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Real-Time tracking and analysis in construction projects: A RealCONs framework

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ABSTRACT

Construction projects increasingly rely on processing vast amounts of data from multiple sources, including consultants (BIM), cloud-based project management platforms (e.g., Aconex), 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.

1. Introduction

Construction project management continues to face persistent challenges, notably delays, cost overruns, safety risks, and inefficiencies in resource allocation [1,2,3,4]. 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 [7,8,9,10,11,12]. 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 [10,14]. Emerging solutions—such as AI, digital twins, and real-time analytics—have shown potential in academic literature [15,16,6], 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 et al. [19], Zhang et al. [20] and Liao et al. [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

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significant financial and operational consequences of delays, as evidenced by recent case studies. For instance, analyse delays in megaprojects, revealing substantial cost overruns and schedule deviations that could have been mitigated through proactive, data-driven management [23,24,25]. Furthermore, Kalf et al. [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 [28,14,29,30,14]. Moreover, the dynamic nature of construction projects, with frequent changes and variations, makes it difficult to synchronise updates across all parties involved [17,31]. 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 [32,19,33]. 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 [34]. From literature reviews [35–37], 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 [35,38]. 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 [39], 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.

2. Research methodology

This study adopts a multi-stage methodology grounded in pragmatic principles [40], 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. Fig. 1 illustrates the 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

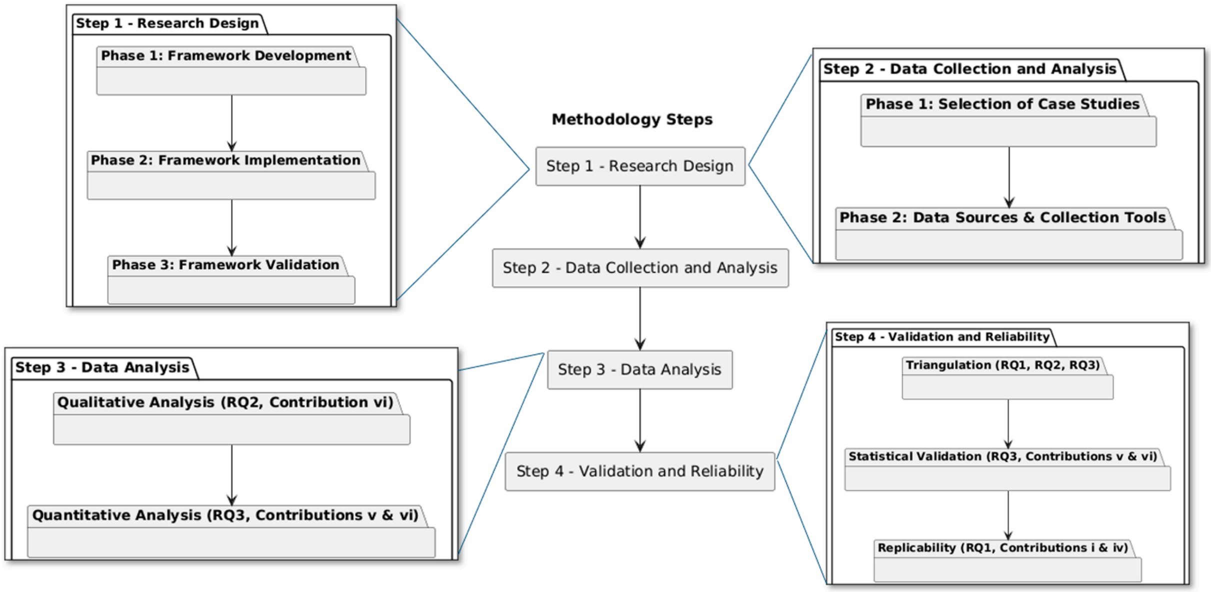


Fig. 1. Methodology's Steps.

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 $100 M. Data was gathered from multiple integrated sources to validate RealCONs' robustness, including:

- o **Construction Area**: On-site progress is captured via QR codes and smartphones.
- o **SQL Database**: Labour hours, material costs, and progress percentages processed for real-time analysis.
- o **BIM**: Integrated 3D models and clash detection reports.
- o **Oracle P6**: Planning and scheduling data for real-time monitoring.
- o **Oracle Aconex**: RFIs, delay notifications, and communication records to assess workflow efficiency.
- o **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 [41] principles of information-oriented case selection, where extreme cases prove particularly revealing about underlying operational mechanisms [42].

3. 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.

3.1. 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 $100 M to $115 M 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 (10,890 m – 14,000 m), containment (12,000 m – 15,800 m), 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.

3.2. Case studies and current data flow processes

To exemplify the data flow processes throughout projects, Figs. 2 and 3 illustrate the interactions among three key actors: the consultant (responsible for BIM, design, and engineering), subcontractors, and the head contractor. Fig. 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.

Fig. 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.

Based on Figs. 2 and 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 Fig. 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.

Table 1
Selected Projects Details: E&I Value and Scale per Project.

