlined processes directly impact project budgets and timelines. The reduction in hours allocated to administrative tasks translates into cost savings, which can be reallocated to critical project activities. Additionally, the enhanced visibility and accuracy of progress tracking improve project governance, reduce rework, and ensure better alignment with project objectives.

6.7.4 Technological Integration and Future Potential

The integration of IoT-based technologies and collaborative tools into the proposed system aligns with industry trends emphasising digital transformation. The method sets a foundation for further advancements, including the incorporation of AI-driven predictive analytics and blockchain for enhanced transparency.



6.8 CONCLUSION

This study presents a practical and efficient approach to managing delays and improving productivity in construction projects, particularly for Electrical and Instrumentation services. By

addressing the limitations of traditional methods, the proposed real-time productivity tracking system enhances time and cost efficiency, supports timely decision-making, and aligns with the dynamic requirements of smart construction projects. The findings highlight a 24% reduction in hours spent on data collection and reporting tasks, demonstrating the effectiveness of integrating smart devices and MS Project monitoring tools. This improvement not only streamlines workflows but also fosters better communication and coordination among stakeholders, enabling a collaborative approach to addressing delays and unproductivity. Furthermore, the proposed method emphasises the critical role of technology in modern construction management. By leveraging IoT-enabled tools and real-time monitoring software, it provides a scalable and adaptable framework for improving project outcomes. The results underscore the importance of adopting innovative solutions to overcome the challenges of traditional methods, paving the way for a more efficient and responsive construction industry. This study contributes to ongoing efforts to advance construction project management practices and serves as a benchmark for future research into technology-driven methodologies. The proposed framework holds the potential to transform decision-making processes, reduce project risks, and optimise resource allocation in large-scale construction projects.

STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

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Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work: ¹ Ratio of student to supervisory team 90:10, Student: Brought and Structured idea, Captured data, created model, Analysed, Drafted and Finilised Text Supervisory team: Conducted Study, Improved conceptual model, Reviewed and Finilised Text			
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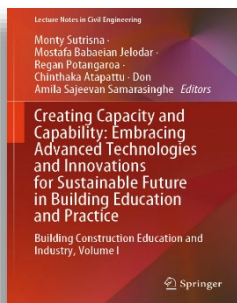
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Chapter 7: AUTOMATED CONSTRUCTION DELAY MANAGEMENT MECHANISM

The current chapter is based on the following article:

Radman K, Jelodar MB, Lovreglio R, Wilkinson S, Ghazizadeh E. (2023). Automated construction delay management mechanism (Earned Value) of Electrical and Instrument works with BIM and Microsoft tools. Proceedings, 46th Australian Universities Building Education Association Conference (AUBEA 2023), ISBN: 978-1-921047-51-0.
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Nature

Objective should be covered:

OBJ_5: Evaluate the Proposed Framework

7.1 SUMMARY

This research proposes an automated construction delay management solution for Electrical and Instrument construction works using BIM, Ms Project, and PowerBI. The proposed solution combines Earned Value Management with BIM to generate accurate project schedules and simulate construction sequences. Earned Value Management is used here to measure the project's performance and identify potential delays. PowerBI is used to analyse and visualise project data, allowing project managers to monitor project progress and take corrective actions in real-time.

The proposed solution was tested on a large-scale construction project case study. The results show that it can significantly improve the accuracy of project schedules, reduce/mitigate delays, and enhance the overall project management process. The study contributes to the construction industry by proposing an automated mechanism to improve construction delay management, optimise resource allocation, and enhance project communication. The proposed solution can also serve as a framework for future research to develop more advanced and comprehensive solutions to manage construction delays in various projects. This chapter is covered by a published “**Automated construction delay management mechanism (Earned Value) of Electrical and Instrument works with BIM and Microsoft tools**” article in Proceedings of 46th Australian Universities Building Education Association Conference (AUBEA 2023).

7.2 INTRODUCTION

The construction industry holds a significant position within various economies and is a critical asset for public or private investors. Regardless of the size of projects, construction projects are distinct due to their inherent risks and hazards, setting them apart from other industries. One notable challenge faced by significant-size projects is the inability to complete them within the designated time frame and allocated budget. Several factors contribute to this, with the primary issues being inadequate project planning and a lack of technical tracking from a time and cost perspective. Consequently, projects mostly face massive deviations from schedule and budget (Khosakitchalert et al., 2019). Because significant investments are required to start and finish a major (primarily commercial) project, Effective and accurate cost management must be applied to construction projects. Cost management incorporates the procedures associated with estimating, creating budgets, and exercising control over costs (Edition, 2018). The activity cost estimates derived from the estimation process are utilised in

the budgeting phase. During project execution, cost control measures are implemented to ensure the project is completed within the targeted budget. Various techniques, including Earned Value Management (EVM) and Variance Analysis, can achieve this objective (Edition, 2018). The primary approach for measuring project performance is earned value, which integrates scope, schedule, and cost within a system which evaluates project performance in financial terms (cash in / out). Utilising the Earned Value technique at any phase of project execution enables the evaluation of budget and schedule status, facilitating effective control over cost and schedule to achieve project objectives. Konior and Szóstak (2020) and Khamidi et al. (2011) have provided evidence that the EVM system allows the project team to assess project status and forecast future performance trends thoroughly. Similarly, some studies proposed modifying the Earned Value technique, which integrates Monte Carlo simulation and fuzzy logic theory (Zawistowski, 2010). This enhanced approach enables more sophisticated risk analysis pertaining to time and cost within intricate project scenarios (Rosłon et al., 2020). The EVM System assumes a critical role in project monitoring by establishing a correlation between the actual completion Vs planned work regarding the elapsed time and spent costs. It enables a comprehensive assessment of the project's progress concerning its scheduled timeframe and financial plan (Smugala and Kubečková, 2022, Radman et al., 2021, Radman et al., 2022b, Radman et al., 2022a).

A Building Information Model (BIM) encompasses a project's physical and functional parameters. It integrates the knowledge repository and centralities them and offers dependable information about the project at every stage of its life cycle. This information is a robust basis for making well-informed decisions (Fazeli et al., 2022, Tiwari et al., 2009). BIM can facilitate collaboration among diverse stakeholders throughout the distinct phases of a project's lifecycle. This collaboration empowers stakeholders to contribute, access, update, or modify BIM information and will reflect stakeholders' roles and responsibilities. Furthermore, BIM enables multinational teams to collaborate, resulting in team working by collectively creating designs

and engaging in collaborative problem-solving to complete the project as quickly as possible (Marzouk and Hisham, 2012, Boddupalli et al., 2019). The 3D BIM model can evolve into a 4D model by linking model elements with timeframes (e.g. schedules). Furthermore, a 5D model by combining cost estimation with the model components is an advanced way. The 5D functionality involves a model-based cost-estimating process that integrates object attributes of the designer's 3D model with cost information from the estimator's database (Tiwari et al., 2009, Kwon et al., 2023). From previous literature reviews, the utilisation of BIM in construction projects is recognised as a significant and, in certain instances, obligatory concept. Nevertheless, the complete implementation of integrated construction management approaches, such as BIM-based output estimation with EVM and process management, remains incomplete. Consequently, three primary obstacles in the successful adoption of BIM have been identified as outlined by He et al. (2022) and Kim et al. (2022): (i) Firstly, one of the significant challenges is the inefficiency and decentralisation of work resulting from the dual management of earned value (EV) and process information. This dual management approach hinders effective coordination and integration of project data; (ii) the existing construction management system necessitates recalculations of quantities to verify outputs against processes for EV charging, leading to inefficient management practices. This verification process adds complexity and can result in delays and errors, and (iii) there is a lack of linkage between information from the design phase and the work processes in the construction phase. This disconnect prevents seamless transfer of information and inhibits the effective utilisation of BIM data throughout the project lifecycle. Each of those obstacles, they are causing different construction delays, such as being behind schedule and over budget, which are common in construction projects, significantly impacting projects from significant financial losses and project completion. Managing construction delays is a challenging task that requires effective project management strategies and tools (Jelodar et al., 2014); if not well managed these delays can have significant detrimental

effects, lead to conflicts and also adverse working relationships (Jelodar and Yiu, 2012, Jelodar et al., 2013). BIM, project management software (e.g., Ms Project) and data analytics tools (e.g., Power BI) have been used to improve construction project management in recent years. This work presents an automated construction delay management solution for Electrical and Instrument (E&I) works using BIM, Ms Project, and Power BI. The proposed solution combines EVM with BIM to generate accurate project schedules and simulate construction sequences. Power BI is used to analyse and visualise project data, allowing project managers to monitor project progress and take corrective actions in real time.

EVM is a crucial tool for delivering value for stakeholders in construction projects. It is an effective tool for enhancing value and measuring project success and failure. However, the limited availability of a suitable performance measurement model for EVM studies hinders its widespread adoption in the construction industry. Contrastingly, although projects have utilised professional tools and techniques such as Primavera (P6), Microsoft Project (MSP), PertMaster, Procore, or Aconex to monitor and analyse project status in terms of cost and time, certain factors such as project complexity lack of analytical skills, lack of keeping historical data and the diverse of project elements pose additional challenges to the effective implementation of EVM. Hence, the critical concern of this research project is to develop a practical and continuous performance measurement approach for EVM, enabling prompt improvements in the EVM process. This study aims to assess project delays and reporting utilisation in construction projects, incorporating research from diverse sources to highlight challenges in various project phases. Specifically, the objectives are to explore the benefits of integrating Building Information Modeling (BIM) and Microsoft Project for timely delay notifications and to investigate Power BI's role in providing valuable insights for informed decision-making based on collected data while employing Earned Value Management (EVM) analysis for practical delay assessment.

7.3 BACKGROUND

Earned value management (EVM), or earned value performance management (EVPM), is an effective control mechanism for managing project scope, cost, and time. However, it serves as a tool for overseeing project progress and ensuring adherence to planned objectives regarding scope, cost, and schedule (Anbari, 2003). The work breakdown structure (WBS) is commonly employed in process management and serves as a physical classification system that organises items based on facilities, spaces, and parts. On the other hand, the cost breakdown structure (CBS) utilised in earned value management (EVM) is a conceptual classification system that categorises items according to work types. While the terminologies and interpretations may differ between EVM and process management, it is essential to note that the quantity indicated by work type in the EVM statement represents an aggregation of quantities based on position and work type and should not be considered as a singular piece of information (Gebremichael et al., 2022). Through Project Management Institute, Earned Value Management (EVM) is a technique developed to offer dependable assessments of project performance and enable managers to conclude the ultimate effects of the project (PMI, 2018). This definition and existing literature reviews encompass the integration of scope, schedule, budget, and the utilisation of available resources; therefore, there has been a notable rise in the utilisation of EVM in various projects, mainly in construction industries (Vertenten et al., 2009, Ahmad et al., 2011, Fatemeh, 2013, Mohammed et al., 2021).

A web-based EVPM system was introduced by Chou et al. (2010) to enable project managers to effectively track and analyse project status from the schedule and cost perspective by integrating project management software and 3D modelling. In a related context, Pajares and Lopez-Paredes (2011) proposed novel indicators to integrate earned value management and project risk management to control and monitor construction projects. They aimed to enhance

project performance by considering both cost and risk factors. Furthermore, some researchers introduced an innovative approach to separate the cost and schedule factors once using EVM (Batselier and Vanhoucke, 2015, Khamooshi and Golafshani, 2014). However, a Monte Carlo simulation and statistical techniques have been used to manage projects in uncertain environments. Their method involved incorporating acquired duration while ensuring the three primary project management elements, scope, cost, and time, interact effectively (Acebes et al., 2015, Acebes et al., 2022). A concept of BIM-based EVM and process management has been developed, wherein the definition of the 3D object unit is established, incorporating time and location aspects. It is further complemented by connecting the Cost Breakdown Structure (CBS) information, which comprises quantity and price based on work type (Kim et al., 2022, Ayman et al., 2022). Direct Digital Construction (DDC) was introduced as a technology-driven process to improve construction efficiency by leveraging design reuse and optimising human perception factors (Zheng et al., 2020). EVM is required three critical parameters to measure project success and failure: Planned Value (PV), Earned Value (EV) and Actual Cost (AC), but other parameters are illustrated in Table 7.1 (PMI, 2018):

Table 7.1: Earned Value Parameters

Parameters	Formula	Warning Indexes
Schedule Variance (SV): Deviation between the actual time and the planned to complete the project	$SV = EV - PV$	If $SV < 0$ means $PV > EV$
Cost Variance (CV): Deviation between actual cost and the planned cost	$CV = EV - AC$	If $CV < 0$ means $AC > PV$
Cost Performance Index (CPI): Actual cost of completing the project based on the performance to date	$CPI = EV / AC$	CPI =1: on budget CPI >1: Under budget CPI <1: Over budget
Schedule Performance Index (SPI): Estimated the projected time to complete the project	$SPI = EV / PV$	SPI =1: on schedule SPI >1: ahead of schedule SPI <1: Behind schedule
Estimate At Completion (EAC): PV of whole project/CPI	$EAC = PV / CPI$	-
Estimated time To Complete (ETC)	$ETC = \text{Original time} / SPI$	-
Planned Value (PV) is Budgeted Cost of Work Scheduled (BCWS) Actual Cost (AC) is Actual Cost of Work Performed (ACWP) Earned Value (EV) is Budgeted Cost of Work Performed (BCWP)		

In the context of Earned Value parameters, "interaction" refers to how different elements or components of the Earned Value management system relate to and affect each other. It represents the interplay or mutual influence between these parameters, such as Planned Value (PV), Actual Cost (AC), and Earned Value (EV), and how changes in one parameter can impact the others. Understanding the interactions between these parameters is essential for effective project monitoring, analysis, and decision-making. So, Figure 7.1 illustrates the graphical interactions of the Earned Value parameters:

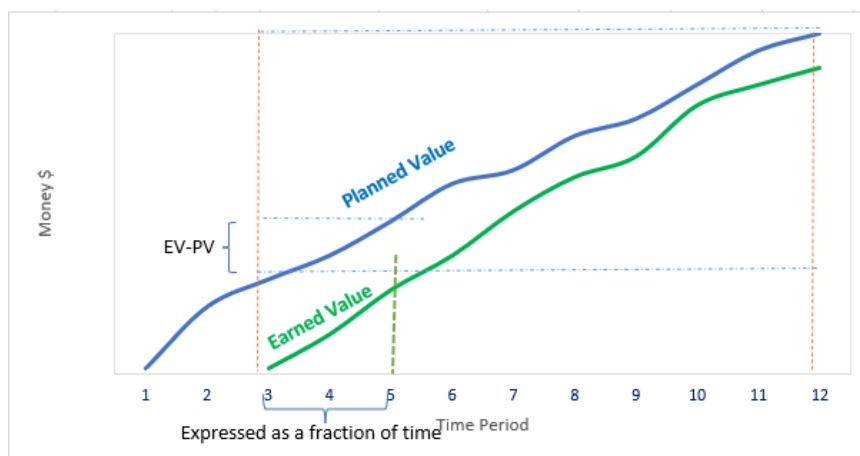


Figure 7.1: Earned Value parameters interaction

7.4 RESEARCH METHODOLOGY

The core objective of this research is to validate the proposed RealCONs framework for data collection, integration, analysis, and visualisation. So, the current study aims to identify delays at the early stage and analysis delays impacts on the major construction projects by using BIM and Ms Project (MSP). Therefore, achieved by leveraging the capabilities of Navisworks/Revit software to incorporate 4D scheduling into the BIM model and synchronise it with the project schedule (Timeline) imported from MS Project or Primavera (P6). For integrating MSP/P6 and Revit, the project schedule is linked to the main activities in the Navisworks/ Revit program, enabling the automation of various processes based on the BIM model. In this case, information

exchange is conducted from MSP/P6 to Navisworks/ Revit by extracting a comprehensive list of all elements and their properties from the Navisworks/ Revit model into a table format. Conversely, all elements' performance information regarding cost and time is collected from MSP/P6 and transferred to Navisworks/ Revit. However, the project analysts can prepare an Excel template for tasks aligned with MSP/P6 and create a relevant formula to calculate EVM data. Based on this input, the Power BI calculates EVM indicators and generates real-time graphs that reflect the performance of each project task through a realistic representation of cost and time aspects. Finally, the research objectives have been accomplished by employing the research methodology illustrated in Figure (7.2):

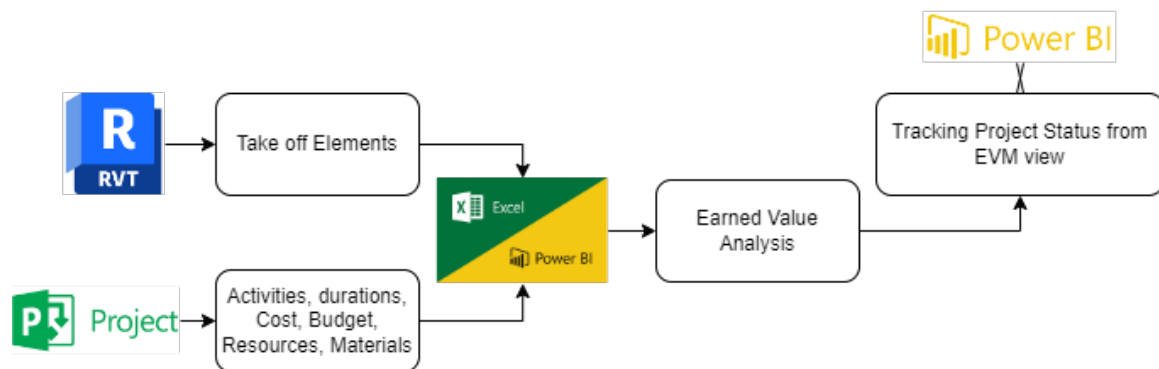


Figure 7.2: Research Methodology

7.5 PROJECT ANALYSIS

7.5.1 Case Study: Introduction

The Mental Health Project (MHP) is one of the significant high-security governmental projects in New Zealand that focuses on providing support and addressing the specific mental health needs of incarcerated individuals. Since its establishment, the project has strived to excel in the quality of services provided to all state ministries. MHP's goals and tasks are aimed at contributing to and supporting the medical economy, leveraging its distinguished position in the

healthcare sector in New Zealand. This project will provide additional care for individuals suffering from unexpected nerve attacks that are difficult to control. As a result, MHP becomes an essential project for the individual's well-being and overall social and community safety. MHP consists of two buildings, each with one story, connected through a covered walkway on a site spanning 1100 x 1100 m². The Electrical work for the project was initially projected to take 12 months, aiming for completion in early January 2024, and the contract value for the Electrical project is \$85 million. Figure 7.3 presents a schematic view of MHP, illustrating two buildings with a walkway in the middle, and Figure 7.4 depicts the 3D model of the Revit version of MHP.



Figure 7.3: Schematic view of MHP (2x buildings and 1x walkway in middle)

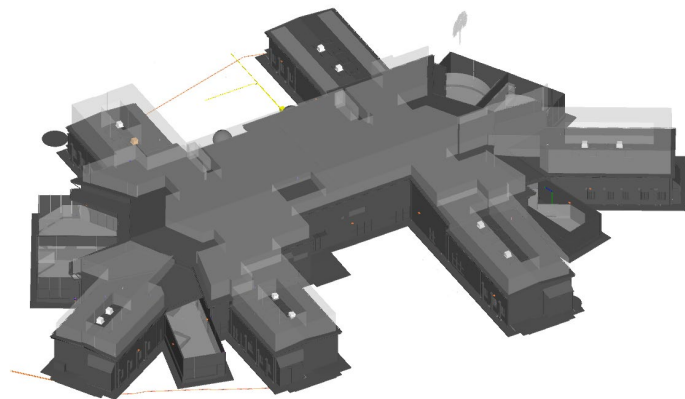


Figure 7.4: 3D view of MHP

More information regarding Electrical works in MHP can be detailed in Table 7.2 as follows:

Table 7.2: Total Planned QTY: Cabling, Containment and Fittings

Features \ Project	MHP
Value (million \$)	85
Cabling (meter)	14,000
Cable Tray(meter)	15,800
Light fitting (#-No)	150

7.5.2 Case study: problem statement

As detailed above, Earned Value techniques are not widely utilised to measure the project performance in our case study. MHP initially had limited use of project tracking tools from an EVM perspective. An EVM system was implemented to address this issue and overcome the current challenges to enable practical EV analysis on the Electrical works into MHP. The implementation of EVM is a valuable tool for identifying and tracking project progress, early delay notification and ensuring a clear understanding of the work accomplished relative to project budget Vs project costs. It allows project stakeholders (especially project managers) the assessment of the project's performance in the immediate future. For instance, a project manager can leverage the data derived from earned value management to make necessary adjustments and improvements to the project delays, aiming to optimise project efficiency and potentially influence the project's completion date (PC date).

7.5.3 Case study: EV analysis

Kerzner (2017) explained that the utilisation of Earned Value metrics can be employed to observe and evaluate the administration of an ongoing project, aiming to assess the effectiveness of project management practices. To analyse the Earned Value (EV) for the MHP (Project Name), the current study utilises the PV (Planned Value), EV, and AC (Actual Cost) data. Table

7.3 presents a comprehensive overview of EV metrics over 12 months for a total project value of 85 million NZ\$:

Table 7.3: Earned Value Metrics

Month	PV	AC	EV	CV	SV	CPI	SPI	EAC	ETC
1	\$7,083,333	\$6,500,000	\$6,200,000	-\$300,000	-\$883,333	0.95	0.88	\$88,971,041	\$82,471,041
2	\$14,166,667	\$13,500,000	\$12,900,000	-\$600,000	-\$1,266,667	0.96	0.91	\$88,776,836	\$75,276,836
3	\$21,250,000	\$20,000,000	\$18,800,000	-\$1,200,000	-\$2,450,000	0.94	0.89	\$90,425,532	\$70,425,532
4	\$28,333,333	\$27,500,000	\$26,000,000	-\$1,500,000	-\$2,333,333	0.95	0.92	\$89,947,090	\$62,447,090
5	\$35,416,667	\$36,000,000	\$29,500,000	-\$6,500,000	-\$5,916,667	0.82	0.83	\$103,578,259	\$67,578,259
6	\$42,500,000	\$40,000,000	\$32,700,000	-\$7,300,000	-\$9,800,000	0.82	0.77	\$103,844,280	\$63,844,280
7	\$49,583,333	\$51,500,000	\$43,200,000	-\$8,300,000	-\$6,383,333	0.84	0.87	\$101,553,319	\$50,053,319
8	\$56,666,667	\$58,000,000	\$50,100,000	-\$7,900,000	-\$6,566,667	0.86	0.88	\$98,322,103	\$40,322,103

9	\$63,750,000	\$66,500,000	\$53,400,000	-\$13,100,000	-\$10,350,000	0.8	0.84	\$105,927,280	\$39,427,280
10	\$75,833,333	\$69,000,000	\$63,700,000	-\$5,300,000	-\$12,133,333	0.92	0.84	\$92,138,385	\$23,138,385
11	\$77,916,667	\$75,000,000	\$69,900,000	-\$5,100,000	-\$7,016,667	0.93	0.9	\$83,600,858	\$14,600,858
12	\$85,000,000	\$80,500,000	\$73,300,000	-\$7,200,000	-\$11,700,000	0.91	0.86	\$93,207,915	\$12,207,915

For instance, in Month 1:

PV: \$7,083,333	AC: \$6,500,000	EV: \$6,200,000
CV: $\$6,200,000 - \$6,500,000 =$ -\$300,000		
SV: $\$6,200,000 - \$7,083,333 =$ -\$883,333		
CPI: $\$6,200,000 / \$6,500,000 =$ 0.954		
SPI: $\$6,200,000 / \$7,083,333 =$ 0.875		
EAC: $\$85,000,000 / 0.954 =$ \$88,971,041		
ETC: $\$88,971,041 - \$6,500,000 =$ \$82,471,041		

From PMI (2018), 1) Cost Variance (CV): CV measures the variance between the earned value and the actual cost. A positive CV indicates that the project is under budget, while a negative CV indicates that the project is over budget; 2) Schedule Variance (SV): SV measures the variance between the earned value and the planned value. A positive SV indicates that the project is ahead of schedule, while a negative SV indicates that the project is behind schedule; 3) Cost Performance Index (CPI): CPI is the ratio of earned value to actual cost. A CPI greater than 1 indicates efficient cost performance, while a CPI less than 1 indicates cost overruns 4) Schedule Performance Index (SPI): SPI is the ratio of earned value to planned value. An SPI greater than 1 indicates efficient schedule performance, while an SPI less than 1 indicates schedule delays.

To assess the "MHP" status, the current study primarily focuses on comparing the EV with the PV and AC for each month analysis, for instance, Months 1 and 2 (Figure 7.5):

Month 1	Analysis
PV: \$7,083,333 AC: \$6,500,000 EV: \$6,200,000	The project has earned less value (EV) than initially planned (PV). The actual cost (AC) is also slightly lower than the planned value. The cost variance (CV) is negative, indicating a slight cost overrun, while the schedule variance (SV) is also negative, suggesting a minor delay.
Month 2	Analysis
PV: \$14,166,667 AC: \$13,500,000 EV: \$12,900,000	The project has earned less value (EV) than the planned value (PV), indicating a potential delay in progress. The actual cost (AC) is slightly lower than the planned value. The cost variance (CV) is negative, suggesting a cost overrun, while the schedule variance (SV) indicates a delay (as a negative).

The same analysis can be done for the remaining months by comparing the PV, AC, and EV values and assessing the cost variance (CV) and schedule variance (SV). Based on this analysis, if the trend continues throughout the project duration, there are indications of potential cost overruns and schedule delays. Further monitoring and analysis of the EV metrics are necessary to accurately assess the overall project performance.

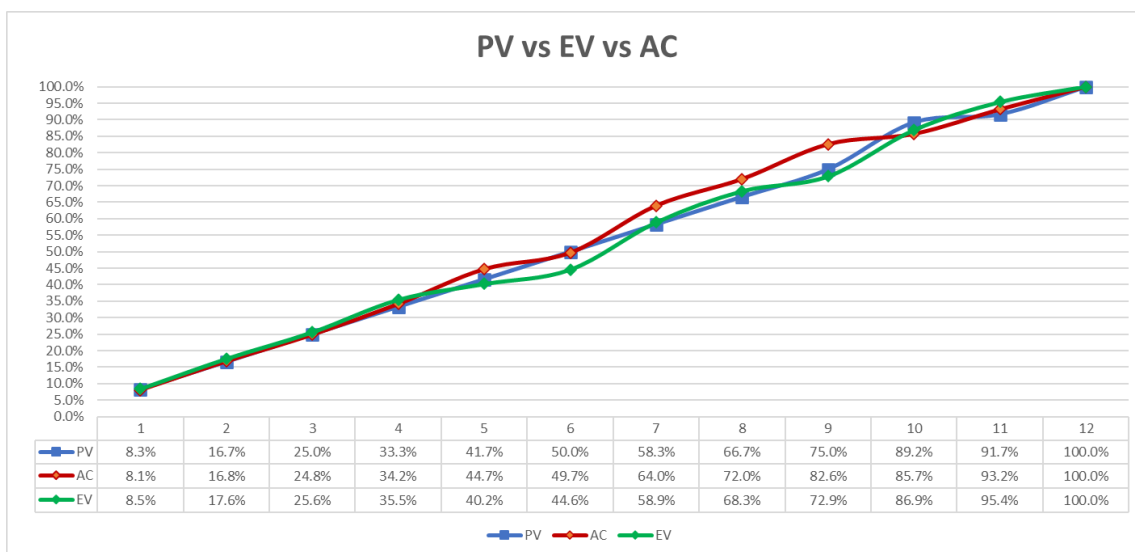


Figure 7.5: PV vs EV vs AC

Moreover, Cost Performance Index (CPI) and Schedule Performance Index (SPI) provide further insights into cost and schedule efficiency. So, through Figure 7.6, Cost Performance Index (CPI) shows that within months 1-12, the project consistently has CPI values below 1, indicating that the project is experiencing cost overruns, while Schedule Performance Index

(SPI) analysis that into months 1-12, the project consistently has SPI values below 1, indicating ongoing schedule delays.

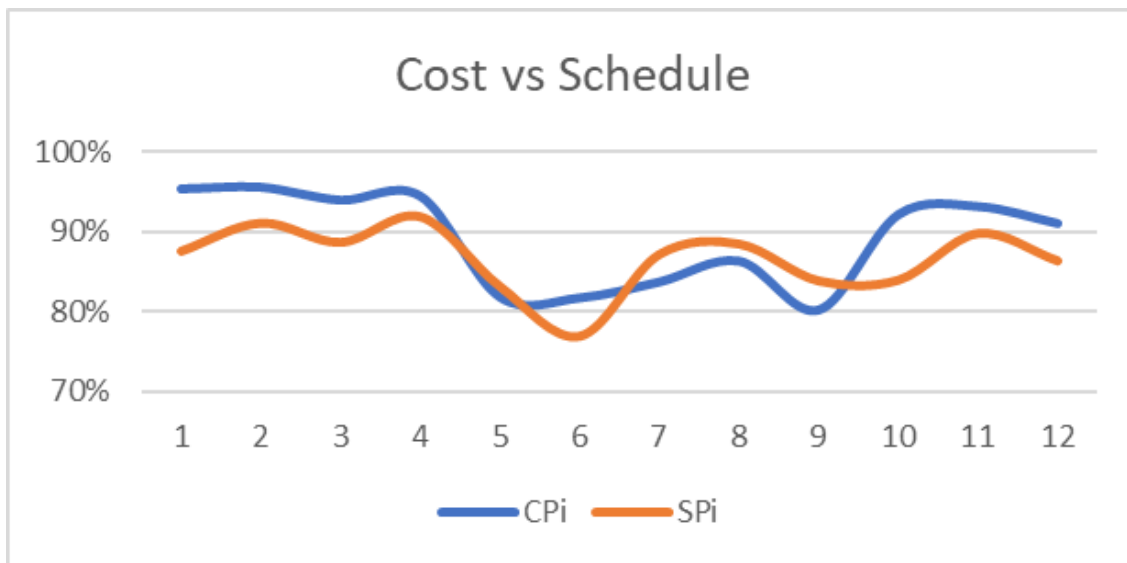


Figure 7.6: CPI vs SPI

However, Figure 7.7 illustrates a comparison between Cost Variance (CV) Analysis and Schedule Variance (SV) Analysis as 1) CV can be split into two:

- Months 1-6: The project consistently has negative CV values, indicating cost overruns during these months.
- Months 7-12: The project has negative CV values, indicating ongoing cost overruns.

While SV analysis shows that within months 1-12, the project consistently has negative SV values, indicating it is consistently behind schedule.