Project Features	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

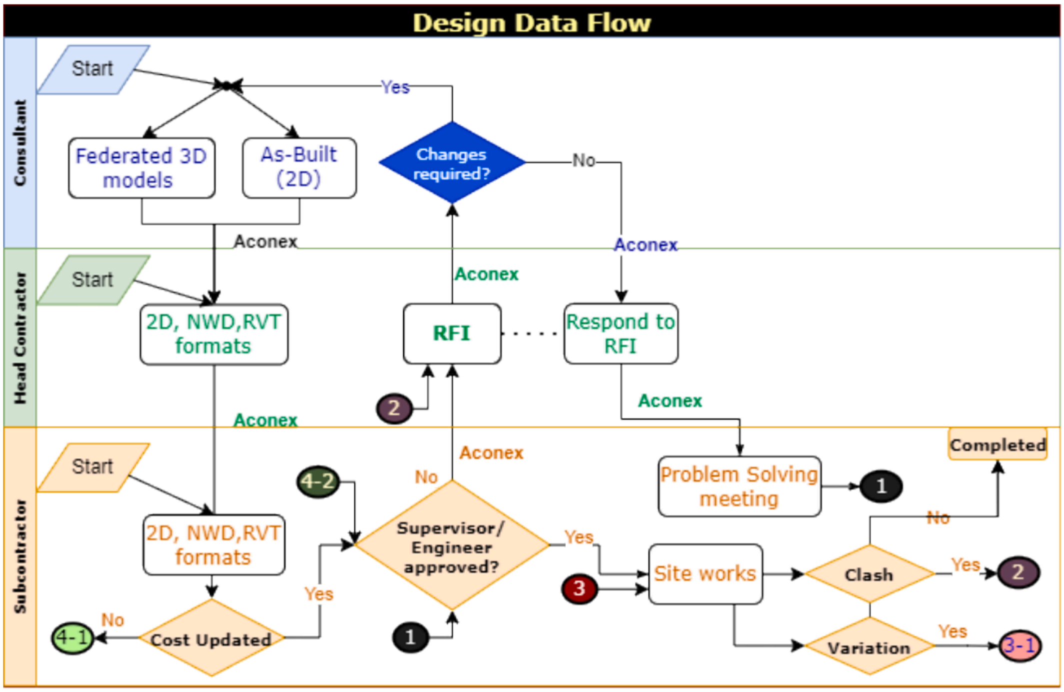


Fig. 2. Existing Drawings/3D Data Flow.

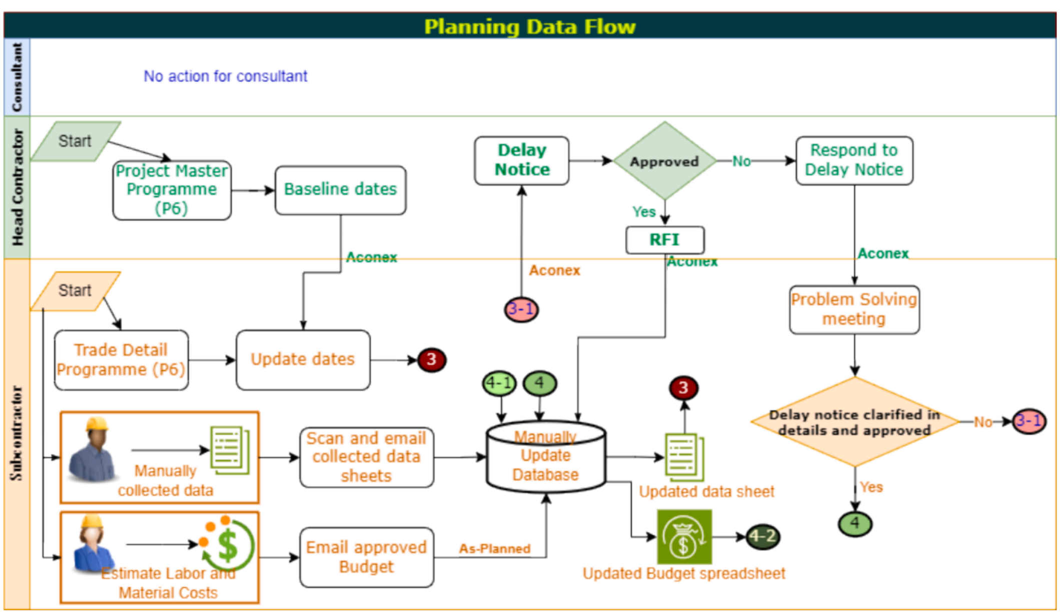


Fig. 3. Existing Project Data Flow Interaction.

In addition to the previous explanation, Figs. 4 and 5 illustrate the activity and sequence diagrams to visualize the data flow processes outlined in Figs. 2 and 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.

4. The proposed conceptual framework

Based on Section 3 (Case Study) and an in-depth analysis [28,29], 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,