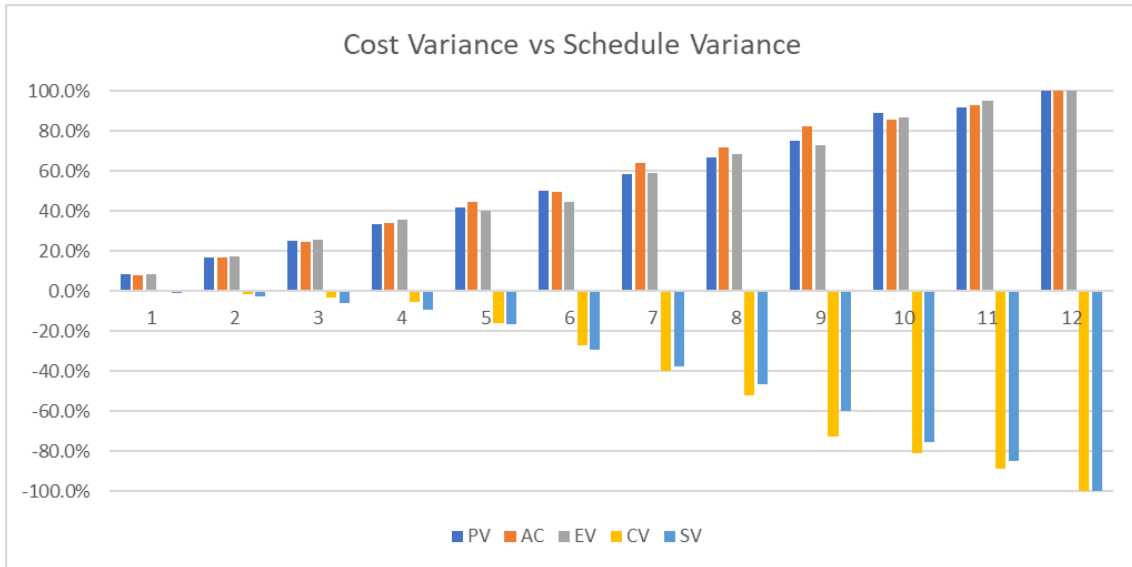


Figure 7.7: CV vs SV

To calculate the projected time required to complete the project, we can use the Schedule Performance Index (SPI) and the remaining Planned Value (PV) to estimate the number of months needed. The formula is as follows (just for two months as a sample):

	SPI = EV / PV	Projected Duration= Total Duration / SPI
Month 1	\$6,200,000 / \$7,083,333 = 0.875	12 / 0.875 = 13.71 months (approximately 14 months)
Month 2	\$12,900,000 / \$14,166,667 = 0.910	12 / 0.910 = 13.19 months (approximately 13 months)

Additionally, it is essential to consider that the projected duration is an estimate and subject to change based on the project's performance and any adjustments made. Finally, based on the above analysis, the project is experiencing cost overruns and schedule delays throughout its duration. It is important to note that the project is not meeting the planned budget and schedule targets. Adjustments and corrective actions may be required to address these issues and bring the project back on track. These monthly notifications can enable project managers and analysts to take timely action and understand the factors causing project delays. By utilising Earned Value (EV) techniques in the MHP (Project Name), project status and schedule forecasts (projected duration) can be tracked monthly. This monitoring allows for pro-active decision-making and facilitates the identification of potential issues, aiding in the timely resolution of delays and

ensuring project success.

7.6 CONCLUSION

This study has set out with clear aims to assess project delays and reporting utilisation in construction projects while incorporating research from diverse sources to figure out the challenges encountered throughout project phases. By determining the benefits of integrating BIM and MS Project, the current study has explained how real-time delay notifications can significantly improve the project management approach. Moreover, using Power BI has highlighted its potential to provide valuable insights for notified decision-making (especially project managers) based on the data collected from construction sites. Additionally, the integration of earned value management analysis has proven to be a compelling method for assessing construction project delays and enhancing project tracking and analysis. The practical implications of this study are significant for stakeholders in construction projects. For instance, project managers can adopt the findings to improve project planning and execution, leading to more efficient and timely project delivery. By incorporating BIM and Ms Project for delay notifications, project teams can mitigate risks and proactively address potential issues, reducing delays and cost overruns. Using Power BI as an analytical tool empowers project decision-makers with real-time and data-driven approaches, enabling them to make well-informed opportunities and improve project outcomes. However, contractors and construction firms will benefit from implementing the current study's approach as it will lead to improved project performance. Real-time delay notifications and informed project decision-makers can prevent costly delays and disputes, positively impacting a project's bottom line. From a theoretical perspective, the current study contributes to the growing body of research on project management in construction areas, particularly delay assessment and reporting utilisation.

Therefore, integrating BIM, Ms Project, Power BI, and EVM analysis, this study presents a comprehensive approach to address challenges related to project delays. The findings highlight the importance of leveraging advanced technologies and data analytics to improve project outcomes and pave the way for future research in similar areas. As summed up, practical implications offer valuable insights for optimising project performance and mitigating delays, while the theoretical implications present an innovative approach that incorporates modern technologies and data analysis. By adopting the recommendations derived from this research, the construction industry can improve its project execution, enhance efficiency, and achieve more successful project outcomes overall.

STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name:	Kambiz Rdaman		
Name and title of main supervisor:	Mostafa Babaeian Jelodar		
In which chapter is the manuscript/published work?	Chapter 8		
Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work: ¹ Ratio of student to supervisory team 90:10, Student: Brought and Structured idea, Captured data, created model, Analysed, Drafted and Finilised Text Supervisory team: Conducted Study, Improved conceptual model, Reviewed and Finilised Text			
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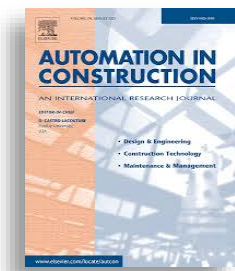
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Chapter 8: A Digital Monitoring, Delay Detection and Visualisation Framework for Construction Projects: RealCONs

The current chapter is based on the following article:

Radman, K., Jelodar, M. B., Lovreglio, R., Ghazizadeh, E., & Wilkinson, S. (2024). A Digital Monitoring, Delay Detection and Visualisation Framework for Construction Projects: RealCONs. *Automation in Construction*, ID: AUTCON-D-25-02892



Under Review with Automation in Construction

Objective should be covered:

OBJ_5: Evaluate the Proposed Framework

8.1 SUMMARY

Accurate and resilient monitoring of construction projects remains a critical challenge, particularly under data uncertainty, fragmented reporting, and system integration delays. This study introduces and evaluates RealCONs, a QR-enabled, automated monitoring framework that integrates BIM, mobile scanning, cloud-hosted SQL databases, and Power BI analytics to support real-time project control. A 90-day comparative case study of two concurrent major projects (GHS and KIT) was conducted against an existing tracking system, focusing on Electrical and Instrumentation (E&I) works. Performance was assessed using Earned Value

management metrics (CPI, SPI, CV, SV) alongside statistical tests, regression forecasting, anomaly detection, and missing data analysis. Results show that RealCONs (S1) delivered significantly higher cost efficiency (CPI: 1.02 vs. 0.90, $p < 0.001$), better schedule adherence (SPI: 1.01 Vs 0.89), and greater data continuity, with 3.2× fewer missing reports. Regression analysis confirmed that missingness in S2 was negatively associated with CPI reliability ($\beta = -0.017, <0.87$), while anomaly detection highlighted that cost overruns and system resets occurred predominantly under S2. The RealCONs framework facilitated the early detection of project delays, enhanced the reliability of forecasting, and delivered transparent, real-time decision support without disrupting existing workflows. While minor challenges were observed in relation to connectivity and authentication, the framework demonstrated both scalability and operational viability. This study contributes to the field of digital construction management by integrating predictive earned value analytics into live project environments, thereby strengthening project control and advancing the objectives of Industry 4.0.

8.2 INTRODUCTION

Delays in large-scale construction projects remain a persistent challenge, particularly within Electrical and Instrumentation (E&I) services such as cable tray installation, cabling, and testing and commissioning [1-5]. These activities are highly vulnerable to trade interdependencies, sequencing constraints, and limited work fronts, with disruptions often cascading across the programme. As E&I tasks are typically situated on the critical path, their timely completion is essential to ensure power availability for commissioning and handover [6]. Consequently, rigorous monitoring and early issue identification are crucial, especially given the limited opportunities for trade overlap [7]. In practice, however, E&I activities are prone to further delays due to incomplete prerequisite works, site congestion, and sequencing misalignments [8-

11]. Traditional progress reporting methods which largely reliant on manual inputs and periodic updates, are time-consuming and error-prone, reducing opportunities for timely corrective action [11-13]. To improve visibility, automated tracking solutions such as laser scanning, RFID, photogrammetry, ultra-wideband (UWB), and wireless sensor networks (WSNs) have been explored [14-20]. While these systems can provide accurate and frequent progress updates [21-23], their high costs, training requirements, and operational complexity limit scalability, particularly in the dynamic, delay-sensitive context of E&I works [24-26].

Mainstream project management platforms such as Primavera P6 and MS Project remain central to baseline development, look-ahead planning, and critical path tracking [27-29]. Yet, they are heavily dependent on retrospective manual updates. BIM-enabled 4D scheduling has improved the visualisation of time–space conflicts and sequencing constraints [9, 30, 31], but its integration with real-time field data remains underdeveloped [32-39]. Similarly, Earned Value and Earned Schedule Management provide structured metrics for performance assessment [40-44], yet their usefulness is undermined by delayed or inaccurate data inputs. As digital workflows gain momentum across the industry, there is a clear need to connect field-level operations with planning platforms through integrated, real-time monitoring, particularly for E&I activities where delays are both frequent and consequential. This study addresses this gap by proposing the RealCONs framework, which integrates QR code-based mobile scanning, a cloud-based SQL database, and dynamic analytics via Power BI. RealCONs creates a closed feedback loop between site-level data, BIM models, schedule baselines, and cost structures, enabling real-time earned value tracking and proactive delay management. The framework advances current practice in three key respects:

1. It integrates existing digital tools into a process-based workflow, reducing the need for additional investment in new systems.
2. It employs BIM-enabled QR code localisation, ensuring precise mapping of on-site progress

to planned tasks.

3. It delivers live delay detection and impact forecasting, empowering project managers to act proactively rather than retrospectively.

However, the research is guided by five objectives:

1. Establish BIM-linked QR code localisation to connect construction tasks to their digital representations.
2. Develop an end-user mobile interface for immediate, on-site data capture.
3. Integrate the mobile application with a cloud-based SQL database for centralised data storage and retrieval.
4. Design a data model for Power BI analytics to evaluate performance using real-time EVM metrics.
5. Validate the framework on real-world E&I projects to assess applicability and impact.

The RealCONs system combines widely available technologies: BIM (Revit 2023) for digital representation, SQL Server (2022, version 16) for structured data storage, smartphone-enabled QR scanning (Android OS 12+ and iOS 15+) for live field input, and Power BI (version 2.145) for interactive dashboards. Together, these components support early warning of delays, evaluation of their impact on cost and time, and proactive project control. Its low-cost, scalable architecture is tailored to the dynamic nature of E&I activities, offering improved coordination and disruption management. The framework was developed following a literature-based gap analysis, built within Power BI, and validated on multiple large-scale E&I projects. The findings confirm its feasibility and demonstrate its potential to support proactive, data-driven decision-making.

8.3 STUDY BACKGROUND

This section outlines the technological and methodological foundations of the proposed framework. It reviews the challenges in Electrical and Instrumentation (E&I) works, recent developments in real-time tracking, the use of smartphones for on-site data capture, and the potential of visual analytics tools such as Power BI to support timely project decision-making.

8.3.1 Smartphone-Based QR Tracking for On-Site Progress Monitoring

Recent developments in Industry 4.0 and mobile computing highlight smartphones as practical tools for construction information management [45, 46]. Mobile applications are now widely used for document control, progress updates, and project tracking [47-53]. Leveraging built-in sensors and connectivity (e.g., Bluetooth, 3G/4G), smartphones can capture and transmit data across large project areas [54-57]. When combined with QR codes, smartphones provide a low-cost, accessible means of real-time monitoring. QR codes placed at installation points allow site crews to record completion data, which is synchronised to cloud databases for centralised analysis [56, 58, 59]. This approach reduces documentation errors, improves coordination, and enhances efficiency. While several studies have highlighted the potential of QR-based tracking, their systematic use to support structured E&I data capture and integration into live analytical dashboards remains underdeveloped [7, 26]. This research builds upon these foundations to establish a more comprehensive, data-driven solution.

8.3.2 Visual Analytics and Performance Monitoring Using Power BI

Descriptive and graphical analytics remain the most widely used approaches to monitor construction progress and performance [60, 61]. These methods provide retrospective insights into "what happened" by visualising historical and real-time data trends. When paired with business intelligence tools such as Power BI, these insights can be presented in interactive dashboards, enabling rapid identification of deviations, supporting decision-making, and

improving communication among stakeholders [62-67]. Power BI is particularly effective for visualising key performance metrics like the SPI and CPI due to its seamless integration with the Microsoft ecosystem and its support for large-scale, cloud-based collaboration [68-71]. Its intuitive interface and analytical features (e.g. DAX, Power Query) make it accessible to both technical and non-technical users, including site managers and engineers [68, 69, 72-74]. Compared with other BI tools, Power BI is cost-effective, scalable, and suitable for real-time construction monitoring [75].

Despite widespread use of these tools individually, the literature highlights a lack of integrated, field-deployable frameworks that combine real-time data capture with performance analytics—especially within E&I scopes. Previous studies have not adequately addressed the modelling of data flow between project entities (e.g. contractors, engineers, consultants), nor the relationships between automated tracking systems and early-stage delay notification mechanisms [76-78]. This study addresses this gap by proposing a comprehensive framework that unifies QR-based mobile tracking, cloud-based data integration, and Power BI-driven analytics for improved delay detection and proactive project control.

8.3.3 Comparative Contribution of RealCONs

To address these gaps, this study introduces the RealCONs framework, which unifies QR-based smartphone tracking, SQL-based data integration, and Power BI analytics. It is novel in three ways: (1) process-based integration of widely available digital tools into a coherent workflow, reducing the need for additional investment; (2) BIM-enabled QR localisation, improving precision in connecting field data to planned tasks; and (3) real-time earned value forecasting, enabling proactive delay detection and early intervention. The unique contribution of RealCONs is highlighted in Table 8.1, which compares its features with those of leading approaches identified in literature.

Table 8.1: Comparative overview of previous studies and RealCONs framework

Feature / Capability	Previous Studies [8, 26, 27, 79, 80]	RealCONs Framework (proposed)
Integration of digital tools	Typically focus on single tools (e.g., BIM for visualisation, RFID for tracking).	Process-based integration of BIM, QR, <u>Planning DB</u> , SQL, and Power BI into a unified workflow.
Real-time Earned Value Management	Limited or absent; usually based on periodic reports.	Live dashboards with EVM metrics (SPI, CPI) supporting early detection of discrepancies.
BIM-QR code linkage	Rare; QR used mainly for material tracking.	Novel use of BIM for QR placement to directly link site data with planned activities.
Data model architecture	Fragmented or tool-specific, often lacking interoperability.	Centralised SQL-based <u>Project DB</u> integrating design, schedule, site, and analytics data.
Early warning and forecasting	Retrospective and reactive in most cases.	Proactive forecasting of time and cost impacts from early discrepancies.
Validation in E&I projects	Rarely tested in complex, fast-paced domains.	Applied to real-world E&I projects, demonstrating robustness and scalability.

8.4 RESEARCH METHODOLOGY

The research method is based on previous studies – described in detail in Sections 2 – on developing and testing digital technologies in project management, particularly in project tracking and visualisation. These studies have developed their own processes and prototypes for data collection, 3D presentation, and project timeline monitoring, though they did not specifically focus on early delay warnings or automated analysis of their impacts on project performance. The method involves developing and testing a digital framework designed to instruct an integrated process for real-time data collection from construction sites and visualising project status. This includes performing specific tasks such as identifying the location of QR codes on site using BIM, integrating smartphones for QR code scanning, and connecting a cloud-based SQL database with Power BI to provide early notifications and analyses their impact using earned value (EV) indexes.

Following its development, the testing involved case studies (e.g. Electrical and Instrumentation works), where real-time installation data and BIM component location codes were centralised to create a data model for presenting analytical reports. The experiment aimed at enabling project managers and key decision-makers to identify issues (e.g. delays) and make timely cost and schedule forecasts. The research method framework is provided in Figure 8.1

below.

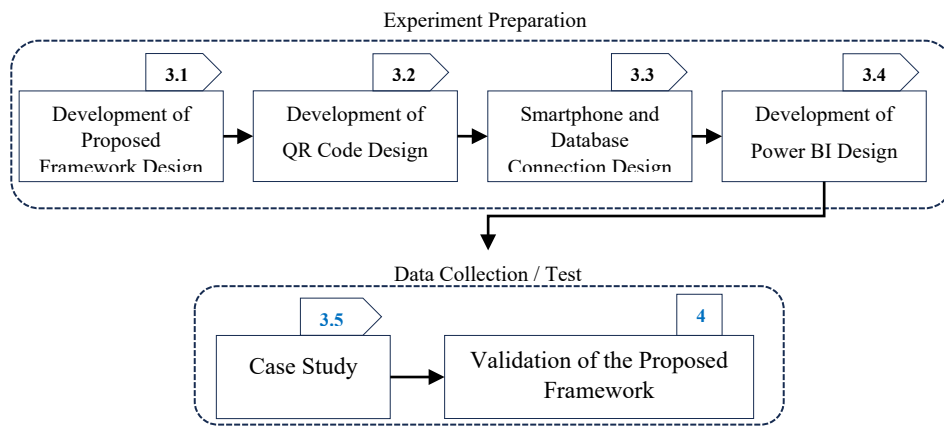


Figure 8.1: Research Method Framework

8.4.1 Proposed Framework Design

8.4.1.1 *RealCONs Overview*

To clarify the structure and interaction between components of the RealCONs framework, it is useful to outline the proposed process on major construction sites, following the sequence of 1) real-time data collection, 2) data integration, and 3) data analysis and visualisation, as illustrated in Figure 8.2.

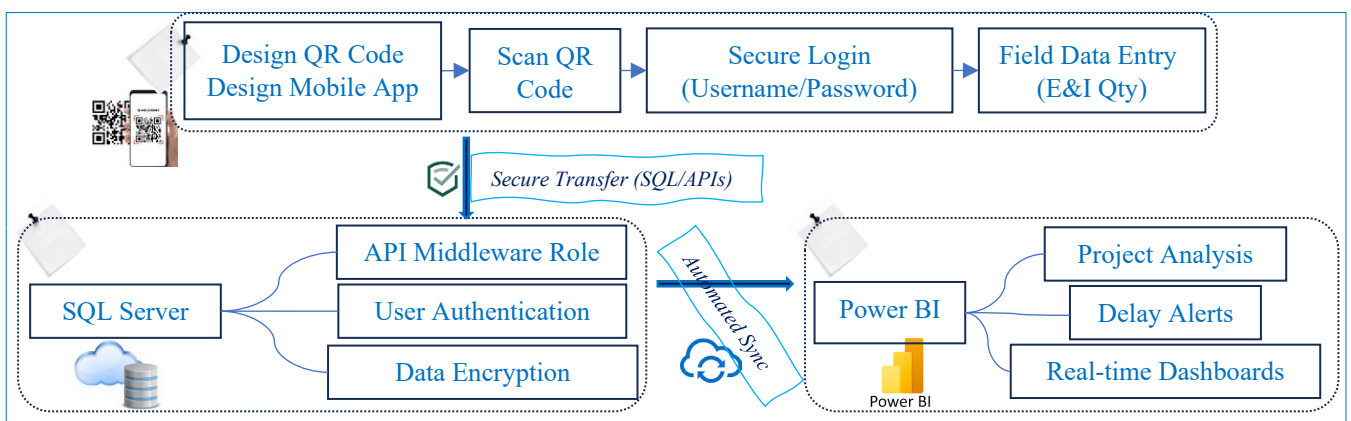


Figure 8.2: Research Conceptual Model

The RealCONs framework was developed to enable real-time acquisition, integration, and analysis of construction site data. As shown in Figure 8.3, its architecture is composed of three

core and two supporting components, designed according to an object-oriented structure. Table 8.2 presents the core and supporting components.

Table 8.2: RealCONs Core and Supporting Components

Type	Components	Description
Core	Site_Work	The front-end module responsible for on-site data capture via QR code scanning, recording user credentials, installation quantities (e.g., cables, trays), building location codes, and issue-related comments
	Project_DB	A centralised SQL Server database that functions as the backbone of the system, storing all project-related records
	Analytical_DB	A Power BI-linked platform facilitating project analytics, including earned value (EV) metrics
Supporting	Planning_DB	A repository for planned schedules (WBS) and cost breakdowns (CBS), derived from MS Project or Primavera P6
	BIM	A 3D environment used to quantify associated installation materials and identify the spatial location of QR codes

These components operate within two functional domains: (i) Project Entry Gate: Where QR codes are generated by Project_DB, supported by data from BIM and Planning_DB; and (ii) Project Management: Where real-time site data, captured via QR code scanning, is transferred to Project_DB (SQL Server) for consolidation before being processed in Analytical_DB (Power BI) for visualisation and analysis. Comprehensive security protocols including credential-based authentication, encrypted transmission, IP-based trust verification, and role-based access control, are implemented throughout all data exchange layers.

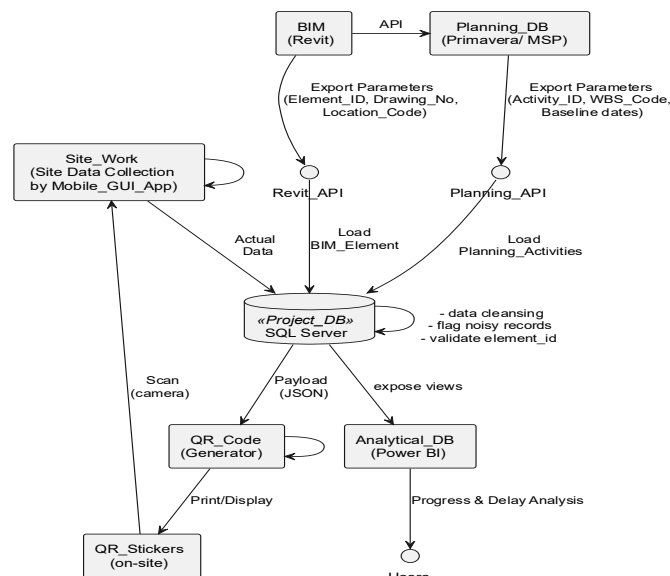


Figure 8.3: Proposed Research Framework and Its Classes

The framework incorporates robust security measures throughout its architecture to ensure

data integrity and controlled access. When users scan QR codes, they are directed to a secure login portal requiring credentials before system entry. All data transmissions occur over encrypted channels, while cloud storage employs multi-layered authentication protocols, including IP-based trust verification and role-based access control. Device-to-database communication is implemented through standard web protocols (HTML forms, PHP/APIs, and MySQL/SQL), supported by a cross-platform graphical interface for operational usability. To enhance reproducibility and reliability, the framework explicitly incorporates error-handling and offline capability. During a QR scan, the mobile application validates the input locally before constructing a payload that is transmitted to the server. If connectivity is unavailable, the record is placed in an offline queue and synchronised automatically when the network is restored. Server-side validation ensures schema correctness, duplication checks, and business-rule enforcement, returning status codes (e.g., 201 Created, 422 Validation Error, 409 Conflict, or 5xx Server Error) to guide the user. Each update is logged in the SQL database, integrated with the BIM model, and forwarded to Power BI which earned value indicators (CPI, SPI) are refreshed. Warnings are issued in cases of incomplete or missing baseline data, ensuring continuity and transparency of reporting. Accordingly, Figure 4 illustrates the revised sequence diagram from site to before full insight steps: the process from QR scan and validation to secure data transmission, conflict resolution, offline recovery, and downstream analytics. This closed-loop design enables real-time monitoring of installations while minimising manual errors and supporting early delay detection. Collectively, this digital approach strengthens efficiency and accountability through seamless and centralised data management. All scripts (database, HTML, PHP), configuration details, Power Query transformations, and DAX measures referenced in the following subsections are provided in Appendix 1.

8.4.1.2 Database Schema and Relationships

To enable integration between BIM data, schedule data, and field-scanned progress records, a

relational schema was designed in SQL Server (Project_DB). This revised schema (presented in Figure 3, adapted from the workflow diagram) consolidates three key streams of information:

- BIM data from Revit (element IDs, geometry references, and quantities),
- Schedule data from Primavera/MSP (WBS codes, activity IDs, planned dates, and resources),
- Real-time site data captured via mobile QR scanning (progress quantities, timestamps, and resource hours).
- Data integrity is ensured through primary and foreign key relationships. The tables are linked as follows:

Table Name	Primary Key	Connected Table	Connection Method	Purpose
BIM_Elements	Element_ID	QR_Code_Register	Foreign Key:Element_ID	Links BIM elements to QR codes
Planning_DB	Activity_ID	BIM_Elements	Attribute Match:WBS_Code	Activities association with BIM elements
		Site_Work	Foreign Key:Activity_ID	Connects schedules to site records
Cost_Records	Cost_ID	Site_Work	Functional Link (unspecified FK)	Actual cost calculations

As seen in Figure 8.5, these one-to-many relationships allow a single BIM element to be associated with multiple scheduled tasks and progress entries. The schema supports real-time queries by analytical tools such as Power BI.

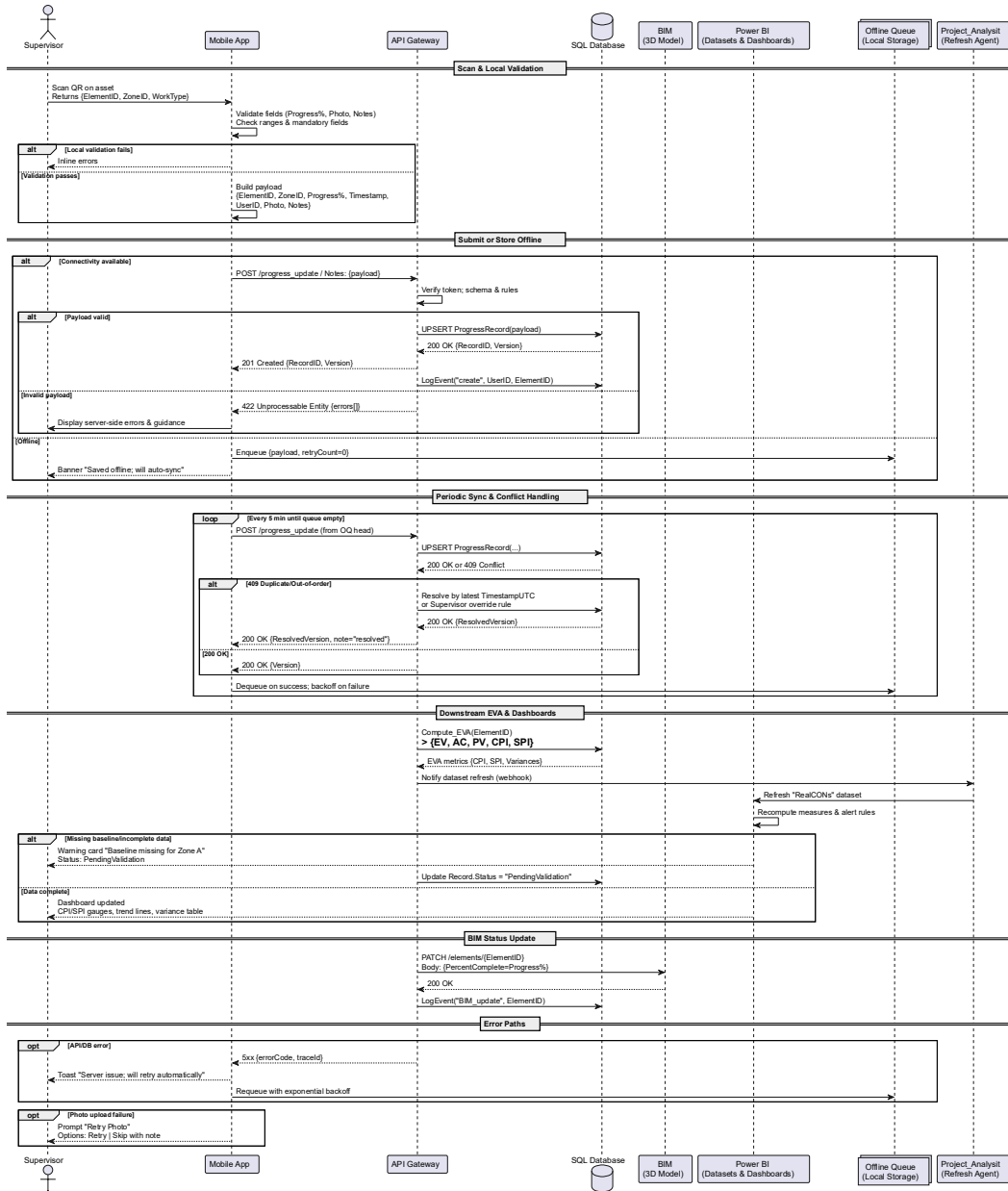


Figure 8.4: Sequence Diagram: Site to Insight

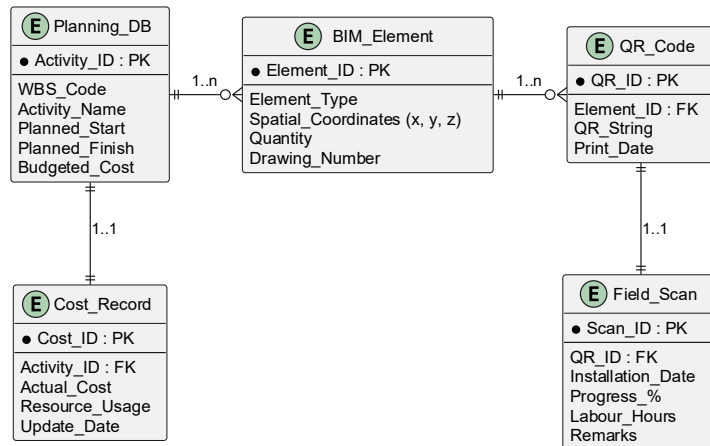


Figure 8.5: Database Schema and Relationships

8.4.1.3 BIM Data Extraction and Integration Workflow

The RealCONs framework requires structured extraction of BIM data to ensure compatibility with both Planning_DB and site-collected progress data. Revit models were used as the primary BIM, and data were exported via API scripts into the Project_DB.

➤ Data Extracted from BIM:

- Element IDs (unique identifiers for each physical component).
- Spatial coordinates (positions of components within the model).
- Quantities (e.g., length of cable tray and cales in metres, volume of fittings).
- System classification codes (e.g., electrical, mechanical, architectural).

➤ Integration with Project Data:

- Each BIM Element ID is mapped to a WBS activity via a lookup table.
- A corresponding QR code is generated that encodes the element ID, drawing reference, and WBS code.
- On-site, the QR sticker is affixed to the physical element, enabling direct progress capture through mobile scanning.

➤ Linking to Schedule Activities:

- WBS codes from the Planning_DB are cross-referenced with BIM element IDs.
- This ensures that scanned progress updates (e.g., 30m of tray installed) are automatically matched to the correct scheduled task in Project_DB.
- The linkage is many-to-one: multiple BIM elements (e.g., tray segments) can feed into a single WBS activity (e.g., “Install cable tray in Zone A”).

➤ Data Flow:

- Extraction: Revit API exports Element ID, quantities, and attributes.
- Transformation: Data stored in Project_DB with WBS lookups.
- Integration: QR codes generated and attached to elements on-site.
- Execution: Field scans update progress in real time.

This workflow ensures seamless traceability, which is central to RealCONs real-time monitoring capability.


8.4.2 QR CODE DESIGN

From Figures 8.3 and 8.5, the QR code generation sequence: BIM model data flows into a centralised SQL Server acting as the primary integration hub. Automated APIs extract element-specific attributes including spatial locations, installation quantities, building codes, and drawing numbers, directly from the 3D model, ensuring digital-physical consistency. These datasets undergo programmatic encoding via Python scripts to embed critical metadata (BIM element identifier, building code, drawing number, location tag) within QR codes, which are subsequently printed and affixed to corresponding on-site locations (Tables 8.3 and 8.4). This process bridges digital design and physical implementation, enabling precise spatial tracking and efficient field data capture.

Table 8.3: QR Code Data key fields and an example

Field	Description	Example Value	Data Format
location	Physical installation site	"Block A, Level 3"	{ "location": "Block A, Level 3", "drawing_number": "DRG-EI-2024-015", "building_code": "GHS-EI-08", "quantity": 12, "unit": "m" }
drawing_number	Reference engineering drawing	"DRG-EI-2024-015"	
building_code	Project-specific asset ID	"GHS-EI-08"	
quantity	Installed units (with unit type)	12 (meters, pieces)	
timestamp	Auto-generated scan time (ISO format)	2024-07-15T14:30:00Z	

Table 8.4: QR Code Generation

Example Code	Sample
<pre>import qrcode, json data = { "location": "Block A, Level 3", "drawing_number": "DRG-EI-2024-015", "building_code": "GHS-EI-08", "quantity": 12} img = qrcode.make(json.dumps(data)) img.save("construction_QR.png")</pre>	

Figures 8.6–8.8 demonstrates project 3D model and construction site real perspectives drawn from a case study validating the framework. However, for confidentiality compliance with case study agreements, actual QR codes captured during field implementation have been systematically obscured in Figures 8.7 and 8.8. Figure 8.6 presents an annotated BIM snippet illustrating unique tag numbers. Notably, QR code symbols which are absent in the original 3D model, have been superimposed onto this visualisation. These symbols serve as digital references

for the strategic placement of physical QR codes at corresponding on-site locations, enabling precise monitoring of installation progress.

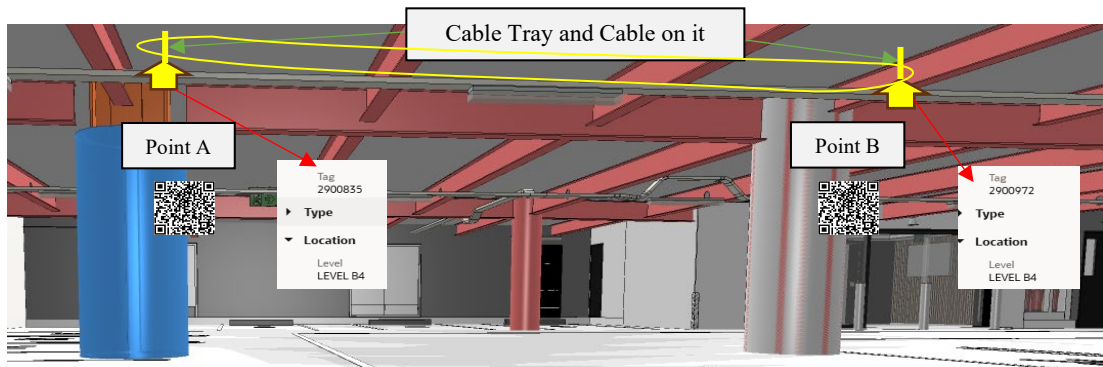


Figure 8.6: QR Codes display locations

In Figure 8.7, supervisors authenticate via mobile app, scan QR codes between designated points (e.g., Point A to Point B) to retrieve installation data from the SQL Server. The system calculates quantity discrepancies in real time. For installations extending beyond threshold markers (e.g., Point C in Figure 8.8), predefined allowances are applied. All captured data tagged with relevant drawing codes, transmits to the cloud-based SQL database, where predefined queries cleanse records, flag unreliable entries (e.g., poor connectivity artefacts), and update work breakdown structure progress.

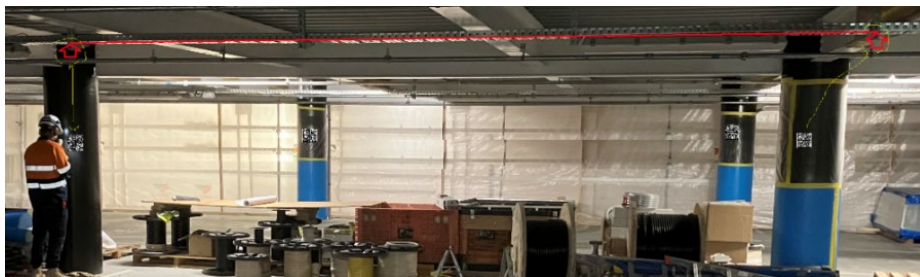


Figure 8.7: point to point



Figure 8.8: point to the threshold

Collectively, this closed-loop framework enhances progress monitoring accuracy, minimises manual errors, and elevates project transparency through BIM-intelligent data workflows.

8.4.3 Smartphone and Database Connection Design

The initial stage entails the development of a user-friendly, HTML-based Graphical User Interface (GUI) to facilitate secure data entry via smartphones. Users are required to log in and input key project details, including login credentials, building identification, supervisor ID, installation quantities (e.g., cabling and cable tray), and the date of installation. This information is transmitted directly to a cloud-hosted SQL database. As further depicted in Figure 9, the mobile application serves as the front-end platform for on-site data collection, while the back-end infrastructure manages data flow and integration. Through this application, supervisors can submit real-time updates on installed quantities (e.g., metres of cable tray and cables installed) along with any site-related issues or comments, all of which are securely recorded in the SQL Server database.

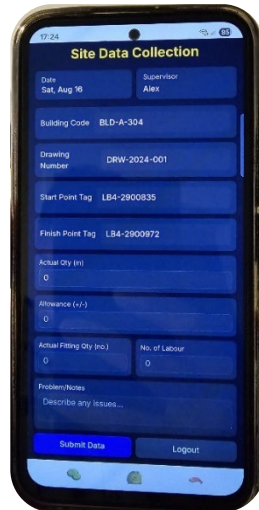


Figure 8.9: GUI on Smartphone

As illustrated in Figure 8.3, the generation of real-time analytical and visual reports through the Analytical_DB necessitates a continuous and structured data flow. To enable this, the Project_DB functions as a centralised repository, consolidating two key data streams: (i) planned installation quantities and associated dates sourced from the Planning_DB, and (ii) actual on-site progress (e.g., installed metres) captured in real time via QR code scanning through the Site_Work interface. To facilitate the transfer of real-time data, a server-side PHP script is employed. This mechanism enables seamless communication between mobile data capture and back-end storage. Consequently, the Analytical_DB gains access to a comprehensive dataset comprising actual and planned metrics, as well as recorded delay event comments, thus supporting robust performance tracking and timely decision-making.

8.4.4 Power BI Design

As illustrated in Figures 8.3 and 8.4, the RealCON framework's data workflow begins with real-time on-site capture of progress updates and delay annotations via QR scanning, stored in a central SQL database (Project_DB). This repository integrates cost/schedule data from Planning_DB and BIM models, feeding Analytical_DB (Figure 8.10) where custom DAX measures compute key Earned Value Management (EVM) metrics: Planned Value (PV), Earned

Value (EV), and Actual Cost (AC), directly from linked BIM, schedule, and field data tables. The resulting visualisations enable early detection of delays and discrepancies through dynamic dashboards, providing real-time identification of cost/schedule deviations. This end-to-end pipeline enhances stakeholder communication and project oversight by supporting data-driven decisions across the construction lifecycle. So, sample of Power BI DAX codes are as follows:

- Planned Value (PV): PV is derived from the budgeted cost of activities proportionate to planned progress by a given date. Dax is:

```
Planned Value (PV) =
CALCULATE( SUM('Planning_DB '(Budgeted_Cost)) *
DIVIDE( DATEDIFF('Planning_DB '(Planned_Start), TODAY(), DAY),
DATEDIFF( 'Planning_DB '(Planned_Start), 'Planning_DB '(Planned_Finish), DAY) ),
FILTER( 'Planning_DB ', TODAY() >= 'Planning_DB '(Planned_Start) && TODAY() <=
'Planning_DB '(Planned_Finish) ))
```

- Earned Value (EV): EV links actual field scans of BIM elements to scheduled activities via the WBS. Dax is:

```
Earned Value (EV) = SUMX( 'Field_Scan', RELATED('Planning_DB '(Budgeted_Cost)) *
('Field_Scan'(Progress_%) / 100))
```

- Actual Cost (AC): AC is drawn directly from cost records linked to each scheduled activity. Dax is:

```
Actual Cost (AC) = SUM('Cost_Record'(Actual_Cost))
```

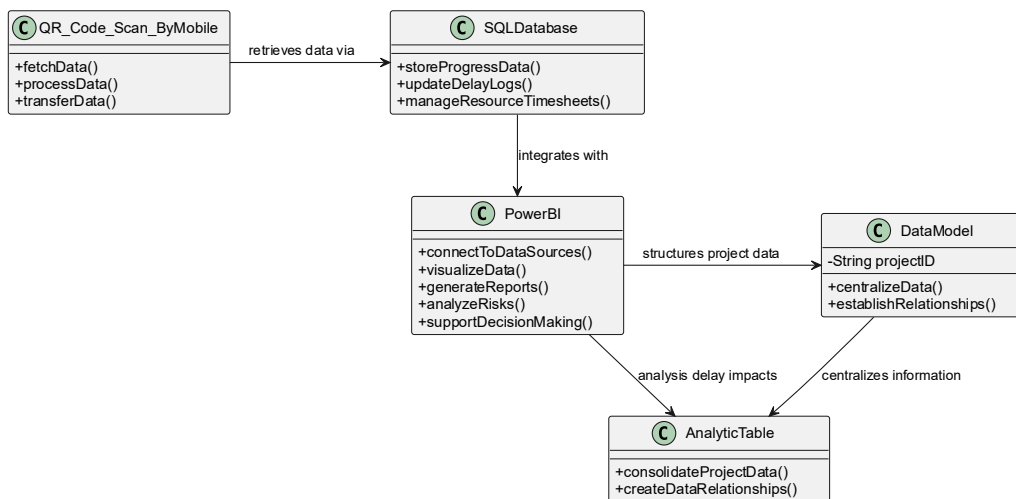


Figure 8.10: Power BI Overview Model

These measures are embedded in Power BI dashboards, allowing stakeholders to compare PV, EV, and AC in real time. This supports proactive identification of variances (Cost Variance,

Schedule Variance) and forecasting metrics (CPI, SPI). By exposing the underlying DAX code, this study ensures full transparency and reproducibility of the analytical workflow, addressing the reviewer's request for technical detail.

8.4.5 Case Study

The Electrical and Instrumentation (E&I) trade was selected for testing the RealCON framework's field applicability, as it represents a critical service trade with distinctive sequencing requirements. E&I works (comprising cable containment installation, cable pulling, equipment installation, termination, testing and commissioning) must precede dependent trades such as mechanical and data/security systems, which require power supply for their commissioning. While limited task overlap may be permissible, this precedence relationship makes E&I activities particularly suitable for validating real-time progress monitoring.

8.4.5.1 Case study introduction and selection

All case studies focus on two-storey, high-security buildings, each with a floor plan of roughly 900 m². Given the stringent security requirements, these projects demand meticulous monitoring of time, cost, and quality throughout their life cycle. Two critical factors underscore this need: (1) the high cost of materials and labour, and (2) the necessity of strict timeline oversight. Consequently, daily productivity tracking is vital to maintain efficiency and adhere to schedules. However, stringent security protocols prohibit the use of RFID tags, embedded sensors, and aerial drones, significantly constraining data collection and monitoring methods. The case studies were chosen based on specific criteria to ensure they align with the challenges addressed by the RealCONs framework: 1) Scale and Value – The selected projects, valued between \$90M and \$100M, represent mid-to-large-scale developments, offering a broad perspective on project complexities; 2) Electrical Scope – Variations in cabling (10,890–14,000 m), containment (12,000–15,800 m), and fittings (120–150 units) provide a robust dataset for analysing delay

factors across different work scopes; 3) Geographic Similarity – All projects were executed under comparable contract structures and construction environments, facilitating consistent evaluation of the RealCONs framework; 4) Data Availability – Each project generated multiple status reports including progress reports (manual forms, MS Excel, MS Project/Primavera) and delay events reports (MS Excel). However, reliance on disparate data sources has compromised accuracy, delayed reporting, and increased response times in both internal (e.g., site supervisors to project managers) and external (e.g., subcontractors to design teams) interactions; 5) Project Stage Similarity – Roofing work is complete across all projects, granting E&I teams site access. Construction progress exceeds 85%, and each project is managed by two executive teams of 15 members, with identical reporting mechanisms; and 6) Stakeholder such as project managers, planners, quantity surveyors, supervisors, engineers were involved. Table 8.5 illustrates that all four selected projects are similar in scale and value.

Table 8.5: Selected Projects Details: E&I Scope

E&I Specs \ Project	GHS	KIT
Value (million \$)	100	100
Cabling (meter)	12,000	11,890
Cable Containment (meter)	13,800	13,000
Fitting (No)	135	138

8.4.5.2 Implementation of the RealCONs framework

The implementation of the RealCONs framework in an active construction environment follows a structured sequence, ensuring that data from on-site activities is accurately captured, processed, and transformed into actionable insights. For the Electrical and Instrumentation (E&I) trade, this process is illustrated using the example of cable containment installation and subsequent cable pulling. For these purposes five steps are designed in Figure 8.12: 1) Preparation and System Setup, 2) Data Capture at the Project Entry Gate, 3) Data Transmission and Storage, 4) Data Processing and Analytics, 5) Visualisation and Reporting in Power BI.

From Figure 8.12, the BIM model is configured to define spatial locations, building codes,

and drawing references for E&I works such as tray installation and cabling. Each section is assigned unique tags to ensure precise traceability, and QR codes are generated using a Python script to encode attributes including location identifiers, tray lengths, and cable quantities. A secure SQL Server (Project_DB) is established in parallel (see section 3), structured into fields such as installation dates, material costs, and labour. To support on-site data capture, a mobile application (Graphical User Interface - GUI) is developed with HTML and Python, while PHP scripts connect the interface to the SQL Server. API permissions are formally obtained from the BIM (Revit) and Planning (Primavera P6) teams, enabling the server to draw element-specific data directly from design and planning systems. On site, QR codes are printed and fixed at BIM-defined locations. Supervisors log into the mobile application, scan the codes, and automatically retrieve the associated building code, drawing number, and start-point tag stored in the SQL Server. Progress is recorded by scanning the corresponding finish-point tag. Where the measured length matches the BIM-defined element, the record is confirmed; where discrepancies occur, a pre-agreed tolerance (e.g., $\pm 10\%$) is applied. These verified records are transmitted securely to the SQL Server and Power BI, ensuring an accurate, real-time record of progress while accommodating permissible site variations.

The RealCON Power BI model integrates three core data streams for comprehensive project monitoring: 1) Planned Data (baselines and forecasts from Planning_DB); 2) Actual Site Data (real-time progress captured via QR scanning and stored in SQL Server); and 3) Calculated Metrics (analytical outputs comparing planned vs. actual values). This integration enables automated Earned Value analysis (Table 6), with data aligned to WBS/CBS structures. Key metrics like SPI and CPI are calculated in real-time, flagging deviations (e.g., cable installation delays despite tray completion) for immediate intervention. The framework automatically detects variances for instance, when only 30m of cable tray or cabling is installed against a 50m target, and triggers alerts for resource reallocation or task resequencing.

Table 8.6: Earned Value Metrics [81]

Parameters	Formula	Warning Indexes
Schedule Variance (SV): Deviation between earned progress and planned progress (time-based)	$SV = EV - PV$	SV < 0: Behind schedule (PV > EV)
Cost Variance (CV): Deviation between earned value and actual cost (cost-based)	$CV = EV - AC$	CV < 0: Over budget (AC > EV)
Cost Performance Index (CPI): Efficiency of cost utilisation (value earned per \$ spent)	$CPI = EV / AC$	CPI =1: on budget CPI >1: Under budget CPI <1: Over budget
Schedule Performance Index (SPI): Efficiency of time utilisation (progress vs. plan)	$SPI = EV / PV$	SPI =1: on schedule SPI >1: ahead of schedule SPI <1: Behind schedule
Estimate At Completion (EAC): Forecasted total project cost based on current performance	$EAC = BAC / CPI$	EAC > BAC: Likely cost overrun

Planned Value (PV) Budgeted cost of work scheduled up to a given date (BCWS): How much work should be done?
Actual Cost (AC) Actual cost incurred for work performed up to a given date (ACWP): How much did the work cost?
Earned Value (EV) Budgeted cost of work actually completed up to a given date (BCWP): How much work was done?
Budget at Completion (BAC) is the sum of all budgets allocated to a project scope

As the analytical layer, Power BI transforms validated SQL data using DAX coding into interactive dashboards featuring: i) Progress curves and productivity rates; ii) BIM-linked work zone status maps; iii) EV trend charts (CPI/SPI); and iv) Budget vs. Actual cost tracking. The cross-device accessible reports enhance decision-making transparency, improving delay management and accountability across E&I works (see Figure 11 and Table 7 for model architecture and constituent tables).

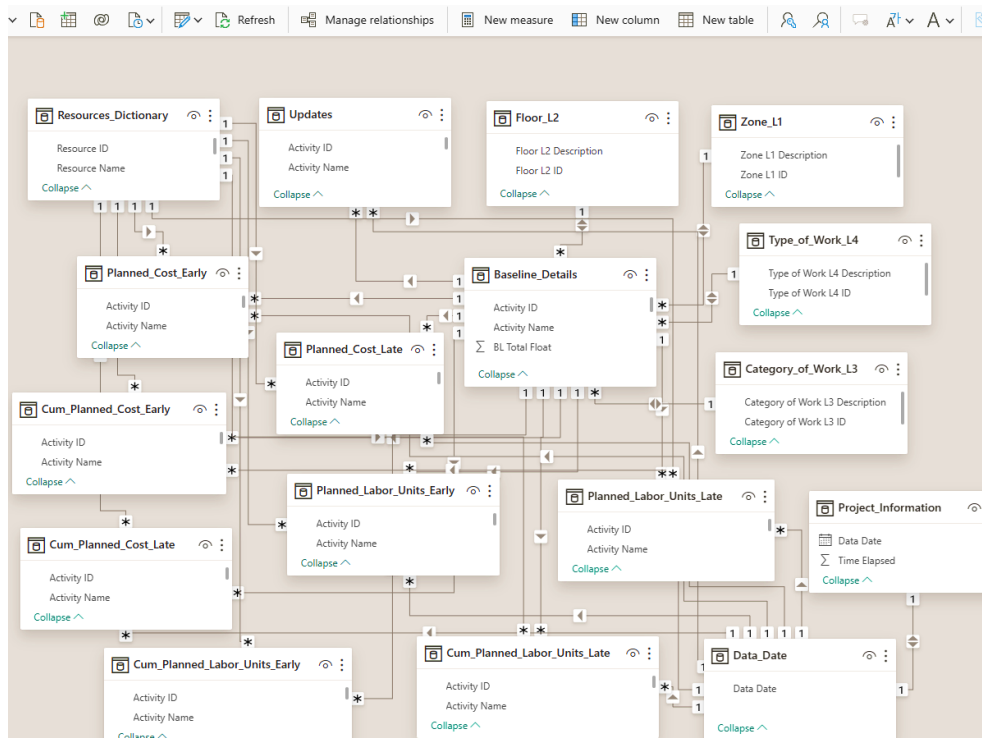


Figure 8.11: Data Model

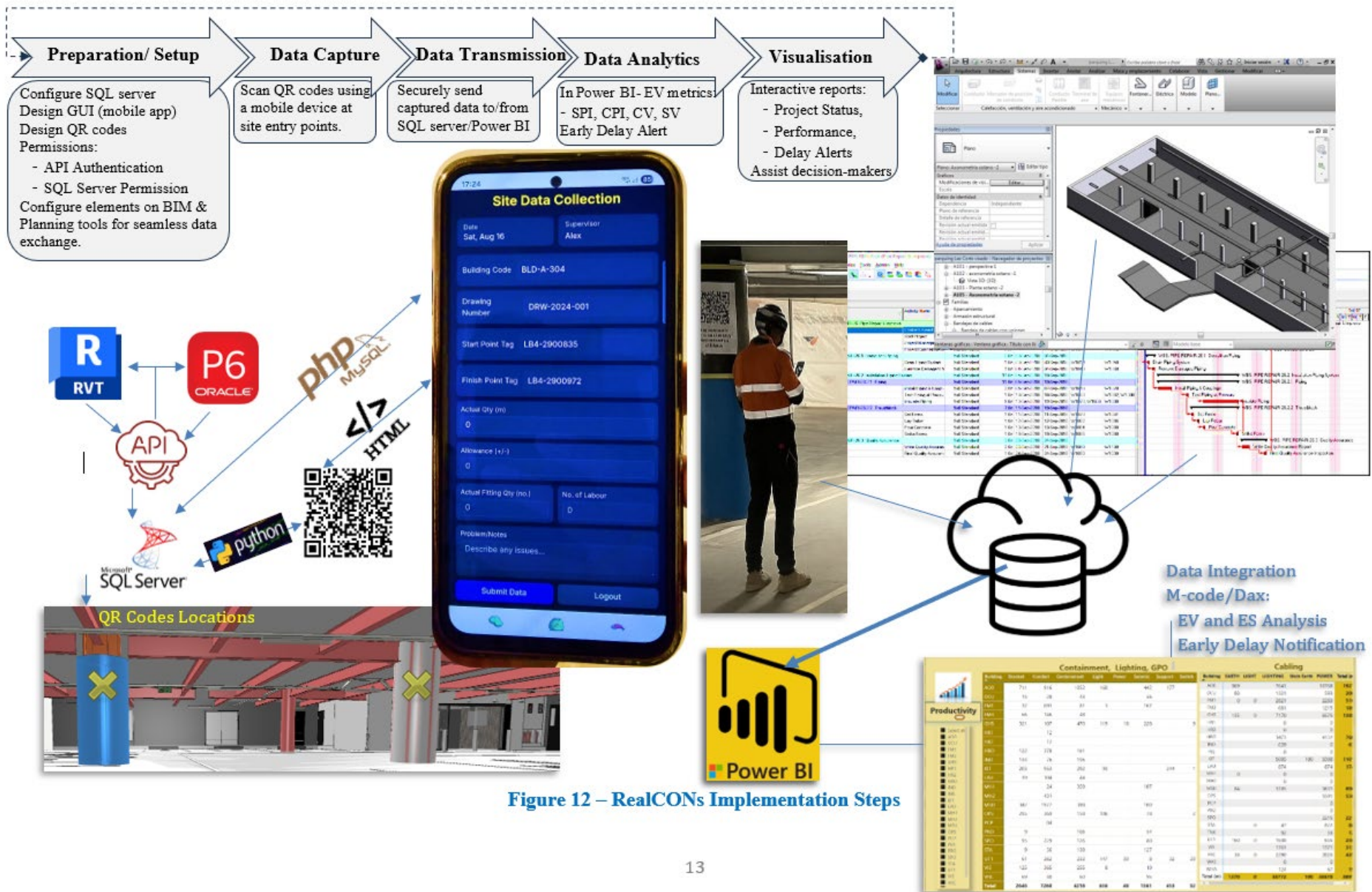


Table 8.7: Power BI Data Tables Grouped By Source Type

Category	Tables / Outputs		Purpose
Planned Data	- Zones and Work Types - Resources_Dictionary - Baseline_Details	- Planned Cost and Labour - Cumulative Plans - Project_Information	Defines project structure (zone/floor/work type), resource catalogues, baseline labour and cost data, and aggregated forecasts.
Actual Site Data	- Updates - Data_Date		Captures site progress (dates, status, quantities) and logs reporting dates for version control.
Calculated Metrics	- Planned vs Actual - Forecasting	- Delay Analysis - Zone/Floor Analysis	Compares planned vs. actual data, forecasts resource/cost needs, identifies schedule delays, and enables location-specific performance review.

8.4.6 Test and Validation of the Proposed Framework (RealCONs)

The proposed RealCONs framework was tested and validated using real-time data from two major construction projects involving electrical and instrumentation (E&I) works. The objective was to evaluate its effectiveness in real-time project tracking, with emphasis on early delay identification and management. The analysis is structured into four parts: (1) Data Continuity, (2) Approach and Rationale for Scenarios S1 (Project KIT) and S2 (Project GHS), and (3) Statistical Analysis. RealCONs' performance (S1:GHS) was compared with an existing reporting system (S2:KIT) over a 90-day data collection period, which aligned with the contractual duration of Construction Phase 1 (Table 8.9).

8.4.6.1 Data Continuity

Daily earned value (EV) data were used to assess reporting continuity (Table 9). Days with EV = \$0.00 were treated as missing and excluded from performance calculations, although such gaps did not prevent invoice payments (based on Actual Cost, AC). For S1 (GHS), only five days had missing EV data (Days 21, 28, 39, 74, and 86). In contrast, S2 (KIT) recorded 35 missing days (e.g., Days 2–3, 11–14, 24–26, etc.), indicating significantly poorer data continuity (Figure 13; Table 8).

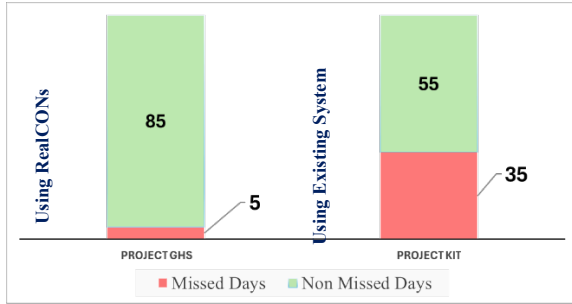


Figure 8.13: Daily Received Reports

Table 8.8: Missing Data

Methods	# Missing Days	%
Via RealCONs (S1)	5	5/90 = 5.6%
Via Exist (S2)	35	35/90 = 38.9%

Excluding duplicates (e.g., day 74, missing in both projects), the dataset contained 39 unique missing days (40 – 1 = 39). This resulted in 51 (90 – 39 = 51) paired daily observations (n) for statistical comparison.

8.4.6.2 Approach and Rationale for S1 and S2

Performance was compared using the Cost Performance Index (CPI) and Schedule Performance Index (SPI). Because data distributions, particularly in S2, violated normality assumptions, non-parametric tests were applied. The Mann-Whitney U test was used for independent group comparisons, while the Wilcoxon Signed-Rank test was applied to paired data which was applied to the 51 paired daily observations. Statistical significance was defined at $p < 0.05$, with Cohen's d used to quantify effect size for paired differences.

8.4.6.3 Statistical Analysis

The standard deviation (Std. Dev.) measures variability of CPI/SPI around the mean: $S =$

$$\sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}} \text{ Eq.(1), where:}$$

- n = Sample size (85 for S1, 55 for S2)
- x_i = Daily CPI value,
- \bar{x} = Mean (CPI:S1=1.03, CPI:S2= 0.87)

Table 8.9: Earned Value Parameters on the “KIT” Project

		Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30		
Project CHS Proposed (S1)	PV:S1&S2	\$1,111	\$2,222	\$3,333	\$4,444	\$5,556	\$6,667	\$7,778	\$8,889	\$10,000	\$11,111	\$12,222	\$13,333	\$14,444	\$15,556	\$16,667	\$17,778	\$18,889	\$20,000	\$21,111	\$22,222	\$23,333	\$24,444	\$25,556	\$26,667	\$27,778	\$28,889	\$30,000	\$31,111	\$32,222	\$33,333			
	EV:S1	\$1,167	\$2,450	\$3,500	\$4,667	\$5,300	\$6,667	\$7,000	\$9,100	\$9,333	\$11,301	\$12,200	\$12,833	\$14,000	\$14,667	\$15,833	\$16,833	\$17,833	\$18,833	\$19,833	\$20,833	\$0	\$24,100	\$25,326	\$26,013	\$27,120	\$28,081	\$29,680	\$0	\$31,258	\$32,142			
	AC:S1	\$1,061	\$2,334	\$3,300	\$4,222	\$4,222	\$5,278	\$6,333	\$7,389	\$8,444	\$9,556	\$10,611	\$11,667	\$12,722	\$15,264	\$16,100	\$16,921	\$18,374	\$18,998	\$20,001	\$21,524	\$21,833	\$22,167	\$22,167	\$23,222	\$24,002	\$25,333	\$26,389	\$27,444	\$28,500	\$29,556			
	CV:S1	\$106	\$116	\$200	\$444	\$1,078	\$1,389	\$667	\$1,711	\$889	\$1,745	\$1,589	\$1,167	\$1,278	-\$598	-\$267	-\$88	-\$541	-\$165	-\$168	-\$690	-\$21,833	\$1,934	\$3,159	\$2,790	\$3,118	\$2,748	\$3,291	-\$27,444	\$2,758	\$2,587			
	SV:S1	\$56	\$228	\$167	\$222	-\$256	\$0	-\$778	\$211	-\$667	\$189	-\$22	-\$500	-\$444	-\$889	-\$833	-\$944	-\$1,056	-\$1,167	-\$1,278	-\$1,389	-\$23,333	-\$344	-\$230	-\$654	-\$657	-\$808	-\$320	-\$31,111	-\$964	-\$1,191			
	CPI:S1	1.10	1.05	1.06	1.11	1.26	1.26	1.11	1.23	1.11	1.18	1.15	1.10	1.10	0.96	0.98	0.99	0.97	0.99	0.99	0.97	0.00	1.09	1.14	1.12	1.13	1.11	1.12	0.00	1.10	1.09			
	SPI:S1	1.05	1.10	1.05	1.05	0.95	1.00	0.90	1.02	0.93	1.02	1.00	0.96	0.97	0.94	0.95	0.95	0.94	0.94	0.94	0.94	0.94	0.00	0.99	0.99	0.98	0.98	0.97	0.99	0.00	0.97	0.96		
	Weekly%					24.09%							20.67%										20.12%									20.06%		
	Weekly EV					\$17,084							\$43,401										\$94,167									\$102,559		\$121,162
	Project KIT Existing (S2)	EV:S2	\$1,222	\$0	\$0	\$4,222	\$4,222	\$5,278	\$6,333	\$9,001	\$8,444	\$9,556	\$0	\$0	\$0	\$14,400	\$14,400	\$14,400	\$14,400	\$15,600	\$16,800	\$18,000	\$16,235	\$17,269	\$18,022	\$0	\$0	\$22,365	\$25,270	\$26,410	\$27,550			
AC:S2		\$1,199	\$2,732	\$3,605	\$4,807	\$4,807	\$6,008	\$7,210	\$8,412	\$9,613	\$10,815	\$12,017	\$13,218	\$14,420	\$14,090	\$14,090	\$14,090	\$15,265	\$16,439	\$17,613	\$24,267	\$23,027	\$22,145	\$22,766	\$24,844	\$26,008	\$28,119	\$31,436	\$32,517					
CV:S2		\$23	-\$2,732	-\$3,605	-\$584	-\$584	-\$731	-\$877	\$589	-\$1,169	-\$1,259	-\$12,017	-\$13,218	-\$14,420	-\$14,090	\$310	\$310	\$310	\$335	\$361	\$387	-\$8,032	-\$8,003	-\$5,005	-\$22,145	-\$22,766	-\$24,844	-\$3,643	-\$2,849	-\$5,026	-\$4,967			
SV:S2		\$111	-\$2,222	-\$3,333	-\$222	-\$1,333	-\$1,389	-\$1,444	\$112	-\$1,556	-\$1,556	-\$12,222	-\$13,333	-\$14,444	-\$15,556	-\$2,267	-\$3,378	-\$4,489	-\$4,400	-\$4,311	-\$4,222	-\$7,098	-\$7,175	-\$7,534	-\$26,667	-\$27,778	-\$28,889	-\$7,635	-\$5,841	-\$5,812	-\$5,783			
CPI:S2		1.02	0.00	0.00	0.88	0.88	0.88	0.88	1.07	0.88	0.88	0.00	0.00	0.00	0.00	1.02	1.02	1.02	1.02	1.02	1.02	0.67	0.68	0.78	0.00	0.00	0.00	0.86	0.90	0.84	0.85			
SPI:S2		1.10	0.00	0.00	0.95	0.76	0.79	0.81	1.01	0.84	0.86	0.00	0.00	0.00	0.00	0.86	0.81	0.76	0.78	0.80	0.81	0.70	0.71	0.71	0.00	0.00	0.00	0.75	0.81	0.82	0.83			
Weekly%						27.05%						20.69%										23.08%										20.42%		
Weekly EV						\$9,667						\$38,612										\$14,400										\$101,595		