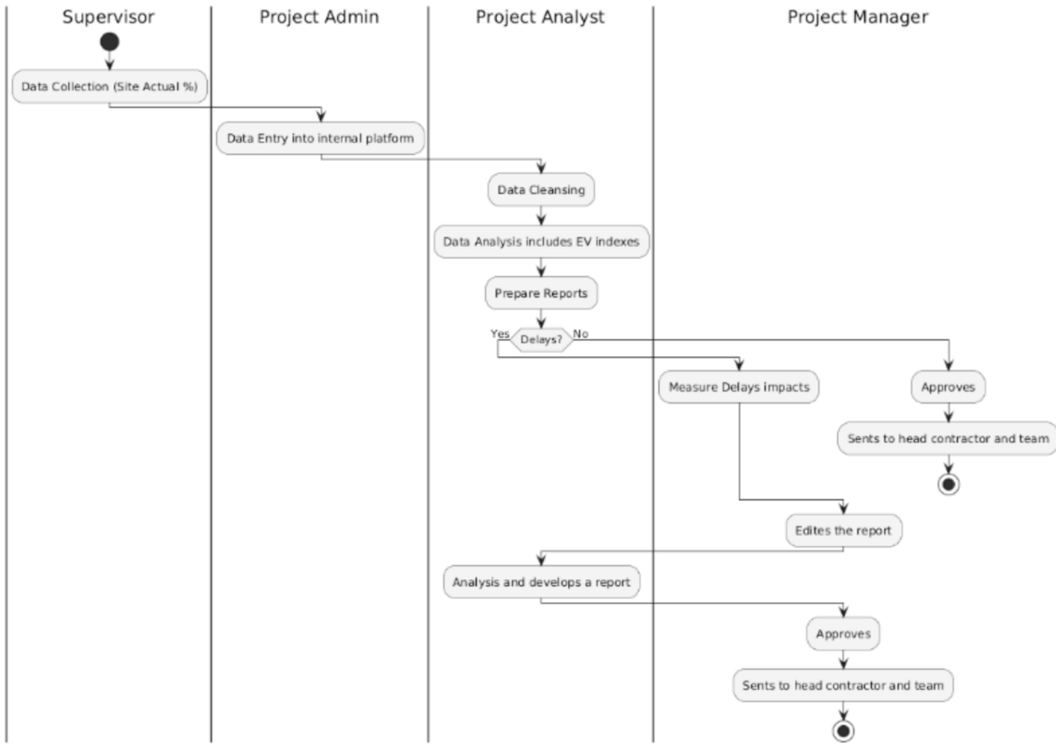


Fig. 4. Existing Process Activity Diagram.

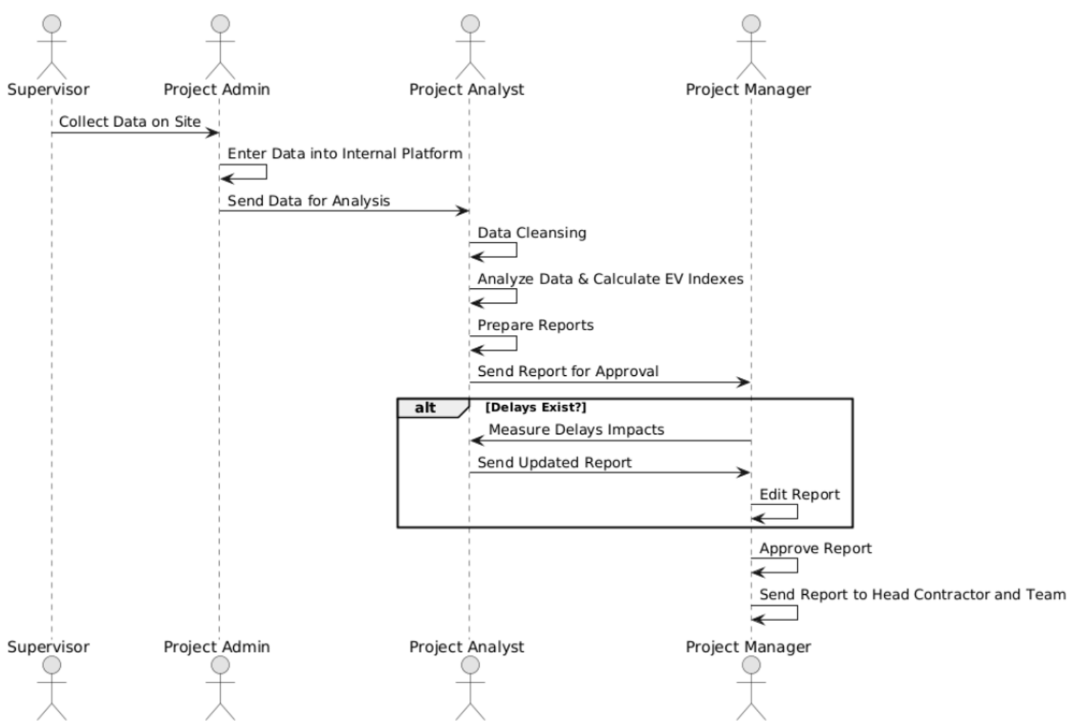


Fig. 5. Existing Process Sequence Diagram.

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:

4.1. Framework components and interactions

As illustrated in Fig. 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)

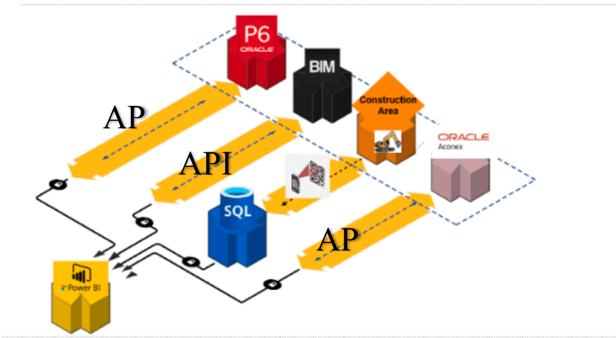


Fig. 6. The Conceptual Framework of RealCONs.

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.

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.

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. Fig. 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:

4.2. *Construction area*

Fig. 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.

Figs. 8–10 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 input data 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.