		Day	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	
Project CHS Proposed (S1)	PV:S1&S2	\$34,444	\$35,556	\$36,667	\$37,778	\$38,889	\$40,000	\$41,111	\$42,222	\$43,333	\$44,444	\$45,556	\$46,667	\$47,778	\$48,889	\$50,000	\$51,111	\$52,222	\$53,333	\$54,444	\$55,556	\$56,667	\$57,778	\$58,889	\$60,000	\$61,111	\$62,222	\$63,333	\$64,444	\$65,556	\$66,667		
	EV:S1	\$33,500	\$34,700	\$35,900	\$37,100	\$38,300	\$39,500	\$40,700	\$41,900	\$0	\$44,300	\$45,500	\$46,700	\$47,900	\$49,100	\$50,300	\$51,500	\$52,700	\$53,900	\$55,100	\$56,300	\$57,500	\$58,700	\$59,900	\$61,100	\$62,300	\$63,500	\$64,700	\$65,900	\$67,100	\$68,300		
	AC:S1	\$30,600	\$31,700	\$32,800	\$33,900	\$35,000	\$36,100	\$37,200	\$38,300	\$39,400	\$40,500	\$41,500	\$42,600	\$43,700	\$44,800	\$45,900	\$47,000	\$48,100	\$49,200	\$50,300	\$51,400	\$52,500	\$53,600	\$54,700	\$55,800	\$56,900	\$58,000	\$59,100	\$60,200	\$61,300	\$62,400	\$63,500	
	CV:S1	\$2,900	\$3,000	\$3,100	\$3,200	\$3,300	\$3,400	\$3,500	\$3,600	-\$39,400	\$3,800	\$4,000	\$4,100	\$4,200	\$4,300	\$4,400	\$4,500	\$4,600	\$4,700	\$4,800	\$4,900	\$5,000	\$5,100	\$5,200	\$5,300	\$5,400	\$5,500	\$5,600	\$5,700	\$5,800	\$5,900	\$6,000	
	SV:S1	-\$944	-\$856	-\$767	-\$678	-\$589	-\$500	-\$411	-\$322	-\$233	-\$144	-\$56	\$33	\$122	\$211	\$300	\$389	\$478	\$567	\$656	\$745	\$834	\$923	\$1,012	\$1,101	\$1,190	\$1,279	\$1,368	\$1,457	\$1,546	\$1,635		
	CPI:S1	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	
	SPI:S1	0.97	0.98	0.98	0.98	0.98	0.99	0.99	0.99	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	
	Weekly%					20.04%						19.90%											20.02%									20.01%	
	Weekly EV					\$179,900						\$166,400											\$239,500									\$329,500	
	Project KIT Existing (S2)	EV:S2	\$28,600	\$29,650	\$0	\$0	\$0	\$0	\$35,950	\$37,000	\$38,050	\$39,100	\$40,150	\$41,200	\$42,250	\$43,300	\$44,350	\$45,400	\$46,450	\$47,500	\$48,550	\$49,600	\$50,650	\$51,700	\$52,750	\$53,800	\$54,850	\$55,900	\$56,950	\$58,000	\$59,050	\$60,100	\$61,150
AC:S2		\$33,784	\$35,020	\$36,256	\$37,492	\$38,728	\$39,964	\$41,200	\$42,436	\$43,672	\$44,908	\$46,144	\$47,380	\$48,616	\$49,852	\$51,088	\$52,324	\$53,560	\$54,796	\$56,032	\$57,268	\$58,504	\$59,740	\$60,976	\$62,212	\$63,448	\$64,684	\$65,920	\$67,156	\$68,392	\$69,628	\$70,864	
CV:S2		\$5,184	\$5,370	\$5,556	\$5,742	\$5,928	\$6,114	\$6,300	\$6,486	\$6,672	\$6,858	\$7,044	\$7,230	\$7,416	\$7,602	\$7,788	\$7,974	\$8,160	\$8,346	\$8,532	\$8,718	\$8,904	\$9,090	\$9,276	\$9,462	\$9,648	\$9,834	\$10,020	\$10,206	\$10,392	\$10,578	\$10,764	
SV:S2		-\$5,844	-\$5,906	-\$6,067	-\$6,228	-\$6,389	-\$6,550	-\$6,711	-\$6,872	-\$7,033	-\$7,194	-\$7,355	-\$7,516	-\$7,677	-\$7,838	-\$7,999	-\$8,160	-\$8,321	-\$8,482	-\$8,643	-\$8,804	-\$8,965	-\$9,126	-\$9,287	-\$9,448	-\$9,609	-\$9,770	-\$9,931	-\$10,092	-\$10,253	-\$10,414	-\$10,575	
CPI:S2		0.85	0.85	0.00	0.00	0.00	0.00	0.85	0.85	0.85	0.85	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	
SPI:S2		0.83	0.83	0.00	0.00	0.00	0.00	0.85	0.85	0.85	0.85	0.85	0.85	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	0.84	
Weekly%						19.10%						20.54%										19.78%										20.34%	
Weekly EV						\$58,250						\$111,000										\$159,200										\$52,600	

		Day	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90
Project CHS Proposed (S1)	PV:S1&S2	\$67,778	\$68,889	\$70,000	\$71,111	\$72,222	\$73,333	\$74,444	\$75,556	\$76,667	\$77,778	\$78,889	\$80,000	\$81,111	\$82,222	\$83,333	\$84,444	\$85,556	\$86,667	\$87,778	\$88,889	\$90,000	\$91,111	\$92,222	\$93,333	\$94,444	\$95,556	\$96,667	\$97,778	\$98,889	\$100,000	
	EV:S1	\$69,500	\$70,700	\$71,900	\$73,100	\$74,300	\$75,500	\$76,700	\$77,900	\$79,100	\$80,300	\$81,500	\$82,700	\$83,900	\$0	\$86,300	\$87,500	\$88,700	\$89,900	\$91,100	\$92,300	\$93,500	\$94,700	\$95,900	\$97,100	\$98,300	\$99,500	\$0	\$101,000	\$10		

For the Mann-Whitney U test: $U = n_1 \cdot n_2 + \frac{n_1(n_1+1)}{2} - R_1$ Eq.(2) , where n_1 and n_2 are sample sizes, and R_1 is the sum of ranks for the first group. For the Wilcoxon Signed-Rank test:

$$Z_score = \frac{W - \mu_w}{\sigma_w} \text{ Eq.(3), where:}$$

- I. W is the Wilcoxon test statistic (sum of signed ranks)
- II. $\mu_w = \frac{n(n+1)}{4}$ (expected mean under null hypothesis)
- III. $\sigma_w = \sqrt{\frac{n(n+1)(2n+1)}{24}}$ (standard deviation)

The p-value interprets the probability of obtaining results at least as extreme as those observed, assuming the null hypothesis is true. A p-value < 0.05 indicates statistical significance.

Effect size was calculated using Cohen’s d: $d = \frac{M_{diff}}{SD_{diff}}$ Eq.(4), where: M_{diff} is the mean of differences between pairs, and SD_{diff} is the standard deviation of these differences.

8.4.6.3.1 Descriptive Statistics

CPI and SPI were calculated daily (Table 6: CPI = EV/AC, SPI = EV/PV). Days with EV = 0 were excluded, giving 85 valid observations for GHS (S1) and 55 for KIT (S2). As seen in Table 8.10:

- IV. S1 (GHS): close to budget and schedule, low variability.
- V. S2 (KIT): indices consistently <1.00, indicating overruns, with high variability.

Table 8.10: Descriptive Statistics for CPI and SPI

Metric	Project	n	Mean	Std. Dev: Eq.(1)	Median
CPI	GHS (S1)	85	1.03	0.12	1.02
	KIT (S2)	55	0.87	0.29	0.90
SPI	GHS (S1)	85	1.02	0.11	1.01
	KIT (S2)	55	0.86	0.25	0.89

8.4.6.3.2 Impact of Missing Data

The effect of missing reports was tested by comparing CPI on days following a missing report

with all other days (Table 8.11):

Table 8.11: Mann-Whitney U Test on CPI (After Missing vs. All Other Days)

Project	Group	n	Median CPI	U statistic: Eq.(2)	p-value
GHS (S1)	After Missing	5	1.01	186.5	0.477
	All Other	80	1.02		
KIT (S2)	After Missing	18	0.79	262.0	0.006
	All Other	37	0.93		

- VI. For GHS (S1): Median CPI remained stable (1.01 vs 1.02), $U = 186.5$, $p = 0.477$. This non-significant result indicates no evidence that missing days distorted S1's performance reporting.
- VII. For KIT (S2): CPI dropped markedly (0.79 vs 0.93), $U = 262.0$, $p = 0.006$. The result indicates strong statistically significant evidence that missing data in S2 concealed deteriorating performance.

8.4.6.3.3 Daily Performance Comparison (51 Paired Days)

A direct comparison was made on the 51 days (n) shows both results (for CPI and SPI) confirm significantly stronger performance in S1, as follows (Table 8.12):

Table 8.12: Wilcoxon Signed-Rank Test on 51 Paired Days

Index	Median (S1)	Median (S2)	Z-score: Eq.(3)	p-value	Cohen's d: Eq.(4)
CPI	1.02	0.90	-4.72	<0.001	0.64
SPI	1.01	0.89	-4.86	<0.001	0.68

8.4.6.3.4 Analysis of Behaviour During a Delay Event (Days 33–37)

From Table 8.9, a significant delay occurred between Days 33 and 37. During this period, S1 captured detailed performance trends, whereas S2 reported no earned value ($EV = \$0$), rendering EVM-based forecasting impossible. This section dived into I) Regression analysis of SPI (S1); II) Cost and schedule Forecasting (EAC and TEAC); III) CPI and SPI Behaviour (Days 33–37); and IV) Managerial implications.

(i). Regression analysis of SPI (S1)

From Figure 8.14, SPI values for S1 declined steadily from 0.97 (Day 33) to 0.90 (Day 37). A linear regression model was fitted ($R^2 = 0.8705$ as: Independent variable (x) = Day number and Dependent variable (y) = SPI value, so regression equation is $y = \alpha + \beta x$, where

$$\alpha \text{ (intercept)} = \frac{(\sum y) - \beta \cdot (\sum x)}{n} \text{ and } \beta \text{ (slope)} = \frac{n(\sum xy) - (\sum x) \cdot (\sum y)}{n(\sum x^2) - (\sum x)^2}$$

$$\text{So } \beta = \frac{5 \times (165.03) - 175 \times 4.72}{5 \times 6135 - (175)^2} = -0.017 \text{ and } \alpha = \frac{4.72 - (-0.017)(175)}{5} = 1.539 \text{ then } R^2 = 0.8705$$

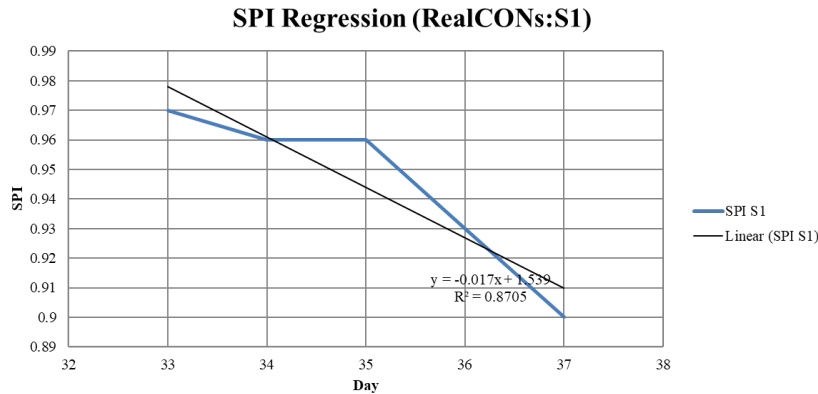


Figure 8.14: Regression analysis of SPI (S1)

This confirms a statistically significant downward trend, with SPI decreasing by ~0.017 units per day. Moreover, SPI was forecast to fall below the 0.87 threshold within three additional reporting days. For the project manager, this regression provides not only a snapshot of current performance but also a forward-looking forecast of when schedule slippage will cross critical limits.

(ii).Cost and schedule Forecasting (EAC and TEAC)

As illustrated in Figure 8.15, the absence of daily reports for project KIT between days 33 and 37 precluded the application of earned value forecasting techniques. Consequently, the quantification of potential cost and schedule outcomes was only performed for project GHS, utilising the RealCONs framework.

Projects	CPI: Day 37	EAC=\$100,000/CPI	SPI: Day 37	TEAC=90 Days/SPI
GHS (RealCONs)	1.03	\$100,000/1.03=\$97,087	0.90	100 Days
KIT (Existing)	-	-	-	-

$$\text{Estimate at Completion (EAC)} = \frac{BAC}{CPI} \text{ and } \text{Time Estimate at Completion (TEAC)} = \frac{\text{Planned Duration}}{SPI}$$

EAC suggests costs will remain within budget, indicating minimal financial risk. However, on day 37 (Schedule Performance Index, SPI = 0.90), the Time Estimate at Completion (TEAC)

forecasts a total duration of 100 days, a 10-day overrun. This implies:

- For GHS (S1): Cost efficiency (CPI \approx 1.03) masked schedule slippage (SPI fell from 0.97 to 0.90). The TEAC of 100 days implies 11.1% schedule overrun, necessitating proactive recovery measures.
- For KIT (S2): A complete work stoppage occurred between days 33–37 (EV=\$0, AC=\$1,483/day). Consequently, EAC and TEAC are incalculable. It means existing systems' EV fails, so it requires root-cause analysis (e.g., resource leveling, scope change) and urgent corrective actions like re-baselining or resource levelling to restore a positive SPI.

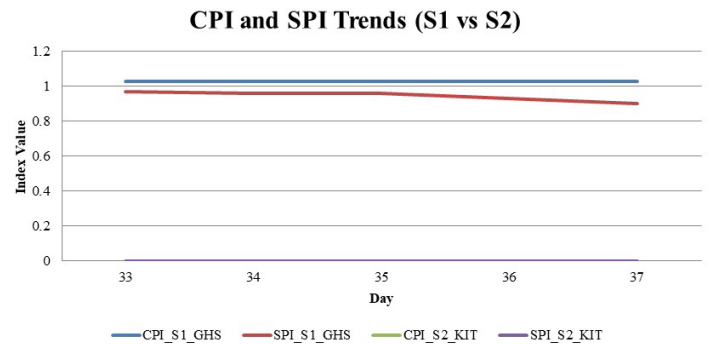
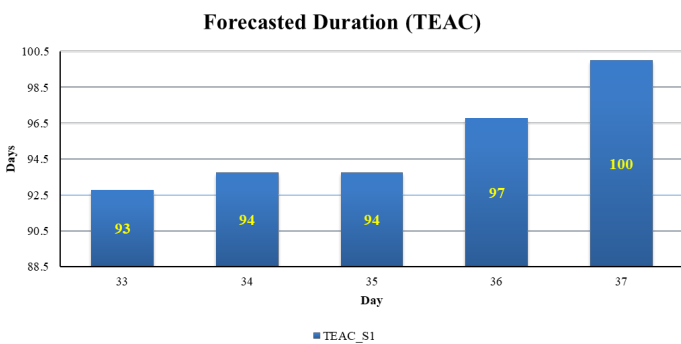


Figure 8.15: Forecasted Duration (TEAC)

Figure 8.16: CPI and SPI Trends (S1 vs S2)

(iii). CPI and SPI Behaviour: Days 33–37

The performance of the two projects diverged significantly. For GHS (S1), a resilient cost performance was maintained, with a stable CPI of 1.03 demonstrating that expenditure growth was contained relative to value earned (Figure 16). However, this masked a steady schedule erosion, where a monotonic decline in the SPI from 0.97 to 0.90 indicated progressively worsening delays, likely stemming from unresolved operational bottlenecks. In stark contrast, KIT (S2) experienced a complete performance breakdown, characterised by a catastrophic halt in progress. This is evidenced by a sustained SPI of zero for five consecutive days and an accumulation of actual costs to \$55,637.54 against zero earned value, confirming a total cessation of work that existing EVM frameworks failed to capture, necessitating immediate root-cause analysis and corrective intervention.

(iv). Managerial implications

The integration of regression analysis with Estimate at Completion (EAC) and Time Estimate at Completion (TEAC) allows project managers to anticipate risks more effectively (Table 13). By forecasting threshold breaches in the SPI, managers can quantify likely impacts such as a 10-day delay, prioritise corrective actions and communicate with stakeholders using statistically validated evidence. In this way, earned value metrics move beyond simple performance reporting and become predictive tools for decision-making.

Table 8.13: Managerial benefits of applying statistical techniques to S1 data

Technique	Analytical Insight	Managerial Benefit
Regression (SPI trend)	SPI declines by 0.017/day; threshold breach forecast	Early warning of schedule risk; enables preventive rescheduling
EAC (Cost forecast)	CPI = 1.03 so EAC \approx BAC (cost stability)	Confirms budget safety; allows focus on schedule recovery
TEAC (Time forecast)	TEAC = 111% of baseline and 10-day delay projected	Provides quantified estimate of delay; supports realistic replanning
	CPI stable, SPI variability = special cause	Confirms signals are reliable; justifies corrective intervention

A notable advantage of the S1 (RealCONs) system lies in its economic efficiency. Unlike the S2 framework, which incurs considerable administrative overhead in gathering daily reports, S1 reduces missing reports from 35 to just 5. This improvement lessens the reporting burden, cuts indirect costs, and strengthens cost performance, as reflected in its superior CPI.

8.5 Discussion

This study tackled the persistent challenge of monitoring Electrical and Instrumentation (E&I) works in complex, high-security construction projects, where traditional reporting systems often fail to provide the real-time insights required for effective decision-making [27]. While advanced technologies such as RFID [18], laser scanning [14], and digital twins [82] show considerable promise, their high costs and technical demands frequently preclude large-scale deployment. The RealCONs framework was developed to provide a practical and operationally viable alternative by synergistically combining ubiquitous QR code-based data capture, mobile devices, and live

cloud-based analytics. In contrast to existing planning and control methods such as the Last Planner System (LPS) [83], 4D/5D (BIM)[84], Digital Twin [85] and Critical Path Method (CPM) [86], RealCONs facilitates continuous, live tracking through dynamic dashboards directly linked to earned value metrics (SPI and CPI). This capability provides an early warning mechanism for delays and cost discrepancies, enabling a more agile response in fast-paced project environments.

The case study findings robustly demonstrated that data collected through the RealCONs framework (S2) was markedly more consistent and reliable than that derived from existing tracking system reporting (S1). The S2 dashboards showed stable CPI and SPI trends, whereas S1 data exhibited irregular updates and frequent gaps, undermining its reliability for proactive control. Furthermore, the Power BI visualisations were found to significantly improve communication across stakeholder groups by providing intuitive, zone-based, and task-specific clarity, thus enhancing collective situational awareness. As summarised in Table 14, a comparative analysis positions RealCONs favourably against established digital tools, highlighting its strengths in real-time monitoring, full life-cycle integration, and proactive delay detection.

Table 8.14: RealCONs Framework Vs Current Digital Tools

Digital Tool/Framework	Real-Time Monitoring	Early Delay Detection	Life-cycle Integration	Cost-Schedule Linkage	Adaptability	Limitations
RealCONs Framework [81]	✓ High	✓ Proactive	✓ Full life cycle	✓ Direct, automated	✓ High	Requires stable internet, authentication protocols
LPS [83]	✗ Manual	✗ Reactive	✗ Execution-focused	✗ Weak	✓ Moderate	Relies on facilitator discipline, no real-time data
4D/5D BIM [84]	✓ Static, Visual	✗ Limited	✓ Design-Execution	✓ Static, Visual	✓ Moderate	Labor-intensive updates, no dynamic cost tracking
Digital Twin [85]	✓ Dynamic	✓ Conditional	✓ Strong	✓ High fidelity	✗ Low	High setup cost, technical expertise required
CPM [86]	✗ Static	✗ post-facto	✓ Partial (Planning, Execution)	✗ Indirect	✗ Low	Poor adaptability to site changes, no real-time feedback

This study contributes a field-tested and scalable solution for the real-time monitoring of major construction projects, in this case focusing on E&I works. The RealCONs framework bridges a critical gap between field execution and project controls by linking on-site data capture

(via QR codes) with earned value metrics and interactive Power BI dashboards. This integration significantly improves project visibility, enables proactive delay management, and strengthens data-driven decision-making. The contributions of this work are threefold: (1) it delivers a live, QR-enabled tracking system, validated on real-world projects; (2) it provides a practical, deployable framework aligned with industry workflows; and (3) it demonstrates the successful integration of Earned Value Management (EVM) within a real-time digital monitoring system. A further novelty of RealCONs is its capability for daily site situation tracking a practice not yet commonplace in construction. Importantly, the framework is cost-effective, leveraging existing technologies through a novel, integrated data-driven approach. It requires minimal staff training (Only on Mobile App) and can be implemented rapidly, with only API connections and authentication permissions requiring initial configuration.

8.6 Research Limitations and Solutions

Although RealCONs delivered tangible operational benefits, its deployment surfaced some key constraints:

- **Connectivity dependency:** The system's reliance on stable internet connectivity meant that authentication failures or weak signal areas disrupted real-time data synchronisation, directly affecting reporting continuity. This underscores the need for offline or hybrid (online/offline) data capture capabilities — particularly in remote or infrastructure-constrained sites.
- **QR code accessibility:** Despite BIM-informed placement, physical damage, suboptimal positioning (e.g., vertical surfaces), or environmental exposure occasionally rendered QR codes unscannable — reducing field efficiency and highlighting the importance of durable, ergonomically placed markers.
- **API reliability:** Analysts noted vulnerability to API disconnections, which risked data flow integrity. Integrating passive data sources (e.g., automated sensor logs) alongside active QR-triggered inputs could enhance overall system robustness and continuity.

8.7 Conclusion and Future Research


This study has presented and validated RealCONs, a real-time, QR-enabled monitoring framework applied to critical building service works, specifically Electrical and Instrumentation (E&I) activities. By integrating mobile QR scanning, a cloud-hosted SQL database, and dynamic Power BI dashboards, the framework addresses long-standing challenges of manual reporting, delayed feedback, and fragmented project visibility. In practice, it delivered measurable improvements in schedule and cost control, demonstrated through stabilised CPI and SPI trends, while enabling early delay detection and continuous, transparent progress tracking without disrupting established workflows. From a theoretical perspective, RealCONs advances construction informatics by offering a hybrid model that connects BIM-based asset localisation with real-time analytics and stakeholder-oriented visualisation. Its architecture centred on mobile capture, centralised data integration, and visual dashboards, bridges the gap between on-site execution and digital oversight, particularly in coordination-intensive domains such as E&I works.

RealCONs has demonstrated strength in managing critical-path activities within high-security building projects, with electrical installations serving as an effective test case. Its principles are inherently adaptable and show strong potential for application in other domains such as heavy civil or structural works, where coordination and real-time oversight are equally valuable. The framework's design—built on widely available technologies and streamlined workflows, positions it well for broader deployment across diverse project environments. Importantly, early implementation highlighted that user training and intuitive design can accelerate adoption, with site staff recognising clear daily benefits once the system's ease of use and efficiency were demonstrated. These experiences underscore RealCONs' capability not only to deliver technical improvements but also to encourage cultural transition towards real-time, data-driven project management. Looking ahead, three directions for further research are particularly important.

First, embedding AI-driven analytics and integrating AI-enhanced Power BI functionality could expand the range and depth of decision-support dashboards. Second, developing offline capabilities would strengthen resilience in environments with unreliable connectivity. Third, deeper integration with enterprise platforms, combined with predictive analytics and machine learning, could extend RealCONs from a monitoring framework into a proactive, decision-support system. In sum, RealCONs offers a significant advance towards transparent, data-driven construction management. It enhances monitoring fidelity, supports timely managerial interventions, and establishes a scalable foundation for future innovations in real-time project control across the built environment.

STATEMENT OF CONTRIBUTION DOCTORATE WITH PUBLICATIONS/MANUSCRIPTS

We, the student and the student's main supervisor, certify that all co-authors have consented to their work being included in the thesis and they have accepted the student's contribution as indicated below in the Statement of Originality.

Student name:	Kambiz Rdaman		
Name and title of main supervisor:	Mostafa Babaeian Jelodar		
In which chapter is the manuscript/published work?	Chapter 9		
Describe the contribution that the student and members of the supervisory team have made to the manuscript/published work: ¹ Ratio of student to supervisory team 90:10, Student: Brought and Structured idea, Captured data, created model, Analysed, Drafted and Finilised Text Supervisory team: Conducted Study, Improved conceptual model, Reviewed and Finilised Text			
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Chapter 9: OPTIMISING DELAY MANAGEMENT IN CONSTRUCTION PROJECTS

The current chapter is based on the following article:

Radman, K., Jelodar, M. B., Lovreglio, R. (2024). Optimising Delay Management: A Comparative Analysis of the Novel SMART Framework Using Early-Stage Delay Indicators. *Journal of Construction Engineering and Management*, ID: JCEM-D-25-00505



Under Review with Journal of Construction Engineering and Management

Objective should be covered;

OBJ_5: Evaluate the Proposed Framework

9.1 SUMMARY

Delay management techniques are essential for achieving project success in terms of time, budget, and quality. Practical delay analysis is key to maintaining project schedules, controlling costs, managing risks, and improving future project efficiency. Traditional techniques such as Time-Impact Analysis (TIA) and As-Planned vs As-Built are commonly applied in construction projects. However, selecting the most appropriate delay analysis method must consider critical factors like real-time delay analysis, data accuracy, software functionality, real-time notifications, and concurrent delay analysis. This article introduces the RealCONs as a novel data-driven SMART (Simple, Measurable, Analysable, Real-Time) framework for real-time project tracking and early-stage delay identification. Using the Analytic Hierarchy Process (AHP), the study evaluates five key criteria, accuracy, real-

time data integration, flexibility, predictive analysis, and stakeholder communication, to compare RealCONs with traditional delay management approaches. By using a case study, the RealCONs' framework demonstrated superior performance, achieving a Schedule Performance Index (SPI) of 0.88 compared to 0.80 for the traditional approach, indicating better schedule adherence. Additionally, the Cost Performance Index (CPI) for RealCONs was 1.11, significantly outperforming the traditional method's CPI of 0.89, reflecting better cost efficiency. Key stakeholders, such as contractors, subcontractors, and consultants, utilise the framework to monitor progress, address potential delays proactively, and enhance communication. These findings highlight the advantages of RealCONs in mitigating delays and improving overall project control through real-time performance tracking.

9.2 INTRODUCTION

The duration of contract performance is a pivotal factor influencing the profitability of construction projects for all stakeholders. Project owners experience financial losses when projects are delayed and cannot be utilised as planned, while contractors face escalating costs due to extended periods of on-site work. These delays disrupt project timelines and strain relationships between stakeholders, often leading to disputes and financial penalties. Standard construction contracts address delays through provisions that classify them based on causation—whether attributable to contractors, owners, or uncontrollable external events. These contracts often include clauses that allow contractors to seek extensions or compensation for excusable delays and empower owners to claim liquidated damages for non-excusable delays [1, 2].

Despite including such provisions, delay claims remain a persistent and contentious issue in the construction industry. Resolving these claims necessitates detailed schedule analysis to

identify the causes of project overruns and assess their implications. However, even with established Delay Analysis Techniques (DATs), disputes surrounding delays escalate into costly legal conflicts. The challenges inherent in delay claims make them one of the most complex aspects of construction project management [2, 3].

This study introduces a novel RealCONs' SMART (Simple, Measurable, Analysable, and Real-Time) Framework. It evaluates its performance compared to existing approaches, using a chosen delay analysis method to address key criteria for real-time project status analysis in early-stage delay notifications. RealCONs is SMART as it is "Simple" because it enables users to focus on specific and achievable planning goals for efficient project management; "Measurable" because it ensures users can accurately track and measure progress toward project goals, allowing for data-driven decisions; The "Analysable" component of RealCONs systematically aligns performance metrics (e.g., SPI, CPI) with strategic goals, leveraging predictive analytics to identify inefficiencies and drive data-led decisions, enabling proactive risk mitigation and resource optimisation. Finally, it is "Real-Time" because it ensures timely notifications to key project stakeholders, facilitating proactive measures to avoid/mitigate delays and risks and enabling prompt decision-making. By integrating early-stage delay notification indexes with advanced analytical techniques, the framework seeks to enhance delay management accuracy, flexibility, and efficiency. The study aims to provide a robust methodology for resolving delay claims and improving project outcomes through a comprehensive comparative analysis of traditional and real-time delay analysis approaches.

9.3 RESEARCH BACKGROUND

Delay management in construction has long been a focus of researchers and practitioners, reflecting the complexity of delay causes and the high stakes involved. Delay analysis seeks to

determine the extent of project delays, identify causative factors, and attribute responsibility for their occurrence. This process facilitates decision-making regarding time and cost compensation. Key questions in delay analysis revolve around comparing planned schedules with actual progress, identifying discrepancies, and assessing their impact on project outcomes.

Delay Analysis Techniques (DATs) can be broadly categorised into Critical Path Method (CPM)-based and non-CPM-based approaches. Popular techniques include As-Planned vs. As-Built, Windows Analysis, Time Impact Analysis (TIA), and Collapsed As-Built methods [4, 5]. Each technique offers unique perspectives and methodologies, yet they share common challenges, such as data reliability, subjectivity, and applicability under varying project conditions. Delays in construction projects are typically classified into three primary types [6]:

- Excusable Compensable Delays (EC): Delays entitling contractors to both time extensions and cost compensation, typically arising from owner-related issues or other compensable events.

- Excusable Non-Compensable Delays (EN): Delays resulting from uncontrollable external factors, such as natural disasters, which excuse performance delays but do not warrant compensation.

- Non-Excusable Non-Compensable Delays (NN): Delays attributable to contractors result in time and cost penalties.

Understanding these classifications is critical for selecting appropriate DATs and aligning them with contractual provisions. However, Prominent industry guidelines, such as the UK Society of Construction Law's Delay and Disruption Protocol (SCL Protocol) and the Association for the Advancement of Cost Engineering International's Recommended Practice 29R-03 (AACE RP-29R-03), provide structured methodologies for delay analysis. These documents distinguish between two main approaches [7, 8]:

1) **Prospective Analysis:** Conducted during project execution as recommended by the SCL Protocol. This approach evaluates the potential impact of delays as they occur, enabling real-time mitigation strategies. Techniques like Time Impact Analysis (TIA) and Impacted As-Planned analysis fall within this category [9, 10] and are recommended by The SCL Protocol.