4.3. *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,

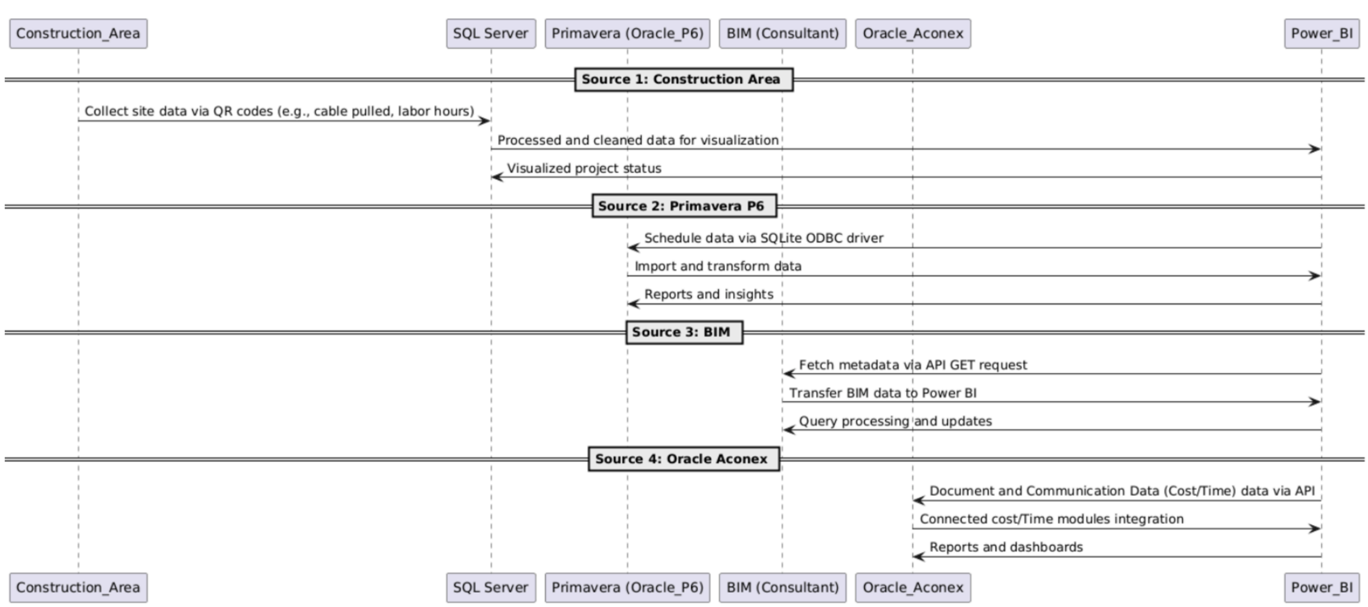
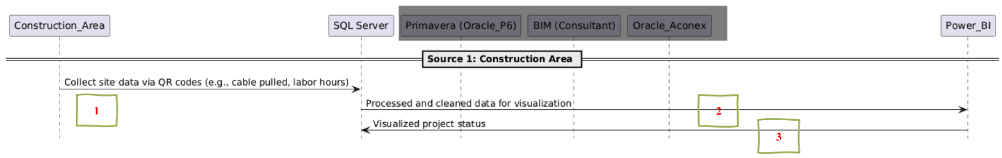


Fig. 7. Type and Direction of Data Flow Throughout RealCONs Framework.



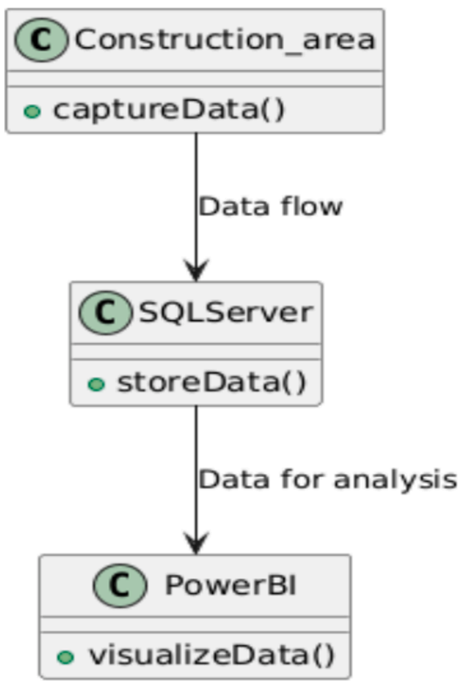


Fig. 8. Section 4.1 Mapping.

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 (See Fig. 11).

4.4. BIM (Consultant)

As shown in Fig. 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, change registers, schedules of quantities, and more, ensuring timely, accurate information for all stakeholders.

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.

Fig. 9. GUI On Smart Devices.

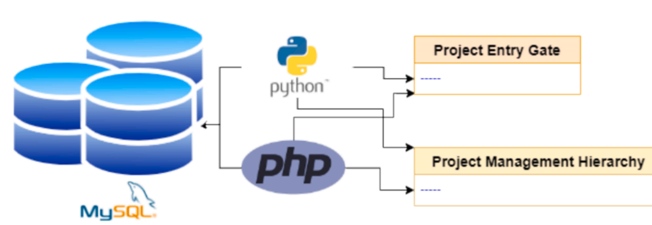


Fig. 10. Interaction Languages.

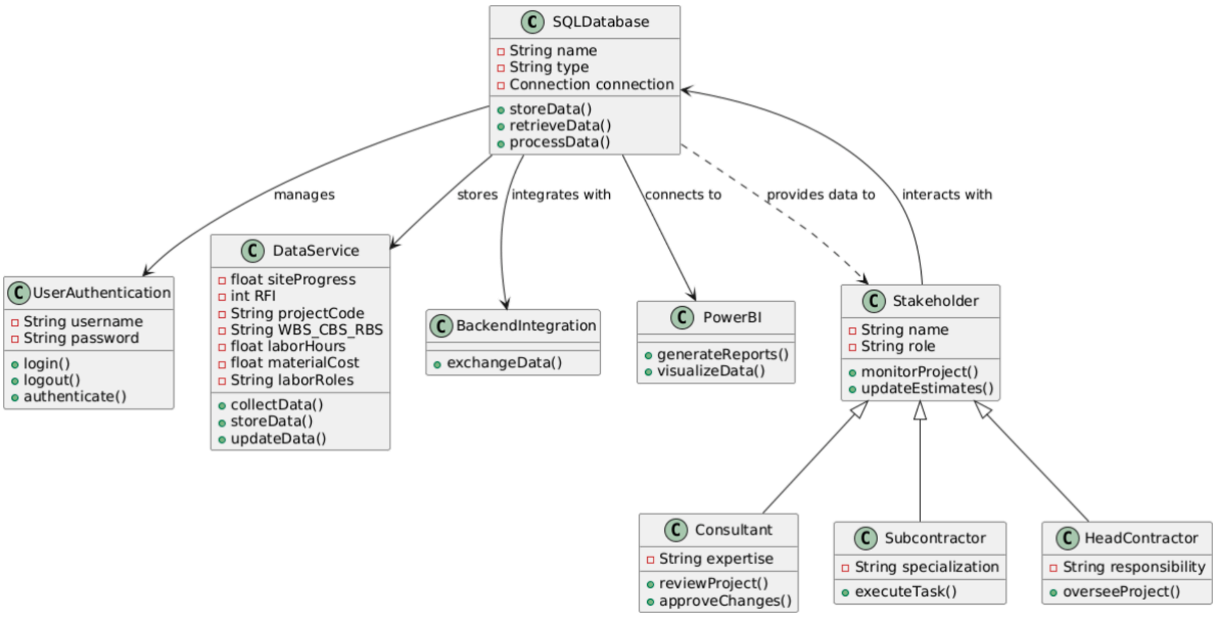


Fig. 11. SQL_Database Mapping.

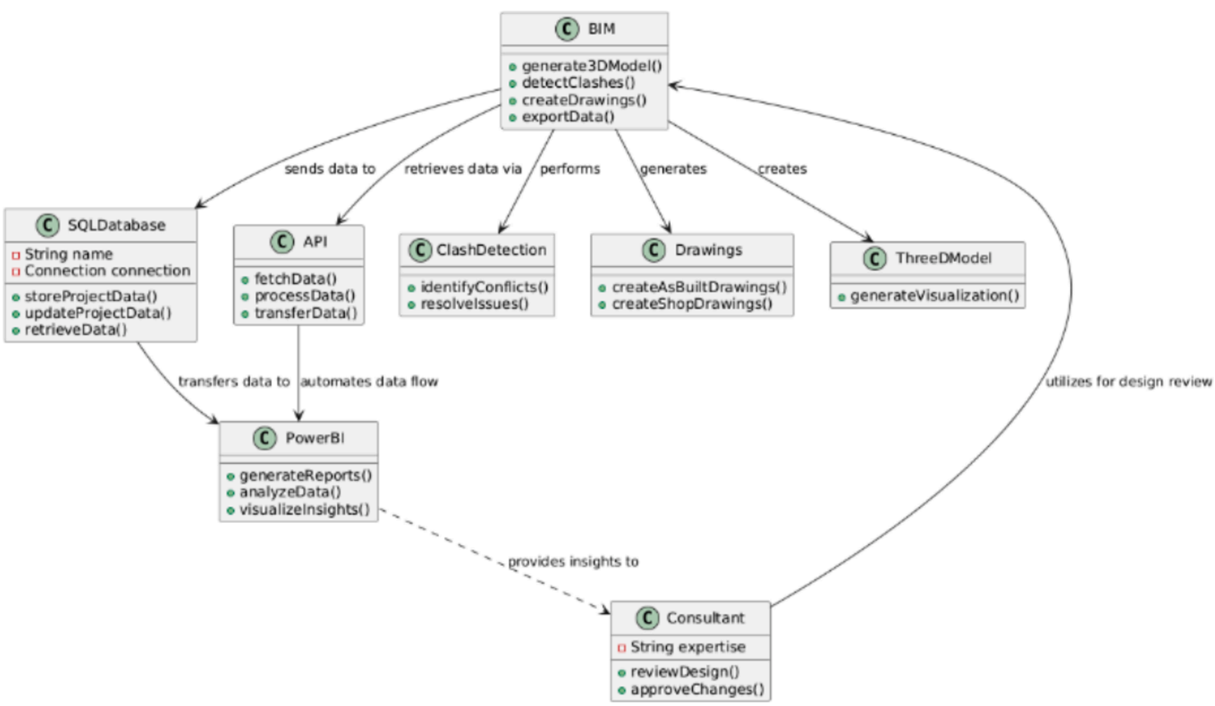


Fig. 12. BIM_Consultant Mapping.

4.5. *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. Fig. 13 illustrates the RealCONs oracle_P6 component mapping approach.