2) **Retrospective Analysis:** Applied post-event recommended by AACE RP-29R-03. Retrospective analysis uses historical data to assess the actual impact of delays. Methods such as Windows Analysis and As-Planned vs. As-Built analysis are widely used for forensic evaluations [11, 12].

While both approaches have their strengths, retrospective methods are often considered more reliable due to actual data availability. However, they lack the real-time applicability crucial for proactive delay management. Moreover, The SCL Protocol acknowledges that no single method works for all situations and lists six commonly used delay analysis techniques: a) Impacted As-Planned Analysis, b) Time Impact Analysis, c) Time Slice Window Analysis, d) As-Planned versus As-Built Window Analysis, e) Retrospective Longest Path Analysis, and f) Collapsed As-Built Analysis. Except for the retrospective most prolonged path analysis, these methods are also mentioned in RP 29R-03 [13-16].

In this study, the judiciary has commented on the strengths and Limitations of each method over time and tested it in court. However, literature reviews often support using specific methods while dismissing others. As a result, it remains unclear which of these six methods is most used in practice for retrospective delay analysis [17, 18]. Figure 1 presents a statistical analysis of the frequency of these techniques, highlighting major trends and discussing why some methods have gained or lost popularity over the past decade [19, 20].

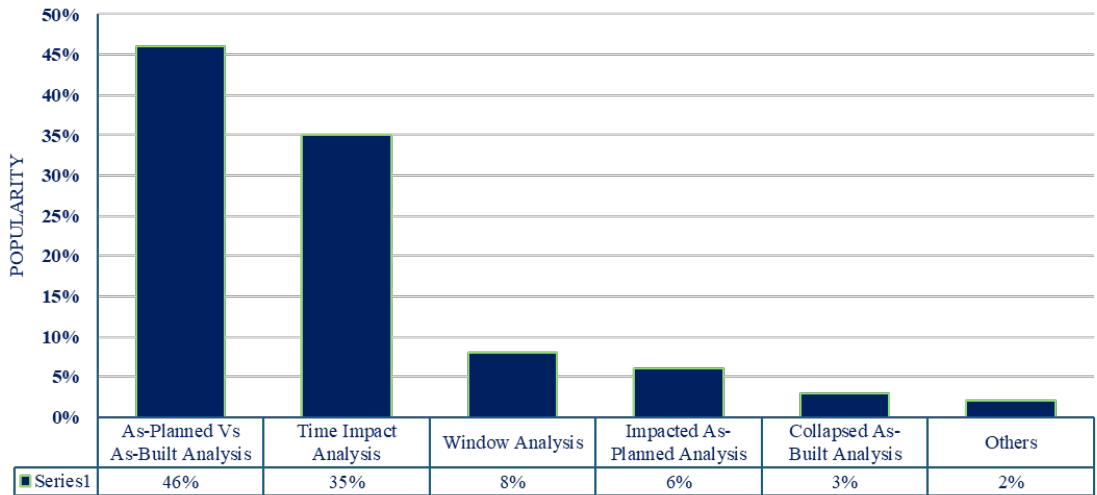


Figure 9.1: Delay Analysis Methods between 2010 and 2024

The statistical analysis reveals that all six methods outlined in the SCL Protocol and ACE RP29R-03 were used between 2010 and 2024. Figure 1 indicates that As-Planned vs As-Built Analysis is the most dominant technique (49%), followed by Time Impact Analysis (TIA) and Window Analysis. In comparison, methods like Impacted As-Planned and Collapsed As-Built (total 11%) are used less frequently. Other delay analysis methods were used in only 2% of cases, and these could include less formal or unconventional approaches to delay analysis.

The following four methods, which are widely used, are explained in Table 9.1, along with some of the limitations identified by [7, 21-23]. Table 9.1 outlines four principal methods for analysing delays in project management, each with distinct features, constraints, and applications. The Windows Analysis Method evaluates delays by dividing the project into defined periods comparing actual progress against the original schedule through periodic updates. While effective for identifying cumulative delays in projects with frequent schedule revisions, it demands comprehensive records and consistent updates and may yield variable results depending on period selection [9, 16, 24]. The Time Impact Analysis focuses on individual delay events by integrating real-time schedule updates and Critical Path Method (CPM) assessments, using 'fragments' to model impacts. Though precise for legal disputes, it

becomes impractical with numerous delays and relies on regularly updated schedules [25]. The Impacted As-Planned Analysis retrospectively assesses delays by inserting them as activities into the original CPM schedule, offering a cumulative impact evaluation. However, relying on a static baseline schedule limits its effectiveness for complex, multi-delay scenarios [26, 27]. Lastly, the As-Planned vs. As-Built Analysis compares planned and actual timelines, identifying total delays but lacking granularity in distinguishing critical path impacts or individual event contributions. While straightforward for contractual evaluations, its aggregated approach overlooks nuanced schedule dynamics. Collectively, these methods serve varied contexts, from real-time assessments to retrospective claims, balancing detail, practicality, and analytical depth.

Table 9.1: TIA popular methods at the glance

Method	Description	Limitations	Key Characteristics	Applicability
Windows Analysis Method [6, 7, 28, 29]	Assess delays by periodically updating the project schedule at specific phases and comparing actual progress with the original plan.	(i) Time-consuming and costly (ii) Requires complete and accurate project records (iii) Results vary with different period selections (iv) Periodic updates are required, or a detailed project record review is needed	Divides project into time periods; compares actual progress with the original plan; updates schedule at defined intervals.	Used in projects with frequent schedule updates; suitable for identifying progressive delay impacts over time.
Time Impact Analysis [6, 7, 30-32]	It focuses on the impact of individual delay events by updating the schedule for each significant delay and calculating the new completion date.	(i) Becomes impractical with many delay events (ii) Time-consuming due to detailed analysis (iii) If a programme is not updated regularly, delay analysis from records takes time	It uses 'fragments' to model delay impact, applies real-time Critical Path Method (CPM) analysis, and focuses on individual delay events.	Best suited for projects requiring real-time delay assessment; commonly used in legal disputes and claims.
Impacted As-Planned Analysis [5, 7, 16, 33, 34]	Evaluates delays by adding them as activities to the original CPM schedule, assessing their impact on the project timeline.	(i) The baseline schedule is not realistic for complete project analysis (ii) Concurrent or multiple resource delays are difficult to manage (iii) Uses a fixed as-planned programme only	Integrates delays as activities in the original schedule; assesses cumulative impact; applied during and after the project.	Ideal for forensic delay analysis; often applied retrospectively to assess overall project impact.

As Planned vs. As-Built Analysis [5, 7, 16, 33, 34]	Compare the initially planned schedule with the actual as-built schedule to determine the overall impact of the delay.	(i) Does not analyse types of delays (ii) Overlooks changes on critical paths (iii) Aggregates all delays without distinguishing critical or non-critical path delays (iv) Does not assess individual delay impacts on project completion	Direct comparison between planned and as-built schedules; identifies total delay impact but lacks detailed event analysis.	Functional for high-level project performance evaluation; commonly used in contractual disputes and claims analysis.
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Despite numerous advancements, the growing global population has increased the demand for construction projects, particularly large-scale infrastructure developments. This surge has intensified the need for construction projects to be executed with greater accuracy, flexibility, and efficiency [35, 36]. However, construction projects face significant challenges, including delays, disruptions, budget overruns on resources and materials, and safety concerns [37-39]. These challenges highlight the necessity for real-time data acquisition, effective project analysis—especially regarding delays and disruptions—and innovative solutions to transform traditional construction management practices [40-42]. Construction projects operate in a highly competitive environment where stakeholders, such as head contractors, subcontractors, and consultants, demand optimal outcomes within specified budgets and timelines. Efficiency and predictive analysis related to cost-effectiveness and resource planning are critical factors for project success [43, 44]. In Table 2, based on previous studies, five standard and essential criteria (accuracy, real-time data, flexibility, predictive analysis and stakeholder communication) for successful construction projects can be identified as follows:

Table 9.2: Descriptions of Criteria

Criteria	Description	Reference
<u>Accuracy</u>	<ul style="list-style-type: none"> • Reliable Project Execution: Accurate data is essential for creating precise project schedules, cost estimates, and resource allocation plans. This reduces the risk of errors that can lead to delays, cost overruns, and misallocation of resources. • Dispute Resolution: Precise data helps identify responsibility for delays or cost increases, which is critical in avoiding and resolving stakeholder disputes. 	[45-47]

<u>Real-time Data</u>	<ul style="list-style-type: none"> • Timely Decision Making: Access to real-time data allows project managers to make informed decisions quickly, vital for mitigating risks and addressing issues as they arise. • Proactive Problem Solving: Continuous data flow ensures that potential delays or cost increases can be identified and addressed in real-time, improving the likelihood of project success. 	[20, 48-50]
<u>Flexibility</u>	<ul style="list-style-type: none"> • Adaptability to Changes: Construction projects often face unpredictable challenges. A flexible framework allows for schedule adjustments, resources, or strategies without causing significant disruptions. • Customisation: Flexibility allows for tailoring the project approach to suit unique requirements, whether related to scope changes, unforeseen delays, or varying project conditions. 	[51-53]
<u>Predictive Analysis</u>	<ul style="list-style-type: none"> • Anticipating Risks: Predictive analysis uses historical data and patterns to forecast potential delays, budget overruns, or resource shortages, helping to prevent issues before they occur. • Optimising Resource Use: Predictive tools help allocate resources more effectively, ensuring that projects remain on schedule and within budget. 	[14, 54, 55]
<u>Stakeholder Communication</u>	<ul style="list-style-type: none"> • Transparency and Accountability: Effective stakeholder communication ensures that everyone is informed about project progress, challenges, and changes. These fosters trust and ensure alignment with project goals. • Efficient Collaboration: Clear communication channels help avoid misunderstandings and ensure that all parties are working toward the same objectives, reducing the risk of delays caused by miscommunication. 	[56-58]

In broader studies, delay analysis can be conducted using various methods, with the choice of method influenced by factors such as project nature, contractual requirements, data availability and reliability, and time constraints. This paper introduces a novel process-based, real-time, data-driven framework for delay management adaptable to different delay analysis methods. The study aims to identify the specifications and limitations of commonly used delay analysis methods when integrated with real-time concepts to address challenges in resolving delay claims. The proposed framework is evaluated through selected delay analysis methods within the framework and traditional approaches. A case study is detailed in the following sections to illustrate a clear comparison between the real-time framework and conventional methods using the same delay analysis approach.

9.4 METHODOLOGY

Evaluation of RealCONs' performance in comparison to existing approaches, using a chosen delay analysis method to address key criteria for real-time project status analysis in early-stage delay notifications is the current research core objective. For this purpose, this section outlines the methodological framework employed in this study, divided into three main approaches:

- 1) Delay Analysis Method Selection Approach: This section presents a decision-making process using pairwise comparisons to rank delay analysis methods based on input from contractors and consultants, identifying the most suitable method for construction projects (section 3.1).
- 2) The Proposed RealCONs as a SMART Framework: This section introduces RealCONs, a real-time, data-driven framework designed to enhance delay analysis and early-stage notifications aligned with industry standards (section 3.2).
- 3) Verification via Case Study: This section evaluates RealCONs through a case study, comparing its performance with traditional delay analysis methods (section 3.3).

9.4.1 Delay Analysis Method Selection Approach

The study utilises the Analytic Hierarchy Process (AHP) as a decision-making tool to rank alternative delay analysis methods. AHP was chosen over other methods due to its ability to handle complex decision-making scenarios in a structured and transparent manner. Unlike other multi-criteria decision-making techniques, AHP incorporates both quantitative and qualitative criteria, making it ideal for evaluating delay analysis methods involving diverse stakeholder perspectives and varying levels of importance across criteria [59, 60].

AHP's pairwise comparison approach ensures a clear prioritisation of alternatives while reducing subjectivity, which is crucial for achieving consensus among stakeholders like contractors, subcontractors, and consultants. Additionally, AHP provides a consistency check, ensuring that decisions are logical and reliable features that other methods, such as weighted scoring or simple ranking, may lack. These strengths make AHP particularly suited for this research's aim to select the most appropriate delay analysis method robustly and defensibly [61, 62]. In contrast, determining the appropriate sample size for conducting the AHP in survey-based research is crucial for ensuring the reliability and validity of the findings. From literature reviews [63], sample sizes for AHP applications can vary widely; therefore, while there is no strict rule, a sample size of 15–50 participants is commonly used in AHP studies. In this research, depending on the scope and complexity of the decision-making process and the diversity of the stakeholder groups, AHP facilitates pairwise comparisons of methods against key criteria, integrating expert insights from workshops involving 15 industry professionals: 5 head contractors, five subcontractors, and five consultants (Figure 9.2). The following four steps address the current approach (3.1) classifications:

- Step 1- Criteria Identification: Five key criteria (accuracy, real-time data integration, flexibility, predictive analysis, and stakeholder communication) were selected based on literature review and industry consultation. The total data points captured were include:

$$15 \text{ participants per workshop} \times 3 \text{ Workshops} = 45 \text{ total participants}$$

- Step 2- Pairwise Comparisons: Participants ranked the relative importance of those criteria and delay analysis methods (Windows Analysis, Time Impact Analysis, Impacted As-Planned, and As-Planned vs. As-Built) using a structured scale. Therefore, the number of comparisons for each criterion was calculated using the formula for pairwise comparisons $\frac{n(n-1)}{2}$, where n was the number of alternatives (n = 4 is the

number of delay analysis methods), so

$$\text{Comparisons per criterion} = \frac{4(4 - 1)}{2} = 6$$

Therefore, for each participant, six comparisons were made for each of the five criteria:

$$\frac{\text{Comparisons}}{\text{Criterion}} \times 5 \text{ Criteris} = 30 \text{ Comparisons per participant}$$

The total comparison across all workshops is 1350 comparisons:

$$45 \text{ Participants} \times \frac{45 \text{ Comparisons}}{\text{Participant}} = 1,350 \text{ Comparisons in total}$$

However, participants rated each alternative against every other alternative for each criterion. For this purpose, use a scale from 1 (equal importance) to 9 (extremely more critical). The results were structured into matrices.

- Step 3- Data Analysis: Pairwise comparison matrices were normalised to calculate priority weights for each criterion and delay analysis method. For this purpose, the average of each row was calculated to determine the priority weights to determine their relative importance or preference. In preparing for the final ranking, the priority weights from all participants were aggregated to get an overall ranking of the delay analysis methods for each criterion.
- Step 4- Final Ranking: Methods were scored by multiplying criterion weights by method ratings, and Time Impact Analysis emerged as the most suitable method

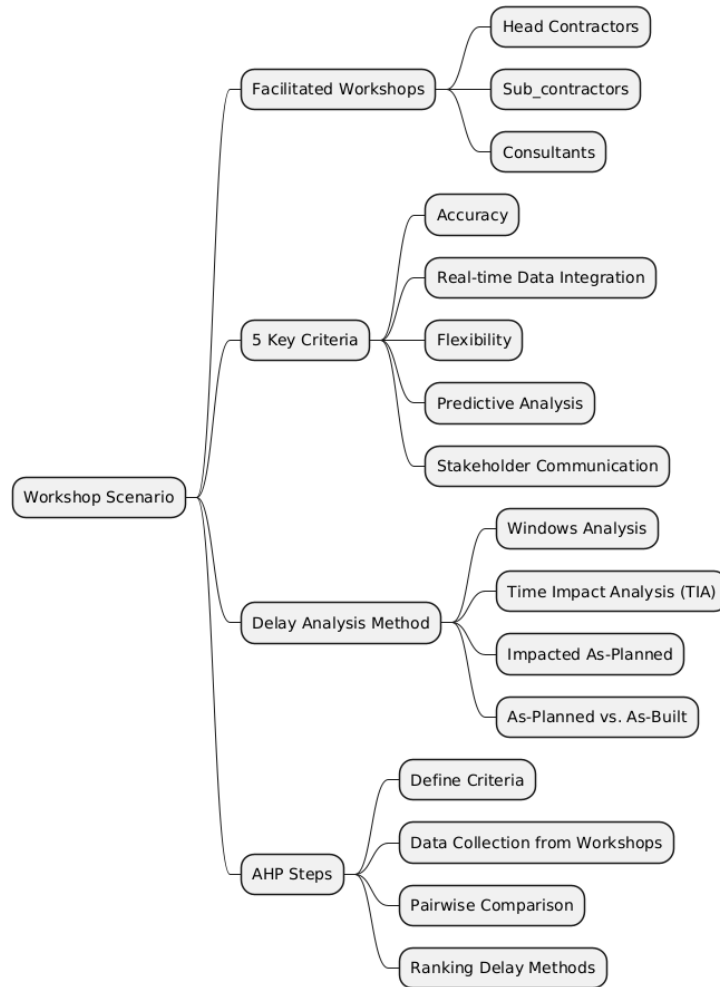


Figure 9.2: Mind map of facilitated workshop scenario

9.4.2 The Proposed Framework-RealCONs

RealCONs was proposed and developed as a SMART framework for this study based on the needs identified from previous literature and expert opinions gathered in the previous stage of the methodology to address limitations in traditional delay management methods by integrating real-time data and predictive analytics. Moreover, the RealCONs' framework integrates multiple tools and systems to enhance project management, communication, and data analysis in construction projects. The following steps map the structure:

- Step 1- Data Collection: On-site data is captured using QR codes scanned by construction supervisors by smart devices.
- Step 2- Integration: the site's real-time data flows into a central SQL server and integrates with tools like BIM, Oracle_P6, Oracle Aconex and Power BI via Application Programming Interfaces (APIs). So, APIs, rules, and protocols allow different applications to communicate. APIs enable the integration of systems, allowing them to exchange data and perform tasks without needing detailed knowledge of each system's internal workings.
- Step 3- Analytical Reporting System: This step involves predictive analysis to identify potential delays by utilising earned value metrics, including SPI, CPI, CV, and SV (Table 9.3). These metrics help monitor project status and mitigate the risk of delays at an early stage, addressing both timeline and cost concerns.
- Step 4 – Visualisation: This step focuses on data modelling to create graphical reports based on the analyses from Step 3, enhancing understanding and observation. By running M codes and mixed queries, a real-time and robust data model is established in Power BI, enabling the development of dynamic dashboards for stakeholders, such as project managers and other key parties.
- Step 5- Decision-Making Support: Early delay warnings enable proactive actions like resource reallocation and task re-sequencing to save unproductivity costs and delays on project milestones completion date.

Table 9.3 [64] delineates Earned Value Management (EVM), a framework for assessing project performance against baselines. Central to this analysis are three foundational measures: Planned Value (PV), defined as the Budgeted Cost of Work Scheduled (BCWS), which

represents the authorised expenditure for activities planned within a specific timeframe; Actual Cost (AC), termed the Actual Cost of Work Performed (ACWP), reflecting the actual costs incurred for completed work; and Earned Value (EV), denoted as the Budgeted Cost of Work Performed (BCWP), quantifying the budgeted value of work accomplished.

Table 9.3: Earned Value Metrics

Parameters	Formula	Warning Indexes
Schedule Variance (SV)	$SV = EV - PV$	If $SV < 0$ means $PV > EV$
Cost Variance (CV)	$CV = EV - AC$	If $CV < 0$ means $AC > PV$
Cost Performance Index (CPI)	$CPI = EV / AC$	CPI =1: on budget CPI >1: Under budget CPI <1: Over budget
Schedule Performance Index (SPI)	$SPI = EV / PV$	SPI =1: on schedule SPI >1: ahead of schedule SPI <1: Behind schedule
Estimate At Completion (EAC): PV of whole project/CPI	$EAC = PV / CPI$	
Estimated time To Complete (ETC)	$ETC = \text{Original time} / SPI$	

Derived from these metrics, Schedule Variance (SV) measures temporal deviation by comparing EV to PV ($SV = EV - PV$), where positive values indicate progress ahead of schedule, while negative values highlight delays. Similarly, Cost Variance (CV) evaluates financial performance by contrasting EV with AC ($CV = EV - AC$), with positive results signalling cost efficiency and negative figures denoting budget overruns. The Cost Performance Index (CPI), calculated as EV/AC , and the Schedule Performance Index (SPI), expressed as EV/PV , provide dimensionless ratios to assess efficiency. A $CPI > 1.0$ signifies cost-effective execution, whereas an $SPI > 1.0$ indicates accelerated progress. These indices and variances collectively facilitate predictive analysis, enabling project managers to refine forecasts for completion timelines and final expenditures, thereby supporting data-driven decision-making in project governance.

To find the loops among those four steps, Figure 9.3 illustrates how the construction supervisor scans QR codes and sends data to the SQL Server while other systems, such as BIM,

Oracle P6, and Oracle Aconex, communicate with Power BI via API. Finally, Power BI will visualise and analyse the data. Moreover, Power BI_User reflects project key decision makers such as project managers, project analysts/planners, and key strategic stakeholders.

In Figure 9.3, APIs ensure efficient data exchange between platforms like BIM, Aconex, P6, and Power BI, enabling real-time updates and analysis. Additionally, the Construction Site system gathers real-time data using smartphones and QR codes, storing this data in an SQL database that connects to Power BI for advanced reporting and visualisation. This integrated structure enhances project tracking, resource management, and performance analysis, providing a comprehensive solution for managing complex construction projects.

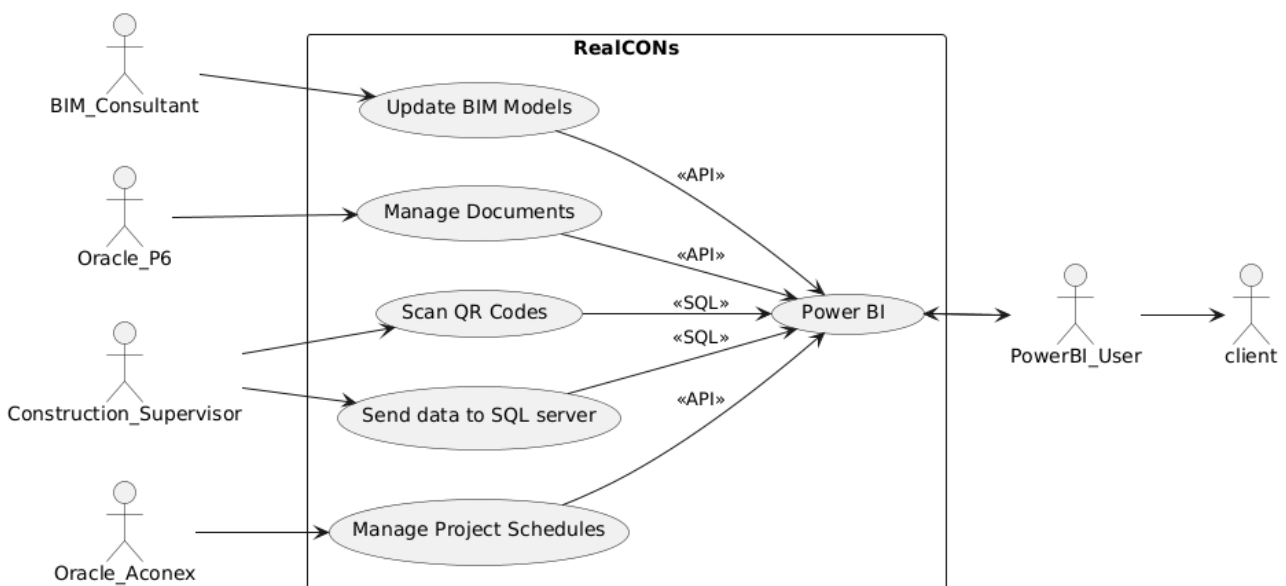


Figure 9.3: RealCONs' framework' uses case diagram between different users

To implement the purpose of steps 3 and 4 (section 3.2), Figure 9.3, a use case diagram illustrates how site supervisors scan QR codes, with data being sent to the SQL Server, while other tools such as BIM, P6, and Aconex communicate with Power BI via APIs. Finally, the analytical dashboard (Power BI) analyses and visually presents reports. In other words, Figure 9.3 consists of five actors (Act1–Act5) and two components (Com1 and Com2), as described below:

Actors	<p>Act1. Construction_Supervisor: All site supervisors are authorised to use smartphones. They use smartphones to scan QR codes to collect actual data from the site.</p> <p>Act2. BIM_Consultant: The engineering and design team, who access the system to review and work with building information models (BIM), such as Revit and Navisworks.</p> <p>Act3. Project Scheduler (Oracle_P6): Project planners, schedulers, and analysts who manage project schedules and timeline tracking using Primavera (P6).</p> <p>Act4. Document Manager (Oracle_Aconex): The head contractor provides all subcontractors with access to upload files, and this role manages project-related documentation.</p> <p>Act5. Power BI User: End users, such as project managers, analysts, and key decision-makers, can access visualised reports. For security purposes, all authorised end users have read-only access to the visualised dashboard, except for project schedulers or analysts, who have full access to develop, modify, and provide reports through Power BI.</p>
*****	<p>*****</p> <p>Com1) SQL Server: As a centralised data repository, information from QR code scans is collected and transferred to Power BI for real-time analysis.</p> <p>Com2) API Connections: Enable seamless data exchange between Power BI and external platforms, including Oracle P6, Oracle Aconex, and BIM.</p>
System Components	

Moreover, a sequence diagram (Figure 9.4) illustrates the interactions between system components (SQL Server and API Connections) and users/actors (Construction_Supervisor, BIM_Consultant, Project_Scheduler, Document_Manager and Power_BI User). In this case, API_Systems is representative of Act2, Act3 and Act4.

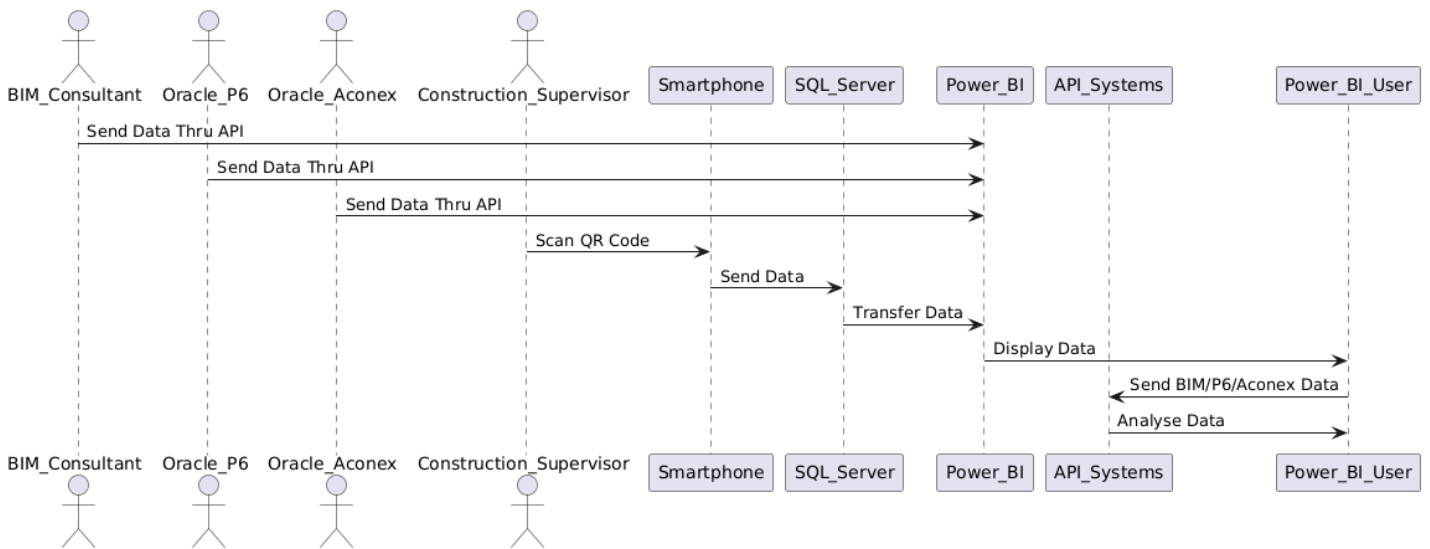

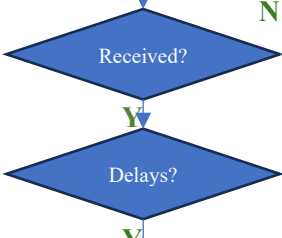


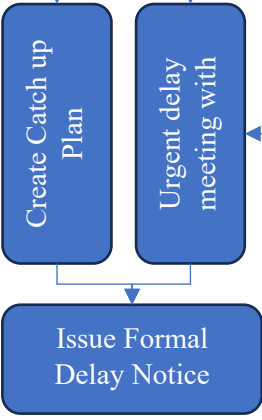


Figure 9.4: RealCONs' framework' sequence diagram

Table 9.4 outlines the general view of the methodology of the RealCONs' framework, detailing the process from data collection to verification and reporting, compared to the traditional approach. It includes a flowchart accompanied by an explanation for each step. The

following section of this article explores how the RealCONs' framework addresses critical factors in selecting appropriate delay analysis methods and how early-stage delay notifications can be effectively implemented.

Table 9.4: General View of Methodology

Flowchart	RealCONs' framework	Traditional Approach
	<p>Real-time data is collected using smartphones to scan QR codes at construction sites.</p>	<p>Relies on supervisors submitting site progress and status data via paper forms.</p>
	<p>All data is recorded promptly, and project stakeholders are notified if reports are not received, using SQL server and Power BI for dynamic tracking.</p>	<p>Reports are manually counted, recorded, and entered into Excel for analysis, with missing reports followed up only after they are noticed.</p>
	<p>It uses Power BI to analyse real-time site data and integrates it with data from the project schedule, consultants, and client feedback. This enables the project manager (PM) to accurately monitor resource usage (burned hours vs. planned hours) and conduct critical path method (CPM) analysis, receiving visual alerts for any delays or potential issues.</p>	<p>Data is manually cleaned in Excel, and Excel-based dashboards are used to track resource usage and earned value metrics like SPI and CPI. The absence of direct links between site reports and the project schedule results in manual updates and less accurate CPM analysis. Missing data and late entries further reduce analysis reliability, forcing the PM to manually assess delays and justify them.</p>
	<p>Automatically issues warnings when the project completion (PC) date slips.</p>	<p>PC date changes must be monitored manually, and programme updates and PM notifications occur later.</p>
	<p>When the PC date changes, the PM conducts a root cause analysis of delays and presents a catch-up plan to the head contractor. This plan includes details on slippage, affected tasks, labour costs, and critical path impacts. The issue is escalated quickly, enabling subcontractors to facilitate formal delay notifications via Aconex.</p>	<p>The PM develops a catch-up plan and root cause analysis, but data inaccuracies lead to conservative reporting to the client. The documentation is lodged through Aconex, requiring frequent follow-up by subcontractors, with response delays from the head contractor often causing further delays.</p>

9.4.3 Verification via case study

The framework was tested using a real-world construction project: a two-single-story mental health hospital in New Zealand. Table 9.5 depicts the details of the case study. The project involved comparing RealCONs and traditional approaches using the selected TIA method. The following steps map the structure:

- Step 1- Baseline Programme: An as-planned schedule with 14 tasks over 40 working days was established.
- Step 2- Delay Events: Five delays (e.g., 7-day finish delay for concrete pouring) were analysed for RealCONs' framework and the traditional approach. Figures 6(B1) and 6(B2) illustrated as-built programmes.
- Step 3- Comparison:
 - o Traditional Approach: Manual delay insertion and reactive adjustments.
 - o RealCONs' framework: Real-time data integration and proactive mitigation strategies.
- Step 4- Metrics Evaluated:
 - o Schedule Performance Index (SPI)
 - o Cost Performance Index (CPI)

Table 9.5: Depicts the details of the case study

Aspect	Details
Project Overview	A mental health hospital (MH1) about 1100 x 1100 m ² : two single-story buildings connected by a covered walkway.
Total Duration and Value	9 months, with completion expected in February 2025 for \$195 million.
Project Phases	- Phase 1: "Building A – Storage Room" (includes the project's critical path highlighted in red). - Phase 2: "Storage Driveway."
Case study trade and area	Electrical and Instrument works in Phase 1
Phase 1- Programme Details	40 working days (55 calendar days)
Notes	- Figure 9.5 presents a schematic 3D Revit model of MH1

	<ul style="list-style-type: none">- Figure 9.6(A) highlights critical tasks in red, the baseline in grey, and non-critical tasks in dark blue. Figure 9.6(A) is a cut section of the Phase 1 planned programme, including 40 working days and 14 tasks.- Figure 9.7 illustrates the case study network diagram.
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As a result, the case study and verification step followed the general methodology presented in Table 9.4 (section 3.2).