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

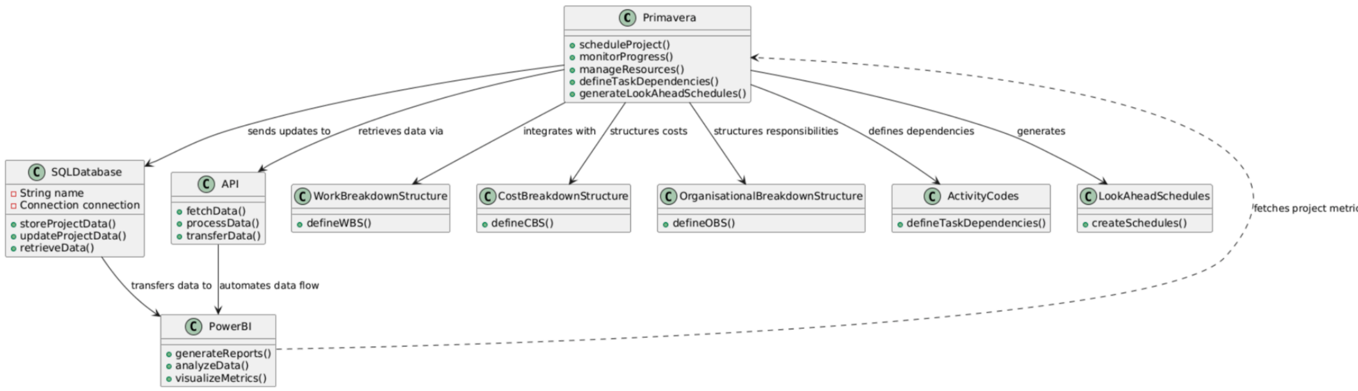


Fig. 13. Oracle_P6 Mapping.

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.

4.6. Oracle-Aconex

As shown in Fig. 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.

4.7. 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

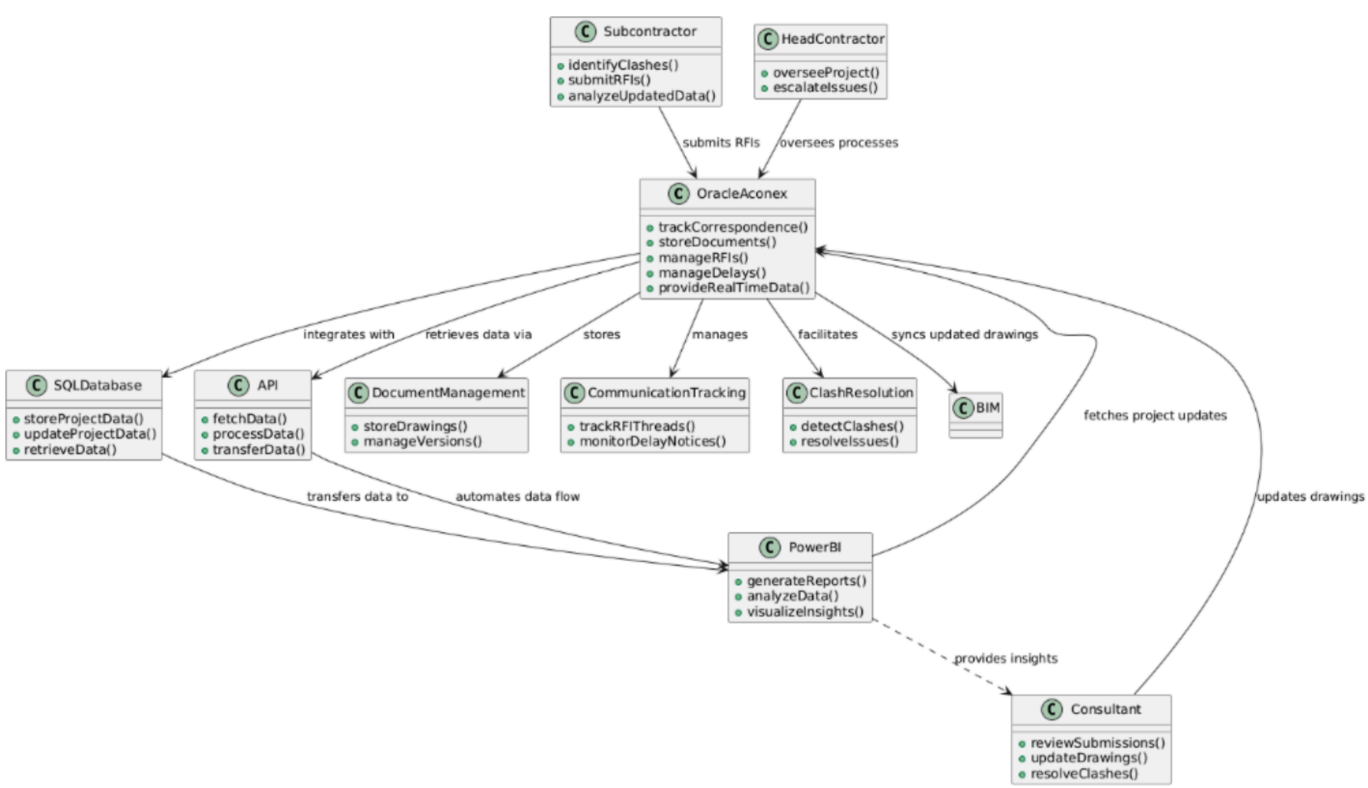


Fig. 14. Oracle_Aconex Mapping.

(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 (See Fig. 15).

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. Fig. 16 illustrates the RealCONs Power BI component mapping approach.

5. 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.

5.1. Overview of the existing process

Figs. 4 and 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.

5.2. Overview of RealCONs framework process

Fig. 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,

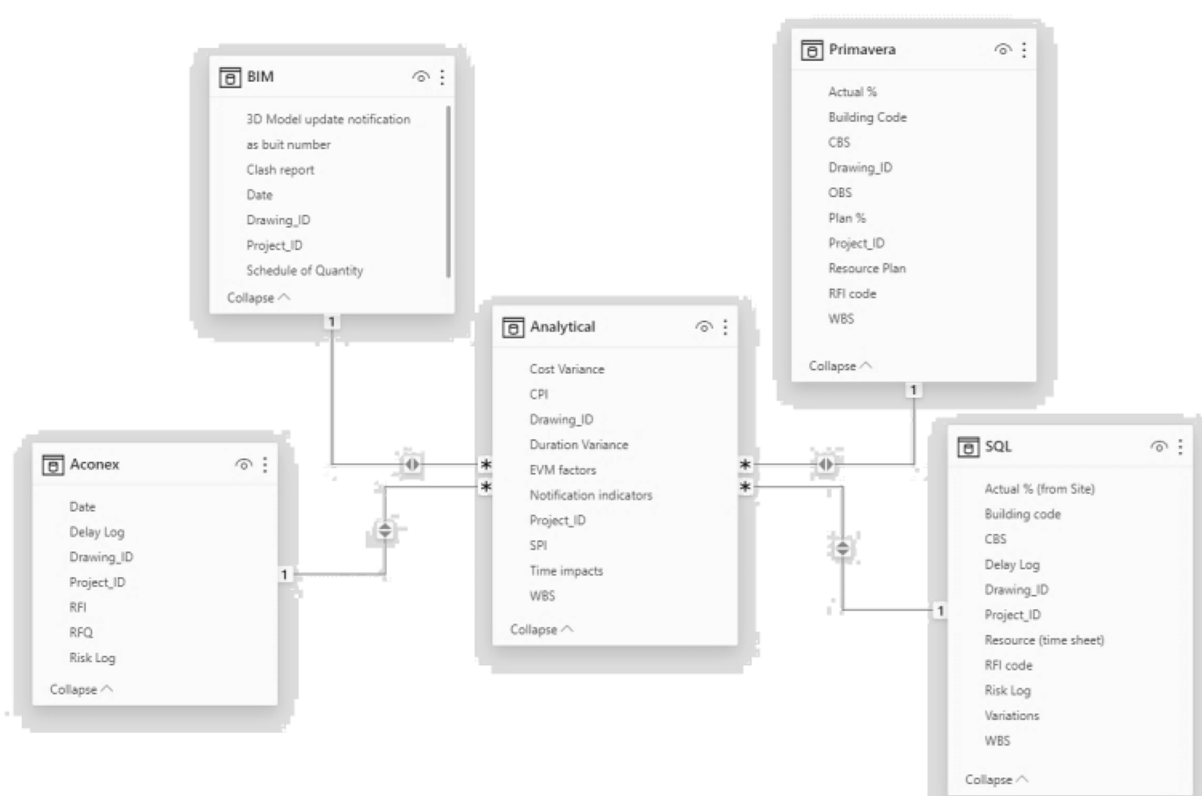


Fig. 15. Power BI Modelling Cutoff View.

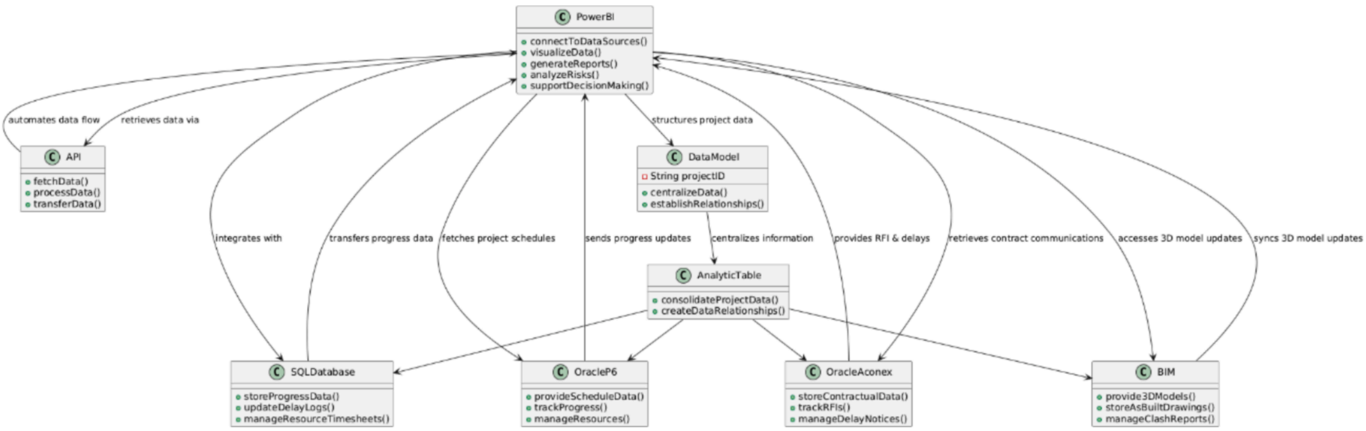


Fig. 16. Power BI Mapping.