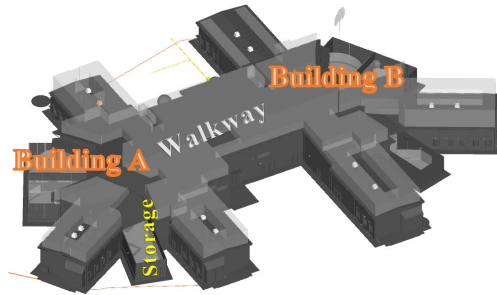


Figure 9.5: 3D view of MH1 (2x buildings and 1x walkway in middle)

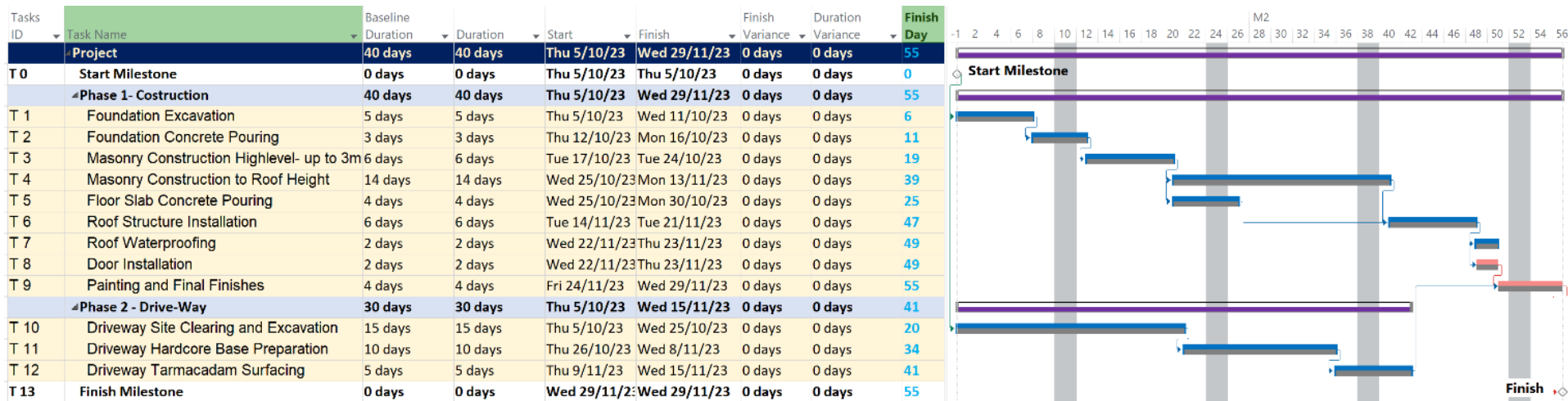


Figure 9.6 (A): As planned programme

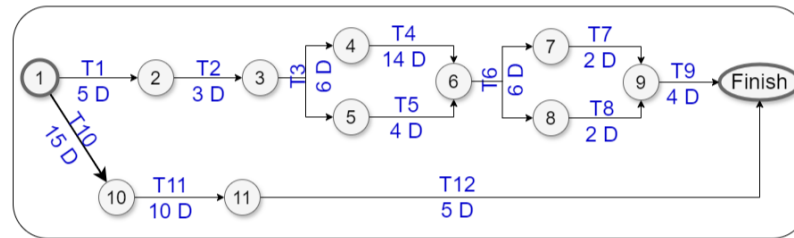


Figure 9.7: Case Study diagram

9.5 DATA ANALYSIS AND RESULT

This section is divided into two subsections for data analysis: 4.1) selecting the delay analysis method using the AHP decision-making process and 4.2) testing the selected method through a case study in both traditional and SAMRT approaches.

9.5.1 AHP decision-making method

Analytic Hierarchy Process (AHP) decision-making method developed by Saaty [65], AHP is designed to address decision-making in complex, multi-criteria situations [66, 67]. This research emphasises the practical application of AHP rather than its theoretical aspects. The following steps outline the detailed AHP analysis process, covering the methodology (Section 3), outcomes from the case study, facilitated workshops, and the identified criteria. The following steps map the practical aspects:

- **Step 1-Structuring the Hierarchy**

For this purpose, step 1 explains the goal of AHP, in this case, to select the best and align four delay analysis techniques (As Planned vs As-Built, Impacted As Planned, Time Impact Analysis, and Windows Analysis) by applying five criteria (Accuracy, Real-time Data Integration, Flexibility, Predictive Analysis, and Stakeholder Communication).

- **Step 2-Pairwise Comparisons of Criteria**

There are two parts: first, a pairwise matrix compares the importance of each criterion against the others and second, a normalised matrix for criteria weights.

Through **Part 1**, each criterion is compared against the others in terms of its importance to the overall goal. The AHP uses a scale of 1 to 9, where 1 indicates equal importance, and 9 indicates that one criterion is more important than another. The comparisons would be made based on input from the workshop participants. For example, suppose participants believe that accuracy is more important than Real-time Data Integration. In that case, they might assign a value 5 in the pairwise comparison matrix, meaning accuracy is "strongly more important." Table 9.6 presents a Pairwise matrix that compares the importance of each criterion against the others.

Table 9.6: Pairwise Comparisons of Criteria

Criteria	Accuracy	Real-time Data Integration	Flexibility	Predictive Analysis	Stakeholder Communication
Accuracy	1	5	3	7	4
Real-time Data Integration	1/3	1	2	4	1/2
Flexibility	1/5	1/2	1	3	1/3
Predictive Analysis	1/7	1/4	1/3	1	1/5
Stakeholder Communication	1/3	2	3	5	1

Table 9.6 reflects the relative importance of each criterion. For example, accuracy is considered significantly more important than predictive analysis (with a value of 7) but only moderately more critical than stakeholder communication (value of 4). However, in the row for Real-Time Data Integration and the column for accuracy, we have a value of "1/3." This means 1/3 means "moderately less important than the other criterion, while the reciprocal value (3) indicates that the other criterion (in the column) is moderately more important. In summary, "Accuracy" is moderately more important than "Real-Time Data Integration", so the reciprocal "3" would appear in the "Accuracy" row and "Real-Time Data Integration" column, indicating that "Accuracy" is 3 times more important.

For normalisation, **Part 2** focuses on the Pairwise Comparison Matrix, which is the sum of the elements in each criteria column of the Initial Pairwise Comparison Matrix. To calculate the weights for each criterion, we should normalise the matrix by dividing each element by the sum

of its column (all sums have been rounded up). For this purpose, we first need to calculate the total sum of each criterion shown below:

Criteria	Accuracy	Real-time Data Integration	Flexibility	Predictive Analysis	Stakeholder Communication
Sum of Column	2.10	6.80	11.40	20.00	5.10

For example, Accuracy column: $1+1/3+1/5+1/7+1/3=1+0.33+0.20+0.143+0.33=2.10$

Further, to get a normalised matrix, each element of the pairwise matrix needs to be divided by the sum of its respective column, as shown below (Table 9.7). For example, cross "Accuracy" and "Accuracy" is calculated as $1/(2.10)=0.476$

Table 9.7: Normalisation

Criteria	Accuracy	Real-time Data Integration	Flexibility	Predictive Analysis	Stakeholder Communication
Accuracy	0.476	0.441	0.439	0.350	0.588
Real-time Data Integration	0.159	0.147	0.175	0.200	0.098
Flexibility	0.095	0.074	0.088	0.150	0.065
Predictive Analysis	0.068	0.037	0.029	0.050	0.039
Stakeholder Communication	0.159	0.294	0.263	0.250	0.196

- **Step 3-Calculate Priority Weights**

After creating the pairwise comparison matrix, the next step is calculating each criterion's normalised weights. This is done by normalising each matrix column and averaging the values across each row. The result gives the relative weight of importance for each criterion. To calculate the weight for each criterion, sum each row and divide by the number of criteria (5) to get the final normalised weight, as seen in Table 9.8. For example, "Accuracy" is calculated as $0.476+0.441+0.439+0.350+0.588=2.29$ and $2.29/5=0.46$

Table 9.8: Weights

Criteria	Sum	Weight (Normalised)
Accuracy	2.29	0.46
Real-time Data Integration	0.78	0.16
Flexibility	0.47	0.09
Predictive Analysis	0.22	0.04
Stakeholder Communication	1.16	0.23

- **Step 4-Pairwise Comparison of Alternatives**

Once the weights for the criteria are determined, the next step is to perform pairwise comparisons of the four delay analysis methods for each criterion. For example, participants would compare how well As-Planned vs As-Built performs against Impacted As-Planned regarding accuracy, and so on for all other criteria. There are two parts: first, a pairwise matrix compares the importance of each method against the others (Figure 9.8) and second, a normalised matrix for method weights (Figure 9.9).

- **Step 5- Calculate Priority Vectors for Each Method**

After normalising the pairwise comparison matrices for each criterion, we can calculate the relative priority (weight) for each delay analysis method under each criterion. Table 9.9 illustrates normalising and averaging the pairwise matrices.

Table 9.9: Each Method Priority Vectors

Alternative	Accuracy	Real-time Data Integration	Flexibility	Predictive Analysis	Stakeholder Communication
As Planned vs. As-Built	0.1	0.15	0.3	0.25	0.25
Impacted As Planned	0.25	0.2	0.1	0.15	0.15
Time Impact Analysis	0.35	0.4	0.25	0.4	0.4
Windows Analysis	0.3	0.25	0.35	0.2	0.2
As Planned vs. As-Built	0.1	0.15	0.3	0.25	0.25

- **Step 6- Final ranking and decision**

The final ranking of the delay analysis methods is obtained by multiplying the weights of each criterion by the corresponding scores for each method and summing the results. Each alternative (method) step 5 normalised pairwise matrix multiple to relevant normalised weight factor matrix from step 3 as below:

$$\begin{pmatrix} 0.1 & 0.15 & 0.3 & 0.25 & 0.25 \\ 0.25 & 0.2 & 0.1 & 0.15 & 0.15 \\ 0.35 & 0.4 & 0.25 & 0.4 & 0.4 \\ 0.3 & 0.25 & 0.35 & 0.2 & 0.2 \\ 0.1 & 0.15 & 0.3 & 0.25 & 0.25 \end{pmatrix} \times \begin{pmatrix} 0.46 \\ 0.16 \\ 0.09 \\ 0.04 \\ 0.23 \end{pmatrix} = \begin{pmatrix} 0.16 \\ 0.20 \\ 0.36 \\ 0.26 \\ 0.16 \end{pmatrix}$$

Alternative	Final Ranking
As Planned vs. As-Built	0.16
Impacted As Planned	0.20
Time Impact Analysis	0.36
Windows Analysis	0.26

The analysis yields the following key outcomes: 1) Time Impact Analysis achieves the highest score (0.36), making it the most suitable method based on the key criteria; 2) Windows Analysis ranks second with a score of 0.26; 3) Impacted As-Planned is third with a score of 0.20; and 4) As-Planned vs. As-Built ranks lowest with a score of 0.16. Consequently, in alignment with Figure 9.1, the SCL Protocol and AACE RP 29R-03, the Time Impact Analysis (TIA) method is the most suitable delay analysis method based on the key criteria. Therefore, the AHP results further confirm the selection from the perspective of experts in major construction projects. Thus, in Section 4.2, the Time Impact Analysis method is validated and tested in both traditional processes and the RealCONs' framework.

9.5.2 Case study results-test and verification

After selecting the time Impact Analysis Method (TIA) by industry expertise perspective and literature reviews as a proper delay analysis aligned with RealCONs' framework, the case study introduced in Figure 9.6(A) is in place to verify the performance of RealCONs' framework and

traditional approach in terms of early delay identification and analysis. Figures 9.6(B1) and 9.6(B2) depict the final as-built programmes for RealCONs' framework and traditional approach after five delay events occurred on T2, T5, T9, T0 and T12 (Table 9.10). Total slippage days from baseline (55 days) are different: 57 and 60 days for RealCONs and traditional approaches, respectively, as seen in the "Finish Day" column.

Method (Alternative) Criteria	As Planned vs. As Built					Impacted As Planned					Time Impact Analysis					Windows Analysis				
	C1	C2	C3	C4	C5	C1	C2	C3	C4	C5	C1	C2	C3	C4	C5	C1	C2	C3	C4	C5
As Planned vs. As Built	1.00	1.00	1.00	1.00	1.00	5.00	4.00	3.00	0.33	0.20	3.00	7.00	5.00	0.20	0.14	7.00	5.00	7.00	0.14	0.33
Impacted As Planned	0.20	0.25	0.33	3.00	5.00	1.00	1.00	1.00	1.00	1.00	2.00	5.00	4.00	0.25	0.33	4.00	3.00	6.00	0.20	0.25
Time Impact Analysis	0.33	0.14	0.20	5.00	7.00	0.50	0.20	0.25	4.00	3.00	1.00	1.00	1.00	1.00	1.00	3.00	4.00	3.00	0.33	0.20
Windows Analysis	0.14	0.20	0.14	7.00	3.00	0.25	0.33	0.17	5.00	4.00	0.33	0.25	0.33	3.00	5.00	1.00	1.00	1.00	1.00	1.00

Figure 9.8: Pairwise Comparison of Alternatives

Method (Alternative) Criteria	As Planned vs. As Built					Impacted As Planned					Time Impact Analysis					Windows Analysis				
	C1	C2	C3	C4	C5	C1	C2	C3	C4	C5	C1	C2	C3	C4	C5	C1	C2	C3	C4	C5
As Planned vs. As Built	0.60	0.63	0.60	0.06	0.06	0.74	0.72	0.68	0.03	0.02	0.47	0.53	0.48	0.04	0.02	0.47	0.38	0.41	0.09	0.19
Impacted As Planned	0.12	0.16	0.20	0.19	0.31	0.15	0.18	0.23	0.10	0.12	0.32	0.38	0.39	0.06	0.05	0.27	0.23	0.35	0.12	0.14
Time Impact Analysis	0.20	0.09	0.12	0.31	0.44	0.07	0.04	0.06	0.39	0.37	0.16	0.08	0.10	0.22	0.15	0.20	0.31	0.18	0.20	0.11
Windows Analysis	0.09	0.13	0.09	0.44	0.19	0.04	0.06	0.04	0.48	0.49	0.05	0.02	0.03	0.67	0.77	0.07	0.08	0.06	0.60	0.56

Figure 9.9: Normalisation

Note: C1: Accuracy; C2: Real-time Data Integration; C3: Flexibility; C4: Predictive Analysis; and C5: Stakeholder Communication

Table 9.10: Delay Event Overview

Event	Description	Impact
#1	T2 - Foundation Concrete Pouring	2 days start delay
#2	T10 - Driveway Site Clearing and Excavation	4 days finish delay
#3	T5 - Floor Slab Concrete Pouring	7 days finish delay
#4	T12 - Driveway Tarmacadam Surfacing	2 days start delay
#5	T9 - Painting and Final Finishes	5 days finish delay

Figures 9.6(B1) and 9.6(B2) present final snapshots of a project completed by two teams (each consisting of 15 members, 9 hour per day, and \$100 per hour), using the Time Impact Analysis (TIA) method to verify the RealCONs' framework's performance against the traditional approach after five delay events. Table 9.4 was used to break down the impacts of these delay events, analysing them based on five key criteria: accuracy, real-time data integration, flexibility, predictive analysis, and stakeholder communication. In the traditional approach, delays were modelled with and without their impact on the schedule to assess their effect on the project's critical path and completion date. Delay events were inserted, and the project end date recalculated. Figure 9.6(B1) illustrates the traditional approach's final as-built programme, where delays were recognized late, after they occurred, without real-time mitigation strategies or predictive adjustments. These delays led to cascading effects on downstream tasks, significantly extending the project timeline. The project team calculated the following delay impacts:

- T2 start delay (2 days): Delayed T3 and subsequent tasks.
- T5 finish delay (7 days): Affected T6 and downstream activities.
- T9 finish delay (5 days): Impacted the final milestone (T13).
- T10 finish delay (4 days): Affected T11 and T12 within Phase 2 (Drive-Way tasks).
- T12 start delay (2 days): Delayed the final milestone by an additional 2 days

Cumulatively, Phase 1 experienced 14 days of delays (T2, T5, T9), and Phase 2 had 6 days of delays (T10, T12), extending the project completion by 20 days.

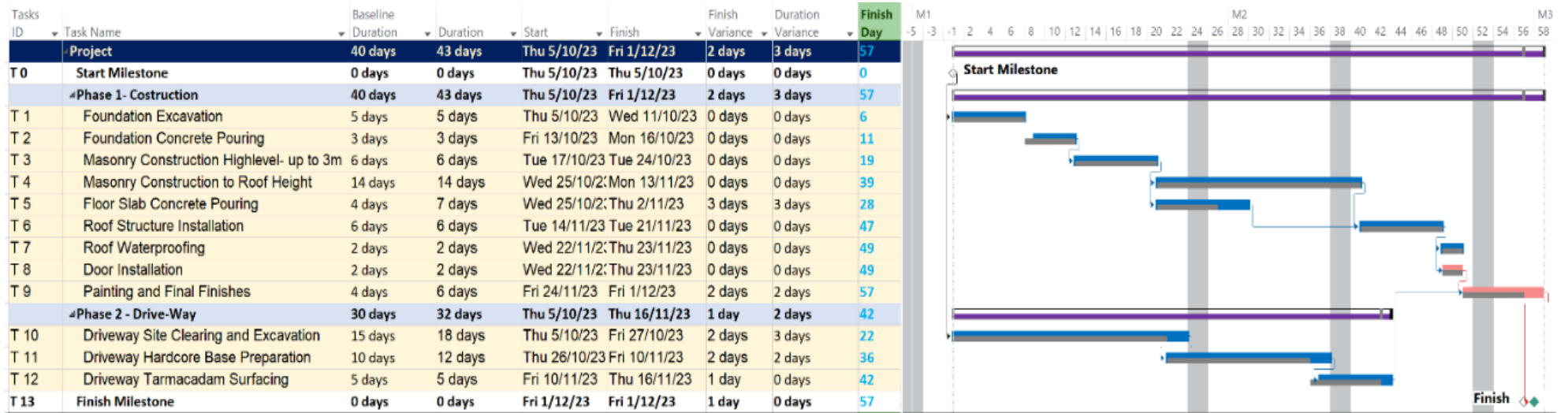


Figure 9.6(B1): As Built Programme – Traditional Approach

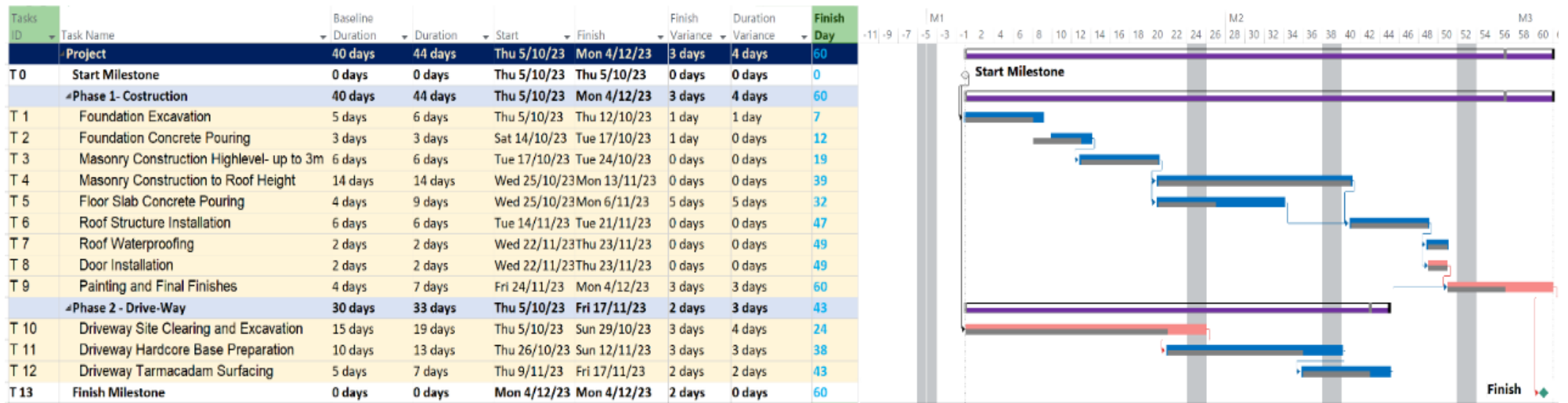


Figure 9.6(B2): As Built Programme – RealCONs Framework

Thus, the total duration under the traditional approach was 60 days (original planned duration + 20 days of variance), as seen in Figure 9.6(B1). Figure 9.6(B2) shows the RealCONs framework's final as-built programme, which demonstrates how early detection and mitigation through TIA helped reduce delay impacts by optimizing resources, performing parallel tasks, and re-sequencing activities. Key mitigating actions included:

- T2 start delay: Early detection allowed acceleration of T3, reducing the overall impact to 1 day.
- T5 finish delay: T6 (Roof Structure) was completed concurrently with T5, reducing the delay to 3 days.
- T9 finish delay: Resource optimization allowed concurrent tasks like T8 (Door Installation) to be completed sooner, reducing the delay to 2-3 days.
- T10 and T12 delays: Proactive adjustments reduced T10's delay to 2 days and T12's delay to 1 day.

With these interventions, the cumulative delay was reduced to 13-17 days, resulting in a project completion of 53-57 days, compared to the 60 days in the traditional approach. The RealCONs framework's ability to mitigate delays early significantly minimized the impact on the overall timeline. To conduct a micro-level analysis of each delay event and its impact on the affected tasks, the following steps were considered:

S1: Impact of Delays on the Critical Path

- Delay Event 1 (T2 - 2 days start delay): This delay affects downstream activities like T3 (Masonry Construction) but does not significantly impact project completion unless on the critical path.
- Delay Event 2 (T10 - 4 days finish delay): The delay in Phase 2 (Driveway) impacts the handover milestone unless the phase has sufficient float time.
- Delay Event 3 (T5 - 7 days finish delay): A significant delay here could affect subsequent tasks like roof construction (T6) and waterproofing (T7), potentially pushing the entire project schedule.
- Delay Event 4 (T12 - 2 days start delay): This delay affects tarmac completion and

could impact the final milestone if it's on the critical path.

- Delay Event 5 (T9 - 5 days finish delay): This delay in final finishes directly impacts the handover milestone, potentially pushing the project completion date.

S2: Comparison between SMART and Traditional Approaches

A comparison of SMART and traditional approaches was made using five criteria, as shown in Table 9.11:

Table 9.11: Comparison between SMART and Traditional approaches

Criteria	SMART (Using TIA)	Traditional (Using TIA)
Accuracy	Real-time updates and precise impact forecasting, enhancing accuracy.	Delays are inserted into the schedule, but without real-time feedback, accuracy depends on historical data and judgment.
Real-Time Data Integration	Continuous tracking of delay impacts as the project progresses, leading to dynamic schedule adjustments.	Adjustments made periodically after delays are assessed, often relying on static data and reactive analysis.
Flexibility	SMART allows adaptive decision-making, with scenarios easily modelled for what-if analyses and alternative strategies.	Traditional TIA is less flexible, requiring manual updates and scenario modelling, making quick adjustments difficult.
Predictive Analysis	Incorporates predictive modelling to anticipate future delays and their cascading effects on the project timeline.	Predictive capabilities are limited, with most analyses based on the immediate impacts of current delays.
Stakeholder Communication	Clear communication through data-driven dashboards, offering transparency to all parties involved, including contractors and clients.	Communication relies on periodic reports and updates, making it harder to maintain clear, real-time communication.

S3: Analysis of the Five Delay Events in RealCONs vs. Traditional Approaches

- Task T2 (2 days start delay):
 - RealCONs framework: Early identification allows for quick mitigation. Real-time data facilitates dynamic adjustments with minimal impact on downstream tasks.
 - Traditional approach: Delays are manually inserted into the schedule, often missing opportunities for optimisation without real-time data.
- Task T10 (4 days finish delay):
 - RealCONs framework: The delay in driveway clearing is captured in real time, allowing for dynamic adjustments like resource reallocation or parallel task execution. Predictive models assess potential future risks.
 - Traditional approach: Impact is manually calculated, leading to a reactive approach and potential underestimation of the delay's effect on finishing works.
- Task T5 (7 days finish delay):

- RealCONs framework: The delay triggers alerts for cascading impacts on roof structure work (T6) and subsequent activities. The system helps explore dynamic mitigation strategies.
- Traditional approach: Adjusting for the 7-day delay could cause a critical path shift, but without dynamic forecasting, identifying the best mitigation strategies becomes challenging.
- Task T12 (2 days start delay):
 - RealCONs framework: The impact on driveway surfacing is managed by real-time adjustments to subsequent tasks. The system proactively mitigates delays by accounting for the updated critical path.
 - Traditional approach: Manually inserted delays show slippage, but limited predictive analysis restricts insights into future impacts.
- Task T9 (5 days finish delay):
 - RealCONs framework: Early flagging of the delay notifies stakeholders in real time. The framework evaluates the delay's impact on the project milestone and enables proactive adjustments to the critical path.
 - Traditional approach: This delay impacts project completion, but without real-time updates, mitigation measures are often delayed and less effective.

This comparison highlights how RealCONs' real-time data integration and predictive capabilities enable proactive management of delays, minimizing their impact, whereas traditional methods rely on manual updates and reactive measures, often leading to greater project disruption.

The RealCONs framework, when using Time Impact Analysis (TIA), demonstrates superior accuracy through real-time data integration and predictive analysis. Its flexibility allows for modelling alternative scenarios, helping to avoid cascading delays. Moreover, the framework enhances communication among all stakeholders through dynamic reporting and visual dashboards. On the other hand, while the traditional approach effectively tracks delays, it lacks the adaptability and predictive foresight that the RealCONs framework provides. As a result, delays are captured, but recovery planning is often inefficient due to reactive analysis. The

RealCONs framework, using TIA, outperforms the traditional method in terms of accuracy, flexibility, and communication, making it a more effective tool for managing and mitigating delays. This research highlights a key mechanism in the SMART framework for early delay recognition, utilising real-time monitoring, predictive analysis, and automated feedback loops. This mechanism is designed to identify delays early and mitigate their impact, potentially keeping the project completion date from moving or minimizing the delay. The mechanism works as follows:

- **Real-Time Data Integration:** The framework continuously tracks project activities through real-time data collected from on-site sensors, software, or manual inputs. For example, smart devices or daily reporting systems capture start times, progress percentages, resource allocation, and any deviations from the schedule.
- **Early Warning System:** The RealCONs' framework includes an Early Warning System that detects deviations from the planned start and finish dates. If a task (e.g., T2 or T12) starts deviating from the schedule, the system flags the delay early—even if it's only a few hours behind. For instance, in T2's 2-day start delay, the system would flag the issue as soon as the delay begins, allowing for quicker action.
- **Predictive Analysis and Scenario Modelling:** Predictive algorithms assess the knock-on effects of any detected delay. If T2 is delayed by 2 days, the framework immediately predicts how it will affect future tasks, such as T3 (Masonry Construction). The system can test multiple recovery scenarios in real-time, such as accelerating tasks or reallocating resources, to identify the best way to recover the schedule.
- **Resource Reallocation and Optimisation:** The framework dynamically adjusts resource assignments. If T2 faces a 2-day start delay, the system may suggest reallocating labour or equipment from non-critical tasks to expedite completion. This prevents downtime and maintains workflow continuity, minimising the delay's impact.
- **Critical Path Monitoring:** The framework constantly recalculates the critical path in real-time, identifying which delays could affect the project's completion date. It adjusts task sequencing or reassigns resources to prevent delays from affecting the critical path,

helping the project stay on schedule.

- **Buffer and Float Management:** RealCONs identifies available buffers or floats in non-critical tasks that can absorb minor delays. For example, if T10 (Driveway Site Clearing) experiences a 4-day finish delay, and there's float in that section, the delay won't affect the critical path. The system can reallocate float from non-critical tasks to prevent the delay from impacting the overall schedule.

Through these mechanisms, the RealCONs framework can identify delays earlier and implement mitigation strategies to minimize or eliminate their impact on the project's completion date. When a delay is detected, such as T2's 2-day start delay, the RealCONs framework immediately proposes mitigation actions. This could involve accelerating downstream tasks, like T3 (Masonry Construction), to allow for a catch-up period without affecting the overall project completion date. The RealCONs framework also enables dynamic re-sequencing of tasks. For instance, if feasible, it may recommend that T5 (Floor Slab Concrete Pouring) and T4 (Masonry Construction to Roof Height) proceed concurrently to ensure both tasks remain on schedule despite upstream delays. Additionally, the framework identifies opportunities for parallel task execution. In the case of T12's 2-day start delay, the system might suggest beginning T11 (Driveway Hardcore Base Preparation) early or running it in parallel with T12 to regain lost time, preventing cascading delays. Through early detection and proactive communication, the RealCONs framework prevents small delays from escalating into larger disruptions. For example, in traditional methods, a 2-day delay in T2 might cause T3 and T4 to start late, pushing the entire project timeline. However, with the RealCONs framework, T3 could be accelerated, or T4 might begin in parallel with adjustments.

The framework's real-time data visualisations and automatic reports keep stakeholders informed, enabling quicker decisions. This avoids delays caused by slow decision-making or late approvals. Early communication with all parties—including subcontractors, head contractors,

and consultants—allows for rapid approvals of overtime, resource reallocation, or scope adjustments to keep the project on track. For clarification, below is an explanation of Delay Event 1 (T2 - Foundation Concrete Pouring, 2 Days Start Delay) comparing the RealCONs and traditional approaches:

Delay Event 1 (T2 - Foundation Concrete Pouring, 2 Days Start Delay)	
Traditional Approach	RealCONs Approach
The delay is only recognized after T2's planned start, and manual changes are made to the project schedule. This leads to a reactive approach, where the project completion date may shift as the impact on T3, and downstream tasks is calculated.	<ul style="list-style-type: none"> ➤ As soon as T2's start is delayed (even by a few hours), the system flags it and immediately calculates the impact on future tasks (T3, T4, etc.). ➤ Predictive models analyse recovery strategies, such as accelerating T3 (Masonry Construction) or performing some tasks in parallel to regain lost time. ➤ Resource reallocation is suggested, and if approved, extra resources are mobilized to avoid further delay. For instance, if additional manpower is available for T3, it can be completed faster, compensating for T2's delay. ➤ Dynamic reporting to stakeholders ensures fast decision-making on mitigation strategies.

As a result, the project completion date may remain unchanged due to early identification and mitigation of the delay. However, if the completion date is affected, the impact is reduced to just a few days, rather than the full 2-day delay. Moreover, early delay identification is critical in construction project management for timely interventions and corrective actions. From Table 9.3 (Earned Value Metrics), SPI and CPI serve as effective tools for early-stage delay notification when used with the Time-Impact Analysis (TIA) method. These metrics enable project managers to proactively address issues before they escalate. Table 9.12 provides a general comparison of the RealCONs framework's early-stage delay notification performance against the traditional approach, showing the advantages of using earned value metrics.

Table 9.12: Case Study SPI and CPI

Task ID	PV (NZD)	EV(NZD)		AC (NZD)		SPI=EV/PV		CPI=EV/AC	
		Traditional	SMART	Traditional	SMART	Traditional	SMART	Traditional	SMART
T1	1,282.89	1,061.60	\$1,208.31	\$1,135.70	\$900	0.83	0.94	0.93	1.34
T2	769.74	605.21	\$742.89	\$595.70	\$540	0.79	0.97	1.02	1.38
T3	1,539.47	1,301.62	\$1,432.07	\$1,135.70	\$1,080	0.85	0.93	1.15	1.33
T4	3,592.11	2,927.61	\$3,007.34	\$2,575.70	\$2,520	0.82	0.84	1.14	1.19
T5	1,026.32	790.08	\$942.78	\$1,675.70	\$1,260	0.77	0.92	0.47	0.75
T6	1,539.47	1,301.62	\$1,432.07	\$1,135.70	\$1,080	0.85	0.93	1.15	1.33
T7	513.16	362.58	\$501.22	\$415.70	\$360	0.71	0.98	0.87	1.39

T8	513.16	362.58	\$501.22	\$415.70	\$360	0.71	0.98	0.87	1.39
T9	1,026.32	811.09	\$954.71	\$1,315.70	\$1,080	0.79	0.93	0.62	0.88
T10	3,848.68	2,949.68	\$3,043.15	\$3,475.70	\$3,240	0.77	0.79	0.85	0.94
T11	2,565.79	2,077.85	\$2,207.77	\$2,395.70	\$2,160	0.81	0.86	0.87	1.02
T12	1,282.89	1,048.48	\$1,208.31	\$1,315.70	\$900	0.82	0.94	0.80	1.34
Total	19,500.00	15,600.00	\$17,181.84	\$17,588.43	\$15,480	0.80	0.88	0.89	1.11

Note: PV, EV, and AC values are divided by 10,000 to improve clarity and readability in the table cells.

Figure 9.10 shows the Schedule Performance Index (SPI), offering insights into the progress of the project against its planned schedule. A declining SPI signals emerging delays. As seen in Table 9.12, continuous monitoring of SPI allows project managers to quickly identify when the project is falling behind, enabling timely investigation and corrective action. While the RealCONs and traditional approaches have SPI values below 1 (indicating the project is behind schedule), the RealCONs' framework, with an SPI of 0.88, demonstrates relatively better performance than the traditional approach's SPI of 0.80. This suggests that although both approaches face delays, the RealCONs' framework manages tasks more effectively. The slightly higher SPI for RealCONs indicates it is better equipped to identify and address delays early, facilitating timely interventions to minimise their impact on the project timeline.

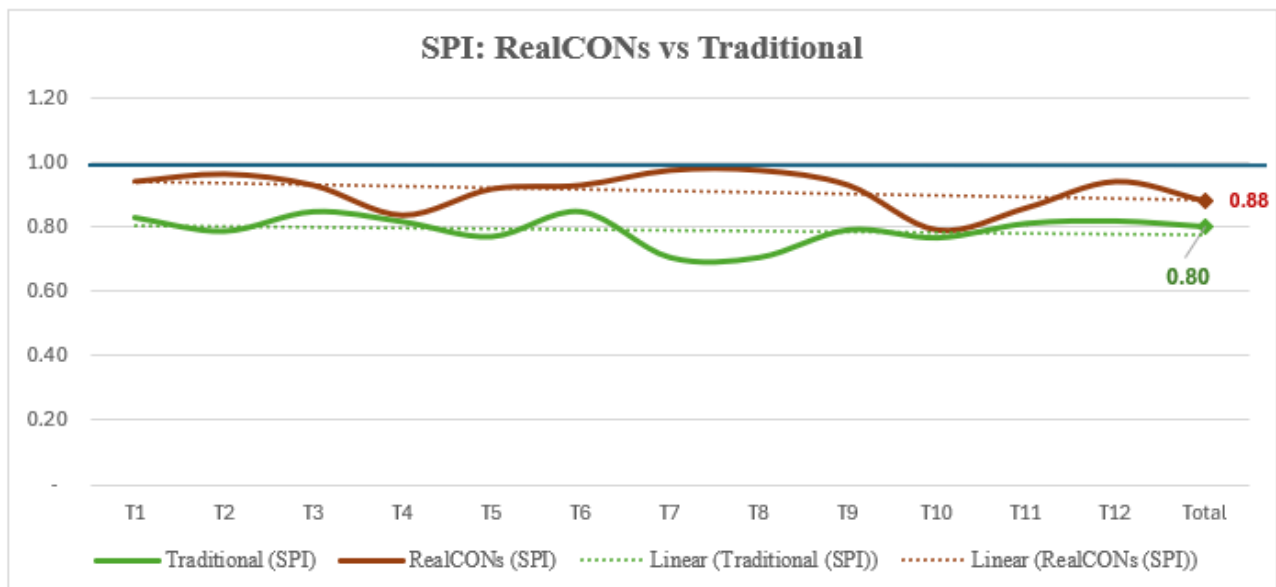


Figure 9.10: SPI Chart

Figure 9.11 illustrates the CPI chart, which assesses the project's budget efficiency. A

declining CPI can indicate financial issues, often tied to delays. Monitoring CPI alongside SPI allows project managers to detect when cost efficiency declines, typically during periods of delay or rework. As shown in Table 9.12, a CPI less than one signals the project is over budget, while a CPI more significant than 1 is a positive sign. With a CPI of 1.11, the RealCONs' framework demonstrates effective cost management operating under budget. In contrast, the traditional approach, with a CPI of 0.88, shows it is over budget. The superior CPI of RealCONs not only highlights its cost efficiency but suggests the project can absorb potential delays without significantly affecting financial performance, allowing for more agile responses to issues.

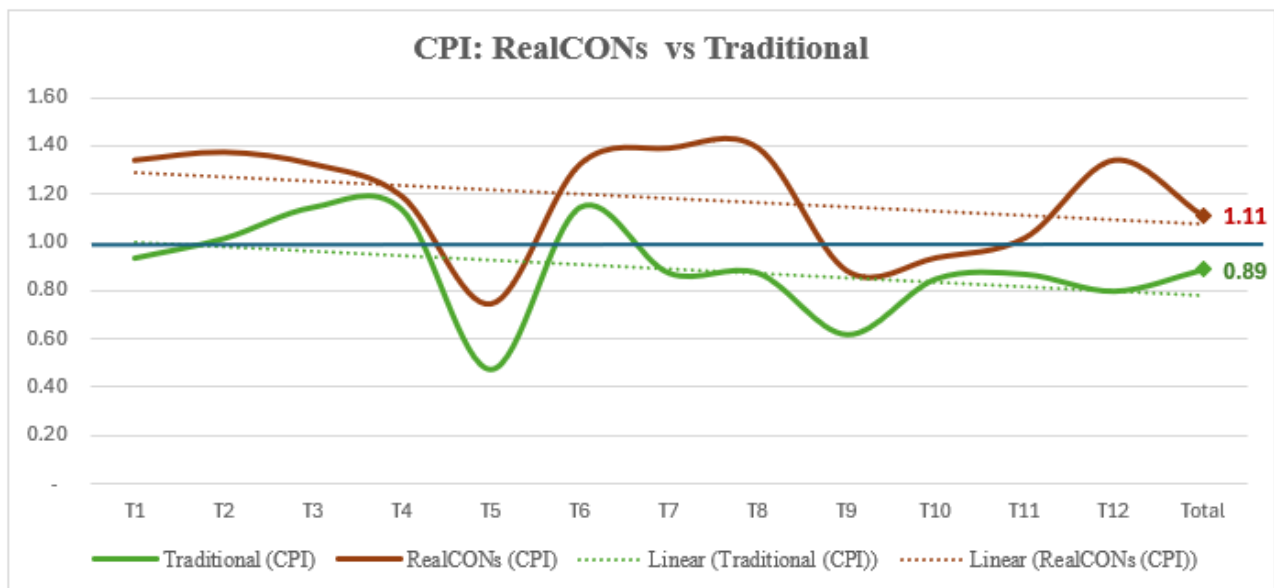


Figure 9.11: CPI Chart

In summary, SPI and CPI are valuable early-stage delay notification tools that help project managers control timelines and costs. The RealCONs' framework, with higher SPI (0.88 vs. 0.80 for traditional) and CPI (1.11 vs. 0.89 for traditional), demonstrates a stronger ability to identify and manage delays early, minimising their impact on project outcomes. This combination of better schedule management (SPI) and cost efficiency (CPI) reinforces the RealCONs' framework's superior performance, emphasising the importance of early-stage delay notifications for successful project delivery. By leveraging these indices, project

managers can make informed decisions and take timely corrective actions to keep projects on track. In conclusion, the data analysis results are presented through visual analytical graphs as follows:

Figure 9.12 shows the project progress over time for both the traditional and RealCONs approaches; Figure 9.13 compares the total delays for individual tasks in both approaches; Figure 9.14 presents charts for cost and time overruns, comparing the actual completion date with the planned completion date (Time View) and the additional delay costs added to the planned budget (Cost View). Figure 9.15 states a spider chart to visualise how each approach scores on the five key criteria.

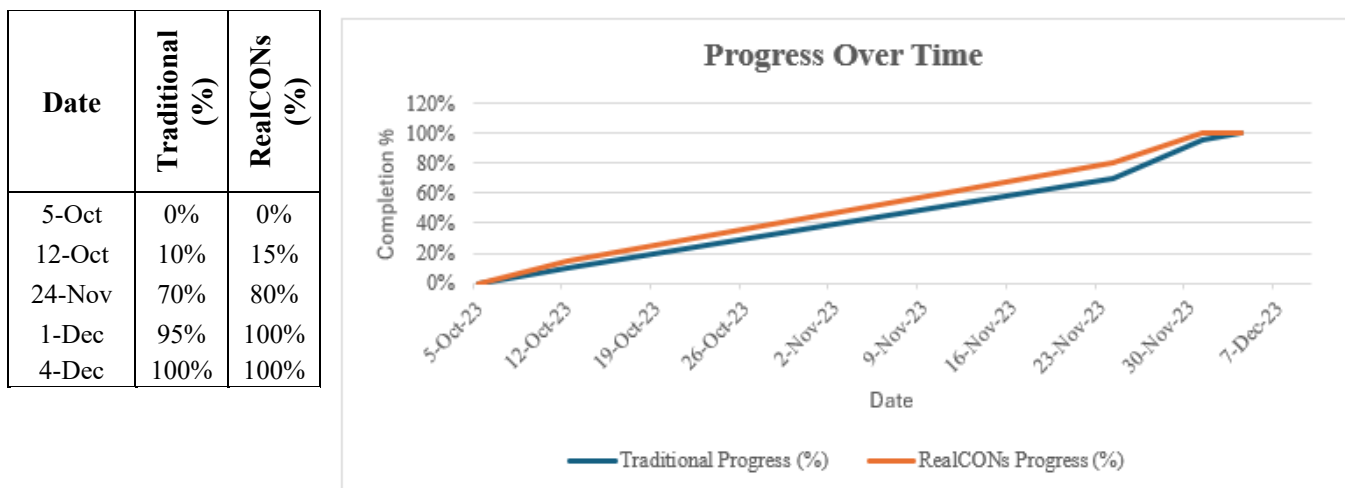


Figure 9.12: Project progress over time: traditional and SMART approaches

As shown in Figure 9.12, the RealCONs approach using the TIA method achieved a faster completion rate than the traditional method at every project milestone. This indicates superior project control, better delay management, and more efficient labour utilisation in the RealCONs' framework. For instance, by October 12th, the RealCONs approach had completed 15% of the project, while the traditional approach reached only 10%. This suggests RealCONs managed early tasks more effectively through improved task sequencing and allocation of labour. By November 24th, the gap widened, with the SMART approach completing 80% of the project, compared to 70% with the traditional approach. This highlights RealCONs'

efficiency in mitigating delays and maintaining project momentum, ultimately completing the project three days earlier.

Figure 9.13 compares the delays for key tasks using the TIA (Time Impact Analysis) method under the traditional and RealCONs approaches. It demonstrates that the RealCONs' framework consistently outperformed the traditional approach by reducing delays across all tasks, resulting in more efficient project delivery. For instance, a significant delay of 7 days occurred in the traditional approach, but the RealCONs' framework shortened it to 4 days, highlighting its superior ability to manage longer delays.

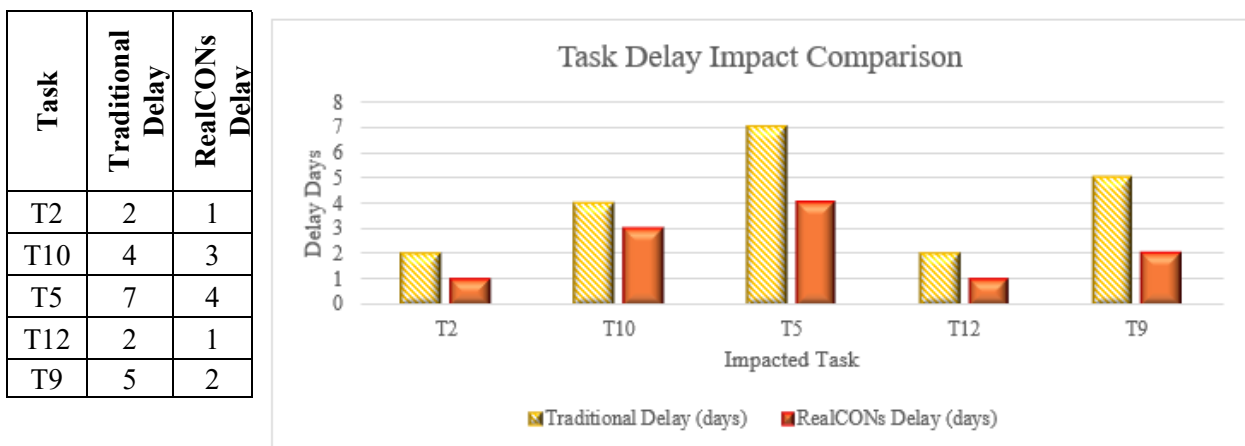
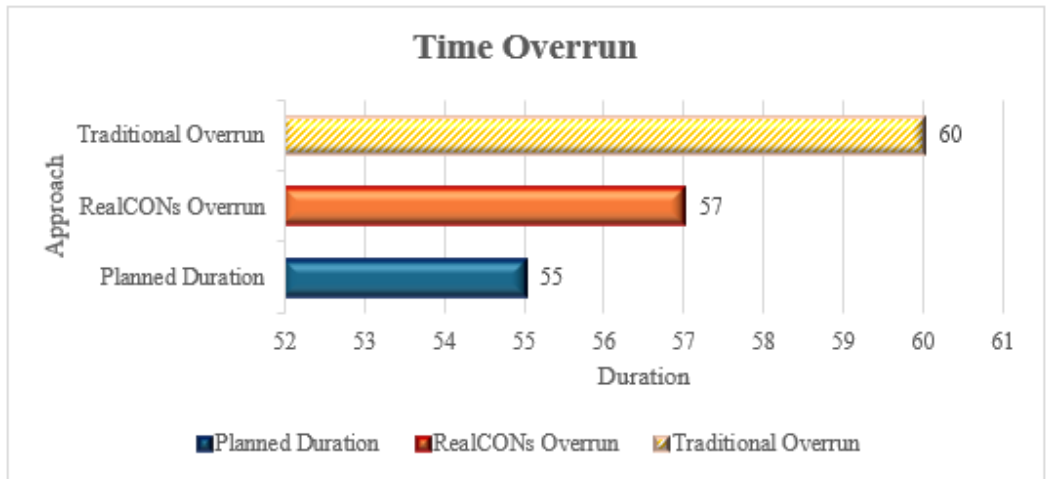


Figure 9.13: Total delay comparison on individual tasks

Figure 9.14 illustrates that using TIA within the SMART approach resulted in a minimal cost overrun of \$5 million, bringing the total cost to \$200 million, while the traditional method had a cost overrun of \$15 million, leading to a total cost of \$210 million. The initial budget for both was \$195 million.

Task**	Value (days)*
PD	55-56
TO	59-60
RO	55-57



* Depends on optimisation level

**PD: Planned Duration; TO: Traditional Overrun; RO: RealCONs Overrun

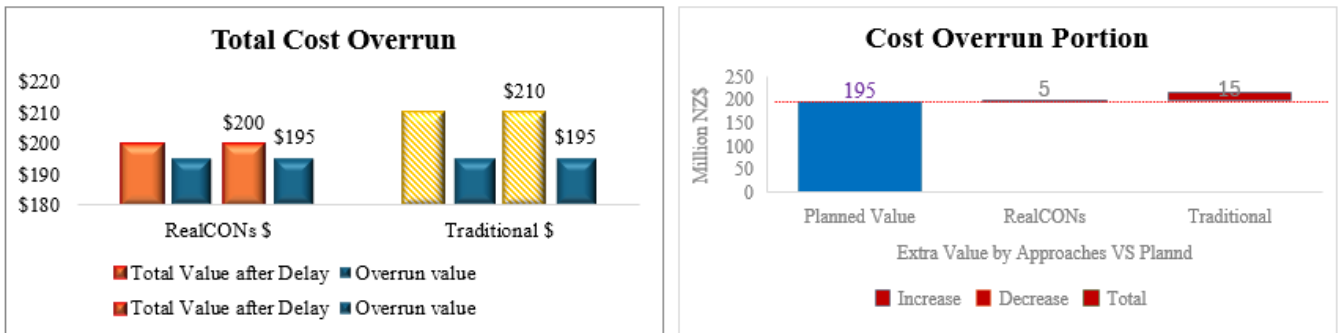


Figure 9.14: Cost Overrun and Time Overrun

Regarding time overrun, the RealCONs' framework effectively managed project delays by adjusting labour and sequencing tasks based on early-stage delay notifications. The RealCONs' framework completed the project on day 57, while the traditional approach finished on day 60, showing that RealCONs can mitigate delay impacts more efficiently, saving time and cost. The planned completion dates were December 4th for the traditional approach and December 1st for RealCONs.

Criteria	Traditional Score	SMART Score
Accuracy	6	8
Real-time Data	4	9
Flexibility	5	8
Predictive Analysis	3	9
Communication	5	8

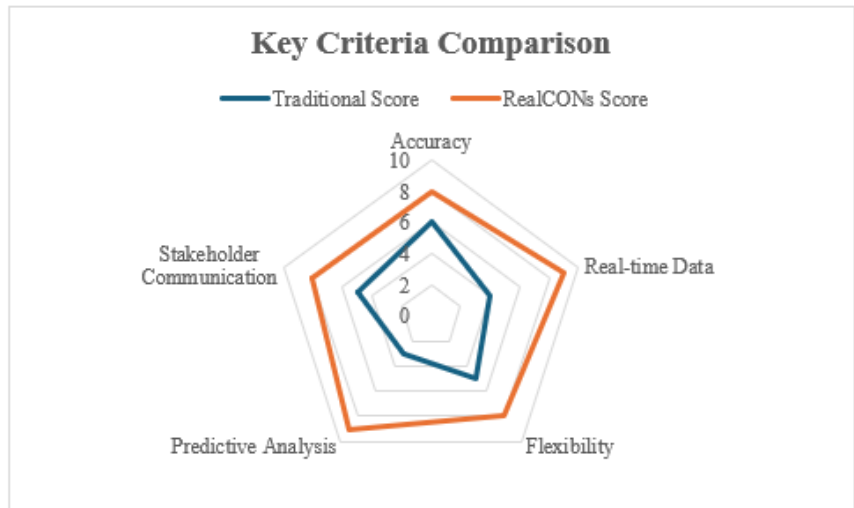


Figure 9.15: Key Criteria Radar Chart

Figure 9.15 presents a spider chart comparing both approaches based on five key criteria. RealCONs outperforms Traditional in all criteria: it scores 8 in accuracy (Traditional scores 6), demonstrating better performance in delivering accurate delay analysis results. In real-time data integration, RealCONs scores nine compared to Traditional's 4, indicating RealCONs's superior capability. RealCONs scores 8 and Traditional 5 for flexibility, showing better adaptability to project changes. RealCONs (9) are more effective in predictive analysis and forecasting project performance than Traditional (3). Finally, RealCONs scores 8 for stakeholder communication, outperforming Traditional (5) in keeping stakeholders informed and engaged.

9.6 DISCUSSION

In this research, through the case study, the Time Impact Analysis (TIA) method was used to evaluate the performance of the RealCONs' framework in comparison with the traditional approach, focusing on five key criteria: accuracy, real-time data integration, flexibility, predictive analysis, and stakeholder communication. The RealCONs' framework demonstrated clear advantages over traditional methods. These features make RealCONs more effective in managing projects and mitigating delays than traditional methods. We split the discussion into

five parts: key findings on how early delay notifications reduce delays and save costs—an analysis using AHP-MCDA, the impact of time overruns, and a general summary of the results.

9.6.1 Research Key Findings

The RealCONs' framework consistently demonstrated superior performance across all five key criteria:

- (i) Accuracy:** The RealCONs' framework consistently demonstrated higher accuracy in identifying and quantifying the impacts of delay events, primarily due to its real-time data integration. While effective in documenting delays, traditional approaches typically rely on manual updates and retrospective analysis, leading to lower accuracy. The continuous monitoring capabilities of the RealCONs' framework allowed it to detect potential delays (e.g., the 2-day delay in Task T2) early, which significantly improved its ability to mitigate these issues and maintain schedule accuracy. In contrast, the traditional method identified delays after they had occurred, missing optimisation opportunities and increasing the risk of schedule overruns.
- (ii) Real-Time Data Integration:** A significant strength of the RealCONs' framework lies in its real-time data collection through on-site sensors, smart devices, and daily reporting systems. This real-time monitoring ensured that delays were identified as soon as they occurred, enabling rapid mitigation strategies. For instance, when Task T2 experienced a 2-day start delay, the RealCONs' framework flagged the delay early, preventing cascading effects on subsequent tasks. This early warning system, combined with predictive analysis, minimised time overruns, a feature the traditional method lacked due to its reliance on manually updated data and delayed recognition of issues.

(iii) Flexibility: The RealCONs' framework also exhibited greater flexibility by dynamically re-sequencing tasks and reallocating resources to mitigate delays. Regarding Task T5's 7-day finish delay, the framework suggested working concurrently on Task T6 (Roof Structure), reducing the overall delay to 3 days. This level of dynamic resource management is challenging to achieve with traditional methods, where delays are addressed reactively and often result in inefficient recovery plans. In contrast, the RealCONs' framework's flexibility allowed for parallel task execution and timely adjustments, reducing potential schedule slippage.

(iv) Predictive Analysis: The RealCONs' framework's predictive analysis capabilities were a critical factor in its superior performance. By forecasting the knock-on effects of delays (e.g., how a 2-day start delay in Task T2 would impact future tasks like T3), the system enabled the project manager to test multiple recovery scenarios in real-time. These predictive capabilities allowed for better decision-making and risk management, unlike the traditional approach, which relies on manual delay insertion and limited forecasting. As a result, the RealCONs' framework mitigated the impact of delays more effectively, minimising their effect on the project timeline.

(v) Stakeholder Communication: Effective communication is essential for minimising the impact of delays. The RealCONs' framework's real-time visual dashboards and automated reporting tools ensured that all stakeholders—subcontractors, head contractors, and consultants—were informed of project status and delay events. This proactive communication allowed for quick decision-making, such as approving overtime or reallocating resources, which helped mitigate the effects of delays. In contrast, the traditional approach relied on slower, manual communication channels, often resulting in delays in decision-making and further project disruption

9.6.2 Reduced Delays and Cost Savings via Early Delay Notification

The RealCONs' framework utilised the Schedule Performance Index (SPI) and Cost Performance Index (CPI) to track project progress and provide early-stage delay notifications. Its real-time data integration allowed for the early identification of deviations in SPI and CPI, enabling corrective actions to prevent significant time and cost overruns. With delayed data entry and slower response times, traditional methods struggled to provide early warnings, resulting in higher costs and longer delays. By maintaining higher SPI and CPI values, the RealCONs' framework effectively minimised delays and ensured projects remained on track.

9.6.3 AHP-Multi-Criteria Decision Analysis (MCDA)

The Analytical Hierarchy Process (AHP) selected the proper delay analysis method to compare the RealCONs' framework and traditional approach across the five criteria. The results are visualised through charts and graphs, such as a radar (spider) chart. The RealCONs' framework outperformed traditional methods in all five categories. The AHP process ensured a structured and quantitative evaluation of each delay analysis method, providing empirical support for the superiority of the RealCONs' framework in managing construction project delays.

9.6.4 Time Overrun Impact

Time overruns are critical in construction projects, often leading to increased costs, contractual penalties, and client dissatisfaction. The RealCONs' framework effectively minimised time overruns by enabling early recognition of delays, predictive analysis, and proactive stakeholder communication. For instance, early identification of Task T2's 2-day delay and subsequent mitigation strategies prevented cascading delays and reduced the risk of schedule slippage. This

proactive approach improved project efficiency and enhanced client satisfaction by minimising unnecessary costs.

9.6.5 Generalisation of Results

The RealCONs' framework's advantages are not limited to the studied project. Its ability to address common challenges in construction project management, such as delay mitigation, improved communication, and adaptive resource management, makes it potentially transferable to projects of varying scopes, complexities, and geographic contexts.

- **Scalability and Adaptability:** The principles underpinning the RealCONs' framework (simplicity, measurability, analytical, and real-time operation) can be tailored to fit different project types and organisational contexts. Its integration with existing project management tools enhances its scalability and ensures seamless adoption.
- **Broader Implications:** While the findings of this research are based on a specific case study, they suggest that the RealCONs' framework can potentially deliver similar benefits in other construction settings. Future studies involving a diverse range of projects are needed to validate these results further and explore the framework's generalisability.

To sum up, the RealCONs' framework offers a robust, scalable, and adaptable solution to common challenges in construction project management. Its proven ability to minimise delays and costs and its predictive and communication capabilities position it as a valuable tool for enhancing project efficiency and stakeholder satisfaction across diverse construction scenarios.

9.7 CONCLUSION

This study advances construction project management by introducing the RealCONs' SMART framework. This innovative approach integrates real-time data acquisition, predictive analytics, and automated feedback loops to enhance delay analysis and mitigation. By addressing persistent challenges in delay claims, the framework enables early-stage notifications, dynamic resource reallocation, and proactive decision-making, thereby improving schedule adherence and cost efficiency. Integrating QR code technology, SQL services, API-driven data synchronisation, and visual analytics provides a structured yet adaptable solution suitable for modern construction projects. The RealCONs framework addresses critical challenges in construction project management by enhancing real-time monitoring, predictive adjustments, and stakeholder transparency. Its implementation demonstrates tangible improvements in schedule adherence, cost efficiency, and delay mitigation across stakeholder groups, including project managers, clients, and contractors. Academically, it advances methodological approaches to delay analysis, while industry applications reveal strengthened operational efficiency and collaboration. Validation through a large-scale infrastructure project underscores its capacity to align timelines, reduce overruns, and optimise resource allocation, positioning it as a transformative tool for modern construction governance.

The RealCONs framework qualitatively enhances construction project governance by fostering stakeholder communication, predictive capacity, and operational transparency. By integrating real-time dashboards and automated alerts, the framework strengthens collaboration and pre-emptive dispute resolution, minimising adversarial claims. Its predictive analytics enable proactive delay forecasting and dynamic resource optimisation, shifting project management from reactive to anticipatory practices. Organisational adoption of the framework supports sustainability through digital workflows, reduces unproductive costs, and accelerates

project timelines. These outcomes collectively improve trust, operational agility, and strategic decision-making. However, its efficacy relies on addressing technological adoption barriers and fostering sector-wide collaboration to ensure scalability.

The Analytic Hierarchy Process (AHP) provided a structured evaluation of the RealCONs framework's performance relative to conventional delay analysis approaches. By prioritising critical factors such as adaptability, predictive capability, and stakeholder engagement, AHP underscored the framework's superiority in addressing complex project dynamics. The methodology highlighted its capacity to integrate real-time data, enhance analytical flexibility, and align decision-making with evolving project requirements. While the framework demonstrates robust performance, its implementation necessitates addressing systemic limitations. Key recommendations include enhancing interoperability between core platforms (e.g., BIM, scheduling tools), prioritising workforce training in digital analytics, and strengthening cybersecurity protocols to safeguard data integrity. These measures ensure the framework's scalability and reliability across diverse construction environments.

Future research should focus on overcoming the framework's limitations by exploring improved connectivity solutions, enhanced data security measures, and harmonising regulatory standards across different regions. This will broaden its applicability in diverse construction environments. The RealCONs framework already marks a significant step forward in real-time delay management by integrating predictive analytics, real-time data acquisition, and automated feedback. Future improvements like advanced AI and blockchain are expected to make it even more effective and reliable at managing delays.

Chapter 10: CONCLUSION AND RECOMMENDATIONS

10.1 RESEARCH OVERVIEW

This doctoral research introduces a novel process-based framework called the Real-Time Data-Driven Project Analysis Framework (RealCONs) to improve early delay notifications in major construction projects, addressing the critical impacts of delays on time and cost. RealCONs is a SMART framework. SMART stands for a simple, measurable, analysable and real-time framework. It is "*Simple*" because it enables users to focus on specific and achievable planning goals for efficient project management; "*Measurable*" because it ensures users can accurately track and measure progress toward project goals, allowing for data-driven decisions; "*Analysable*" as it ensures that project targets are realistically attainable within specified timeframes. Aligns project values and critical goals, conducting thorough analysis for effective decision-making. Finally, it is "*Real-Time*" because it ensures timely notifications to key project stakeholders, facilitating proactive measures to avoid/mitigate delays and risks enabling prompt decision-making.

The main goals were to develop a framework for tracking and analysing construction major projects with focusing on early-stage delay notifications. Through innovative digital technologies and data-driven methods, the research showed how early alerts can lower the risks of time overruns and cost increases, ensuring more predictable and successful project outcomes for projects stakeholders especially project managers. The following chapters detail the objectives, methods, and key findings, highlighting the benefits of early notifications and the frameworks developed in this research. All the objectives of this doctoral thesis were presented and investigated through 9 journal and conference papers as the publication outputs of the study. Thus, each chapter of the thesis presented one paper as

used in the original manuscript. This research is structured into ten (10) chapters, comprising eight (8) core chapters that encompass the eight (8) papers mentioned above, along with an introduction and a conclusion (Table 10.1).

Table 10.1: Summary of doctoral thesis objectives according to each chapter

Chapter #	Objective #	Objective Title
CH_2	OBJ_1	Identify the general causes of delays and their implications on the relationships between construction parties across different stages
	OBJ_2	Evaluate and analyse the causes and effects of delays in major construction projects
CH_3	OBJ_3	Identify and conceptualise real-time technologies used in construction projects, with a focus on delay alert management
		Evaluate the advantages of integrating combined digital technologies versus stand-alone systems in construction project tracking management including delay and risk tracking
		Evaluate digital technologies for managing data acquisition, screening, analysis, and presentation in construction projects, with an emphasis on delay alerts
CH_4	OBJ_4	Develop a process based real-time data-driven construction project analysis framework (RealCONs) focus on and classify Early Delay Notifications Indexes using EVM indexes
CH_5	OBJ_5	-Validate the proposed RealCONs framework for data collection, integration, analysis and visualisation -Evaluation of RealCONs' performance in comparison to existing approaches, using a chosen delay analysis method to address key criteria for real-time project status analysis in early-stage delay notifications
CH_6		
CH_7		
CH_8		
CH_9		

The thesis begins with **Chapter 1**, which introduces the scope, context, and significance of the research. This chapter outlines the research problem, objectives, and methodology, incorporating a literature review, facilitated workshops, and a scoping study. The analysis critically evaluates existing research and industry practices to identify gaps in current delay management systems. Key deliverables include defining the concept of early-stage delay notification and emphasising its importance in construction project management. The chapter sets the foundation for exploring data-driven, real-time solutions to improve project outcomes.

Chapter 2 focuses on the causes of delays in smart and complex construction projects. It addresses two core objectives: Identify the general causes of delays and their implications on the

relationships between construction parties across different stages (OBJ_1) and evaluate and analyse the causes and effects of delays in major construction projects (OBJ_2). Using Literature Review and Mixed methods approaches, this chapter employs citation and content analysis alongside the Relative Importance Index (RII). The findings highlight key delay factors, such as stakeholder miscommunication and technological limitations, and their impact on project outcomes. These insights lay the groundwork for developing effective delay notification systems.

Chapter 3 presents a systematic review of digital solutions for data-driven delay management, addressing three objectives: identify and conceptualise real-time technologies used in construction projects, with a focus on delay alert management (OBJ_3), evaluate the benefits of integrating combined digital technologies versus stand-alone systems in construction project tracking management including delay and risk tracking (OBJ_3), and evaluate digital technologies for managing data acquisition, screening, analysis, and presentation in construction projects, with an emphasis on delay alerts (OBJ_3). Through a framework analysis, the chapter identifies the strengths and limitations of various digital tools, emphasising their role in early-stage delay notification. The findings are integral to the development of the RealCONs framework.

Chapter 4 introduces the novel process-based framework called RealCONs framework. This chapter is spine of the doctoral thesis and covers a main core objective (OBJ_4): “develop a process based real-time data-driven construction project analysis framework (RealCONs) focus on and classify Early Delay Notifications Indexes using EVM indexes”. This real-time, data-driven construction project analysis framework focuses on classifying early-stage delay notification indexes using earned value metrics such as the Schedule Performance Index (SPI) and Cost Performance Index (CPI). Developed using design science research and expert feedback, the framework is validated through case reviews. This chapter demonstrates the practical application of RealCONs in enhancing delay detection and management.

Chapters 5 to 8 evaluate the proposed RealCONs framework for data collection, integration, analysis and visualisation (OBJ_5). They are iteratively and incrementally, focusing on different aspects to achieve comprehensive validation as follows:

- **Chapter 5** presents a case study on the design and implementation of a real-time progress tracking system in a construction project. It analyses the effectiveness of real-time stakeholder communication and the system's ability to track milestones and identify delays. The findings underscore the system's role in fostering collaboration and accelerating decision-making. In other words, Chapter 5 investigates the development and effectiveness of real-time project progress tracking tools for construction projects, focusing on the integration of digital solutions to monitor milestones and productivity.
- **Chapter 6** explores real-time productivity tracking in smart construction projects, analysing the impact of tracking systems on planning, construction, and quality data. The chapter demonstrates how real-time systems enhance efficiency, providing insights into minimising delays and improving productivity. Moreover, this chapter explores the application of advanced technologies in smart construction projects, specifically how real-time data and analytics can enhance productivity tracking and decision-making.
- **Chapter 7** focuses on automated delay management systems for electrical and instrument works. By integrating Building Information Modelling (BIM) with Microsoft tools, the chapter showcases a system that automates delay detection and scheduling accuracy, offering precise control over project timelines. However, Chapter 7 develops an automated system using BIM (Building Information Modelling) and Microsoft tools to manage delays in electrical and instrumentation works, incorporating Earned Value Management (EVM) for better project control.
- **Chapter 8** presents a case study on using smart devices for real-time data collection and analysis in electrical and instrument works. The findings highlight the benefits of real-time

data in project execution, decision-making, and delay reduction. In other words, this chapter implements a real-time, data-driven analysis model for electrical, and instrumentation works, focusing on using real-time data to predict delays and enhance project outcomes in construction projects.

- **Chapter 9** synthesises the RealCONs framework into the SMART framework, addressing OBJ_5. This chapter evaluates the framework’s performance compared to existing approaches using early-stage delay notification indexes such as SPI and CPI. The proposed framework integrates multiple digital technologies, demonstrating its effectiveness in reducing delays and optimising construction project management.

To clarify the timing and method of its alerts, the RealCONs framework generates and issues early notifications of delays and risks through the continuous, real-time monitoring of project performance. This process works by automatically comparing planned schedules, performance indices, and real-time data on actual progress:

WHEN	<ul style="list-style-type: none"> - Work is incomplete by the planned finish date, or actual progress is significantly behind schedule. - Tasks not on the critical path start consuming float, threatening critical successors. - Power BI’s look-ahead filter shows upcoming tasks at risk of delay due to slow predecessors. - EVM and ESM metrics slipped 												
HOW	<p>If any of the following conditions are met, RealCONs triggers early alerts:</p> <table border="1" style="width: 100%; border-collapse: collapse;"> <thead> <tr> <th style="width: 20%;">Step</th> <th>Description</th> </tr> </thead> <tbody> <tr> <td>1. Monitor</td> <td>Real-time site data and progress from QR scans</td> </tr> <tr> <td>2. Compare</td> <td>Match against Primavera baseline and EV/ES metrics</td> </tr> <tr> <td>3. Analyse</td> <td>Calculate SPI, SV, SV(t), and float consumption</td> </tr> <tr> <td>4. Trigger</td> <td>Early notification logic initiates if thresholds are exceeded</td> </tr> <tr> <td>5. Notify</td> <td>Alerts are sent via Power BI, email, and mobile apps</td> </tr> </tbody> </table>	Step	Description	1. Monitor	Real-time site data and progress from QR scans	2. Compare	Match against Primavera baseline and EV/ES metrics	3. Analyse	Calculate SPI, SV, SV(t), and float consumption	4. Trigger	Early notification logic initiates if thresholds are exceeded	5. Notify	Alerts are sent via Power BI, email, and mobile apps
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4. Trigger	Early notification logic initiates if thresholds are exceeded												
5. Notify	Alerts are sent via Power BI, email, and mobile apps												

Condition	Triggered If...	Consequence
SPI < 1	Progress is slower than planned	Schedule risk
SV(t) < 1	Earned work lags behind time	Delay warning
Actual Finish > Planned Finish	Task slippage	Immediate alert
Float consumed	< 1 day float remaining	Risk to critical path
Critical successor impacted	Predecessor delayed	Time Impact Fragment created

Finally, **Chapter 10** concludes the thesis, summarising the research contributions and how the objectives were achieved. The chapter discusses the limitations of the study and provides recommendations for future research, focusing on enhancing real-time data collection, analysis, and visualisation techniques for improved delay management.

10.2 RESEARCH OBJECTIVES DEVELOPMENT

This research aimed to address three key questions: Q1) *What causes delays in major construction projects and how they affect stakeholder collaboration?* Q2) *How digital technologies being used to improve major construction projects key performance (e.g. delay, risk)?* and Q3) *How proposed framework to be designed and evaluated (focusing on performance and in-depth early delay detection and their impacts)?* These questions were explored through a series of interconnected objectives, methodologies, and analyses, with the findings systematically presented in the respective chapters. Figure 10.1 depicts this research objectives, methodologies and outcomes.

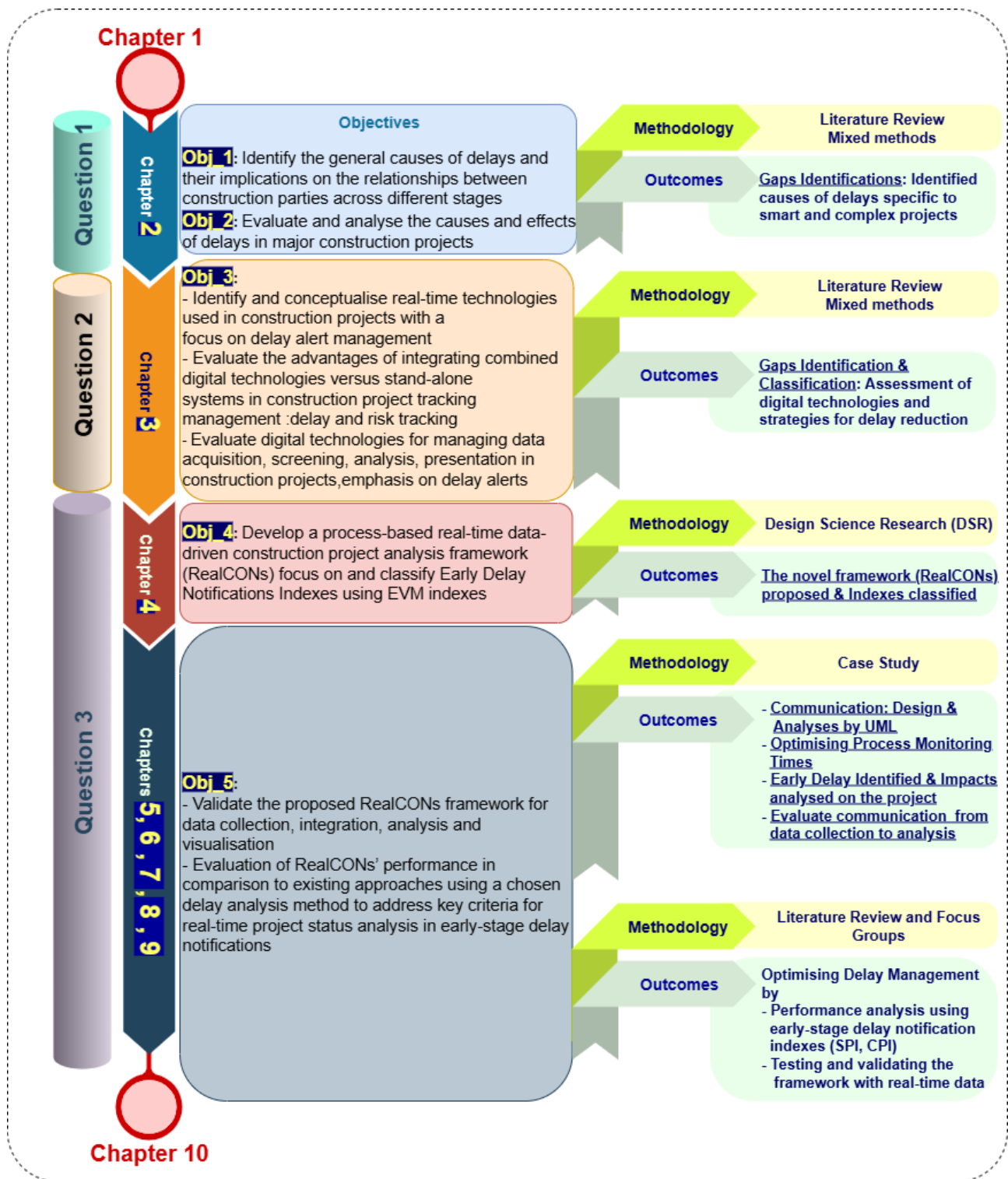


Figure 10.1: Doctoral research objectives, methodologies and outcomes

The first two questions (Q1 and Q2) sought to design a smart, centralised data acquisition and management system to address the challenges of early-stage delay notification across the project life cycle. This was achieved through a comprehensive examination of the causes of delays in Chapter 2.

Using literature review and mixed methods, the chapter identified key delay causes specific to smart and complex construction projects. The analysis employed techniques such as citation analysis, content analysis, and the Relative Importance Index (RII), providing an in-depth understanding of the root causes of delays and their implications for stakeholders. These findings laid a foundational understanding critical to the development of a robust delay notification system.

Chapter 3 built upon this understanding by systematically reviewing existing digital technologies and strategies for managing delays. Addressing Objectives 3, 4, and 5, the chapter used systematic and framework analyses to evaluate the effectiveness of stand-alone and integrated digital technologies for delay reduction. The findings provided a comprehensive assessment of these technologies across the construction data lifecycle, particularly their capacity for early-stage delay notification. This chapter highlighted the potential of emerging technologies to address current limitations in delay management, further informing the design of the proposed system.

The second research question (Q3) focused on validating an integrated, real-time framework for effective delay management. Chapter 4 introduced the RealCONs framework, directly addressing Objective 6 and the first research question. Through Design Science Research (DSR) and expert feedback, the chapter presented a real-time, data-driven construction project analysis framework. The analysis employed case reviews and comparative methods, proposing a solution tailored to the unique needs of construction projects. The RealCONs framework demonstrated how a centralised system could support early-stage delay notifications by leveraging data integration and advanced analytics.

Chapters 5 to 9 collectively addressed this by evaluating the RealCONs framework through iterative case studies. Chapter 5 presented the design and implementation of a real-time progress tracking system, offering practical insights into its application. The findings underscored the system's capacity to enhance stakeholder communication and facilitate the timely identification of potential delays.

Chapter 6 further explored the practicality of the RealCONs framework by examining real-time productivity tracking in smart construction. The analysis highlighted the system's effectiveness in improving planning, execution, and quality metrics, thereby contributing to overall project efficiency.

Chapter 7 expanded on this by showcasing an automated delay management system specifically for electrical and instrument works. Through Earned Value Analysis (EVA) and automated delay detection, the chapter demonstrated how real-time tools could improve scheduling accuracy and control project timelines.

Chapter 8 provided a detailed performance analysis of real-time data in project execution, focusing on electrical and instrument works. The findings demonstrated how real-time data collection and analysis enhanced decision-making, reduced delays, and improved project outcomes.

Finally, Chapter 9 synthesised these findings into the RealCONs as a SMART framework, addressing Objective 8. Using methodologies such as content analysis, comparative analysis, and the Analytic Hierarchy Process (AHP), the chapter evaluated the RealCONs framework's performance against existing approaches. The framework was validated using early-stage delay notification indexes such as SPI and CPI, demonstrating its effectiveness in optimising delay management across various construction contexts.

In conclusion (chapter 10), the research successfully addressed both questions, achieving all objectives through rigorous methodologies and analyses. The RealCONs framework provides innovative, data-driven solutions for delay management, offering significant contributions to the field of construction project management.

10.3 RESEARCH CONTRIBUTION AND RECOMMENDATIONS

This doctoral thesis has made significant contributions of theoretical, technical, and practical value. The methodologies employed in this research—namely (1) Literature Review, (2) Mixed Methods (focus groups combining qualitative and quantitative analysis), (3) Design Science Research (DSR) for the design and development of the RealCONs framework, and (4) Case Studies for implementation and validation—have enabled triangulation and strengthened evidence-based conclusions. By adopting a multidisciplinary approach, this study integrates theoretical frameworks from various disciplines, laying the groundwork for importing new concepts and enhancing understanding within construction project management. The inclusion of expert opinions from the construction industry has validated the research findings and reinforced their practical relevance. Moreover, the study bridges theory and practice, offering insights that form a foundation for managerial recommendations. The analysis of real-world delay scenarios has enriched the research outcomes, presenting classified strategies that can make this knowledge area more accessible to construction professionals while raising awareness about critical issues in delay management.

10.3.1 Integration of Saunders' Onion Model

The research philosophy underpinning this doctoral study is closely aligned with Saunders' Onion Model, a framework that offers a structured and systematic approach to research design by addressing successive layers of philosophical, methodological, and practical considerations. Each layer of the model provides clarity and coherence to the research process, ensuring its alignment with the study's objectives and context. At the core of this research lies a positivist paradigm, which focuses on objective analysis and evidence-based conclusions. This philosophical stance is well-suited to the research objectives, as it seeks to develop a data-driven framework for delay management


in construction projects. The positivist approach is complemented by a pragmatic orientation, allowing the research to balance theoretical rigour with practical relevance.


The methodology adheres to the deductive reasoning approach, a hallmark of positivist research, wherein hypotheses are systematically developed and tested through empirical evidence. This study leverages mixed methods, including qualitative and quantitative analyses, as well as Design Science Research (DSR). DSR serves as the central strategy, enabling the iterative development, refinement, and validation of the RealCONs framework. This process not only aligns with the methodological layer of Saunders' Onion but also demonstrates adaptability to the complexities inherent in managing delays within construction projects. The layers of methodological choice and strategy outlined in Saunders' model are evident in the research design. The incorporation of case studies as a primary strategy provides a real-world context for validating the theoretical constructs of the RealCONs framework. These case studies exemplify the pragmatic stance of the research, allowing for iterative testing and refinement based on real-time project data. Furthermore, the integration of mixed methods, including content analysis, expert feedback, and comparative analyses, ensures a comprehensive exploration of the research questions, supporting the methodological rigor of the study.


In essence, the alignment of this research with Saunders' Onion Model underscores its structured approach to tackling a multifaceted problem in construction project management. By systematically navigating through the layers of the Onion Model—from philosophical underpinnings to practical application—the research ensures that the RealCONs framework is not only theoretically robust but also practically relevant. This alignment reinforces the methodological integrity of the thesis, ensuring that the research process remains both comprehensive and adaptable to the challenges of the construction industry.


10.3.2 Theoretical Contributions

This doctoral research provides a range of research novelty and theoretical contribution that significantly advance the body of knowledge in delay management for construction projects as follows:

 **Real-Time Delay Detection and Forecasting:** Integrates live site data for proactive delay identification before critical path impact.

 **Multiple Data Resource Integration:** Bridges planning (WBS, CPM), ERP (Aconex), BIM, and real-time streams into a unified delay modelling platform.

 **Actionable Delay Notifications:** Converts alerts into intelligent, evidence-based triggers for coordinated team response.

 **Dynamic Use of Time Impact Analysis (TIA):** Transforms TIA into a real-time, continuously updated project control mechanism.

Contribution to Construction Informatics

- Proposes a novel framework merging data analytics, simulation, and collaboration.
- Introduces a new classification of delay causes in complex projects.
- Advances theory using DSR methodology and SPI/CPI indicators.
- Validated through empirical case studies ensuring rigour and relevance.
- Offers recommendations and future research directions for the field.

By addressing these aspects, the research establishes a multidisciplinary theoretical foundation for delay management in construction, paving the way for future studies to build upon these

contributions. Each chapter adds a distinct layer to the academic discourse, collectively advancing the understanding and application of real-time, data-driven systems in the construction industry.

10.3.3 Practical Implications

The RealCONs framework offers a structured approach to real-time data collection, integration, analysis, and visualisation, enabling project stakeholders to make informed decisions and proactively manage delays. The framework is designed to be utilised by key stakeholders, including head contractors, subcontractors (Power BI users), BIM consultancy teams (engineering and design professionals), project analysts (planners and schedulers), and site supervisors. However, functionality of RealCONs framework includes data input, data processing and integration and output and decision-making support which can be listed as follows:

1) Data Input:

- Site Supervisors collect real-time data using smartphones and QR code scanning, capturing progress updates, resource usage, and delay events.
- Subcontractors (Power BI users) enter and review task progress, material deliveries, and productivity metrics.
- BIM Consultancy Teams integrate 4D scheduling using Navisworks/Revit and synchronise it with the project timeline imported from MS Project or Primavera P6.
- Project Analysts (Planners and Schedulers) process collected data, analyse Earned Value Management (EVM) metrics, and validate schedule impacts.

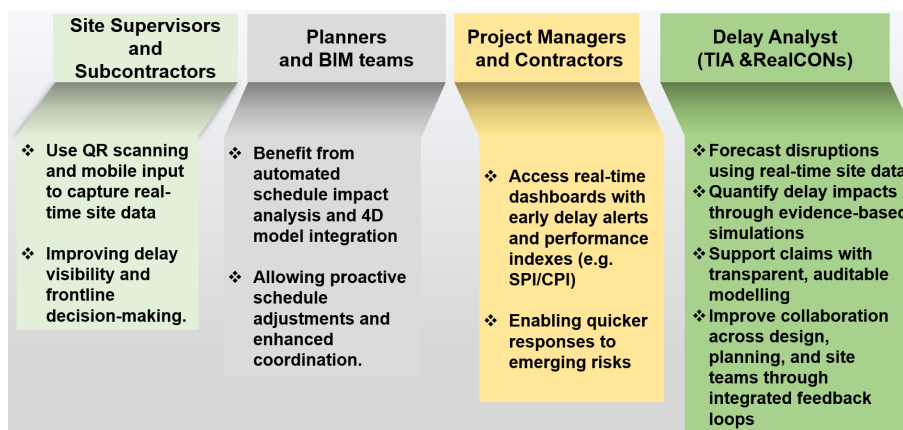
2) Data Processing and Integration:

- The collected data is centralised in a cloud-based SQL database, where it is structured and prepared for analysis.

- The framework processes this data using automated scripts to generate analytical reports and dashboards.

3) Output and Decision-Making Support:

- Project Managers and Head Contractors access real-time dashboards displaying Early Delay Notification Indexes, cost performance (CPI), and schedule performance (SPI).
- BIM Teams and Engineers visualise delays within the 4D model, ensuring better coordination in design and construction sequencing.
- Planners and Schedulers receive detailed impact analyses to refine project schedules and mitigate risks proactively.



As a result, traditional delay analysis methods, such as Time Impact Analysis (TIA) and As-Planned vs. As-Built, primarily focus on retrospective assessments, often identifying delays only after they have significantly impacted the project. These methods rely on periodic schedule updates, manual data entry, and subjective analysis, limiting their ability to detect and address delays proactively. In contrast, the RealCONs framework transforms delay management by enabling early-stage delay identification through real-time data collection and automated performance tracking.

RealCONs integrates site-collected data via QR scanning, BIM-based 4D scheduling, and cloud-based SQL databases, ensuring real-time data integration with project schedules. This immediate access to live project data enhances accuracy, reducing the reliance on outdated reports

and minimising human error. Additionally, RealCONs incorporates predictive analysis by continuously monitoring Earned Value Management (EVM) metrics, such as Schedule Performance Index (SPI) and Cost Performance Index (CPI), to forecast potential delays before they escalate. The framework's flexibility allows seamless integration with project management tools like MS Project and Primavera P6, providing dynamic schedule updates. Furthermore, its interactive dashboards improve stakeholder communication, ensuring that head contractors, subcontractors, planners, and site supervisors receive timely alerts, enabling proactive decision-making. By shifting from reactive to real-time delay management, RealCONs significantly enhances project efficiency and reduces costly disruptions.

10.4 RESEARCH LIMITATIONS

While this doctoral research has contributed significantly to the field of delay management in construction, several limitations must be acknowledged to provide a balanced perspective on the study and its findings:

- 1) *Scope of Case Studies*: The case studies conducted to validate the RealCONs framework were limited to specific construction projects, particularly in electrical and instrumentation works. While these provide valuable insights, the findings may not fully generalise to other types of projects, such as infrastructure or residential construction, which may involve different complexities and stakeholder dynamics.
- 2) *Focus on Select Delay Analysis Methods*: The study primarily focused on integrating selected delay analysis methods, such as Time Impact Analysis (TIA), within the RealCONs framework. Other methods, such as the Collapsed As-Built technique, were not included in the framework's validation, potentially limiting its comprehensiveness in certain scenarios.

- 3) *Real-Time Data Limitations*: The research assumes the availability of reliable and consistent real-time data. However, in practice, the quality and completeness of real-time data may vary due to issues such as sensor malfunctions, incomplete reporting, or technological limitations, which could affect the framework's performance.
- 4) *Technological Dependency*: The RealCONs framework relies heavily on digital technologies and tools for real-time data acquisition and analysis. This dependency may pose challenges for adoption in construction organisations with limited technological resources or expertise, particularly small and medium-sized enterprises (SMEs).
- 5) *Limited Consideration of Cost Implications*: The study primarily focuses on delay management without extensively addressing the cost implications of implementing the RealCONs framework. The financial feasibility of adopting the framework in projects with tight budgets has not been analysed in detail.

10.5 RECOMMENDATIONS FOR FUTURE RESEARCH STUDIES

Based on the findings and limitations of this research, the following recommendations are proposed to enhance the RealCONs framework for early-stage delay identification while aligning with Green Project Management (GPM) principles and the 17 Green Rules:

- 1) ***Advanced Data Screening with AI and Green Computing***: Future research should explore AI-driven data filtering techniques that minimise energy consumption and computational waste. Machine learning algorithms can enhance accuracy by reducing errors and noise in real-time data collection, ensuring a more **sustainable** and **efficient** screening process.
- 2) ***Optimised Data Analysis for Resource Efficiency***: Researchers should develop eco-friendly analytics platforms that optimise data processing while minimising carbon footprints. Energy-efficient

cloud computing and blockchain-enabled **green data management** can improve delay predictions without excessive energy consumption.

- 3) **Sustainable Data Visualisation Techniques**: Future studies should investigate low-energy digital dashboards and interactive platforms that enable **clearer and more actionable** delay notifications. This includes integrating real-time graphical representations that reduce paper-based reporting and enhance stakeholder engagement.
- 4) **Integration of Smart and Sustainable Digital Technologies**: Exploring the combination of **IoT, AI, and blockchain** can lead to **transparent, real-time monitoring** of construction processes while reducing waste and inefficiencies. For instance, IoT-enabled sensors can **track material usage**, detect **resource wastage**, and optimise project schedules to support greener construction practices.

At the end, while this research has advanced early-stage delay notifications in construction project management, future studies should focus on integrating green technologies to improve real-time data collection, analysis, and visualisation. By aligning RealCONs with sustainable project management principles, construction delays can be minimised while ensuring environmentally responsible project execution.

Appendices

Appendix 1: Ethics Approval and Documentation

Appendix 2: Facilitated Workshops Questions

Appendix 3: Statement of Contribution form

Appendix 1: Ethics Approval and Documentation



Date: 12 January 2021

Dear Kambiz (Cam) Radman

Re: Ethics Notification - 4000023782 - Delay Management: IoT based Data Fusion for Smart Progress Tracking for Construction Projects

Thank you for your notification which you have assessed as Low Risk.

Your project has been recorded in our system which is reported in the Annual Report of the Massey University Human Ethics Committee.

The low risk notification for this project is valid for a maximum of three years.

If situations subsequently occur which cause you to reconsider your ethical analysis, please contact a Research Ethics Administrator.

Please note that travel undertaken by students must be approved by the supervisor and the relevant Pro Vice-Chancellor and be in accordance with the Policy and Procedures for Course-Related Student Travel Overseas. In addition, the supervisor must advise the University's Insurance Officer.

A reminder to include the following statement on all public documents:

"This project has been evaluated by peer review and judged to be low risk. Consequently, it has not been reviewed by one of the University's Human Ethics Committees. The researcher(s) named in this document are responsible for the ethical conduct of this research."

If you have any concerns about the conduct of this research that you want to raise with someone other than the researcher(s), please contact Professor Craig Johnson, Director - Ethics, telephone 06 3569099 ext 85271, email humanethics@massey.ac.nz."

Please note, if a sponsoring organisation, funding authority or a journal in which you wish to publish requires evidence of committee approval (with an approval number), you will have to complete the application form again, answering "yes" to the publication question to provide more information for one of the University's Human Ethics Committees. You should also note that such an approval can only be provided prior to the commencement of the research.

Yours sincerely

Professor Craig Johnson
Chair, Human Ethics Chairs' Committee and Director (Research Ethics)

Research Ethics Office, Research and Enterprise
Massey University, Private Bag 11 222, Palmerston North, 4442, New Zealand T 06 350 5573; 06 350 5575 F 06 355 7973
E humanethics@massey.ac.nz W <http://humanethics.massey.ac.nz>

Appendix 2: Facilitated Workshops Questions

The purpose of the facilitated workshops is to gather expert insights and collaborative feedback to evaluate and refine the proposed real-time, data-driven delay management framework (RealCONs). These workshops aim to assess the framework's effectiveness in addressing key challenges associated with delay management in construction projects. Specifically, the workshops will focus on validating the framework's capacity to enable early-stage delay notifications, enhance data accuracy, and streamline decision-making processes. By aligning the discussions with research objectives, the workshops will provide a structured environment for participants to evaluate the integration of advanced digital technologies and their impact on project tracking, stakeholder communication, and delay analysis. The findings from these workshops will contribute to the development of a robust framework that can support decision-makers throughout the project life cycle, ultimately improving project performance in terms of time and cost efficiency.

The participants, drawn from a diverse pool of construction professionals, represent a balanced mix of head contractors, subcontractors, and engineering consultants. Each workshop will include 15 experts, ensuring equal representation of the three stakeholder groups, whose combined perspectives will provide a comprehensive understanding of the challenges and opportunities in managing delays. Participants bring extensive experience in large-scale construction projects and are familiar with advanced project management tools and methods, enabling them to provide informed opinions on the proposed RealCONs framework. Their involvement ensures that the framework is evaluated in real-world contexts, accounting for the practical realities and varying priorities of different construction roles. This diversity of experience and expertise will help ensure that the workshop outputs are both practically relevant and academically robust.

Facilitation Notes

- **Format:** Each question will be explored in a structured discussion format, allowing participants to share insights based on their experience.
- **Objective Alignment:** Ensure discussions address both research questions and align with the objectives outlined.
- **Participant Engagement:** Encourage diverse perspectives from head contractors, subcontractors, and consultants to ensure a balanced and comprehensive evaluation.
- **Output:** Consolidate findings into actionable recommendations for improving the RealCONs framework and supporting real-time delay management in construction projects.

✚ **Main Research Questions:**

- 1) How can a smart, centralised data acquisition and management system be designed to support the entire project life cycle, enabling early-stage delay notification?
- 2) How can an integrated, real-time, data-driven framework be developed and validated for effective delay management in construction projects?

✚ **Objectives-Based Questions**

❖ **For Research Question 1:**

1) **Delay Causes and Relationships:**

What are the most common causes of delays in construction projects, and how do they affect relationships between contractors, subcontractors, and consultants at different stages of the project?

2) **Analysis of Delays:**

How can major delay causes and their effects be effectively identified and analysed to improve project outcomes?

3) **Technological Application:**

What real-time technologies have you used or observed in construction projects for delay notification, and how effective were they?

4) **Integration vs. Stand-alone Systems:**

What are the perceived benefits or challenges of integrating digital technologies compared to using stand-alone systems for project tracking and delay management?

5) **Digital Technologies for Data Management:**

How do you evaluate the effectiveness of digital tools in managing data acquisition, screening, analysis, and presentation, specifically for addressing delay alerts?

6) **Development of RealCONs Framework:**

What features should a real-time data-driven framework (e.g., RealCONs) include to effectively classify and manage Early Delay Notification Indexes (EV metrics)?

❖ **For Research Question 2:**

1) **Evaluation of RealCONs:**

Based on your experience, how could the RealCONs framework be evaluated in terms of its ability to collect, integrate, analyse, and visualise real-time data for delay management?

2) **Comparative Performance:**

How should the performance of RealCONs be compared to existing delay analysis methods to address key criteria such as accuracy, flexibility, and real-time status updates?

Appendix 3: Statement of Contribution form

The DRC 16 form has been completed, signed for each chapter, and included at the beginning of each chapter separately.

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