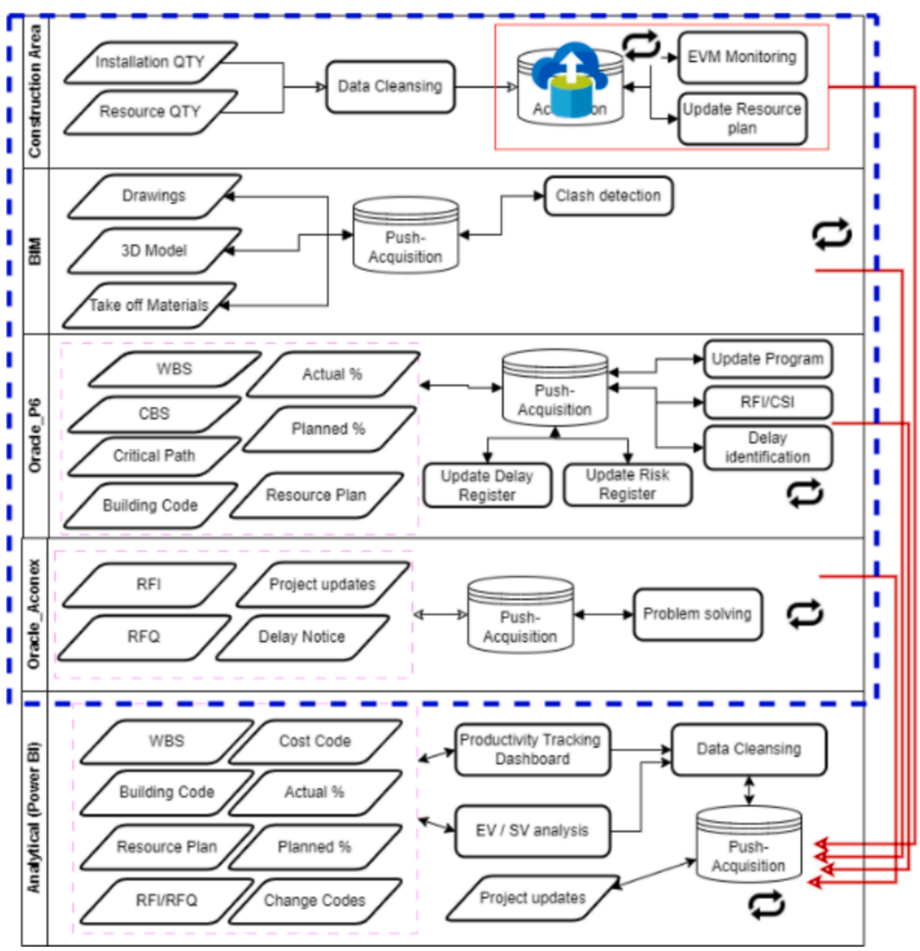


Fig. 17. Technical View of RealCONs.

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 Fig. 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.

Fig. 18 outlines three steps: Data Acquisition, Analysis &

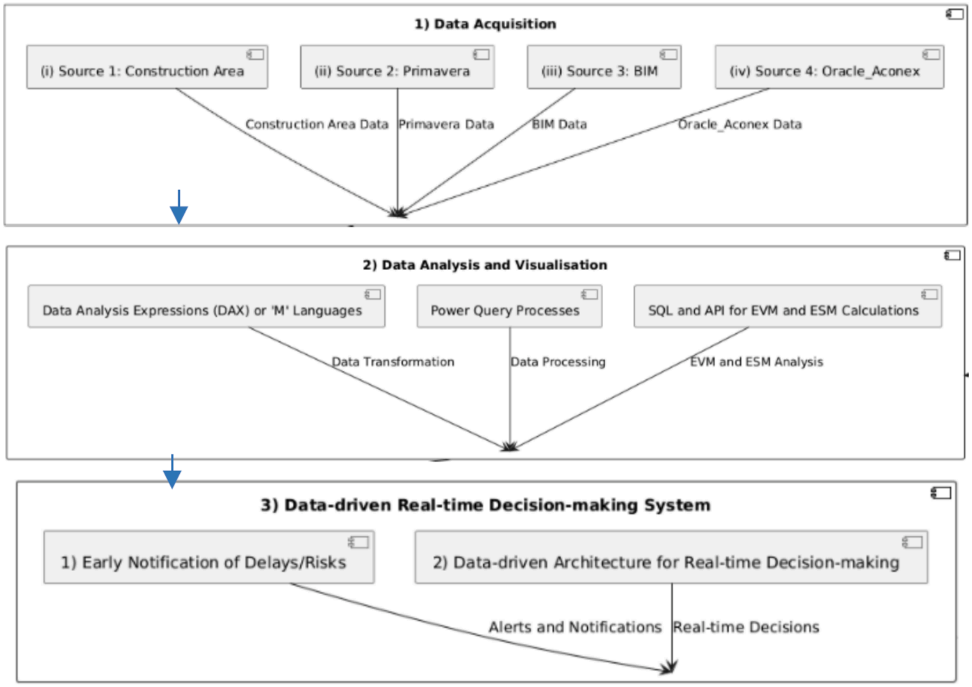


Fig. 18. Steps of RealCONs framework process.

Visualisation, and Data-driven Real-Time Decision-Making.

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 Fig. 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. Figs. 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 (Fig. S1/1).

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 (Fig. 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.

Fig. S1/2. point to the threshold.

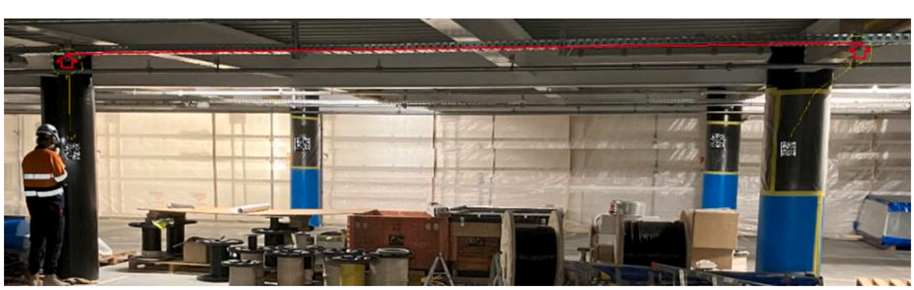


Fig. S1/1. point to point.

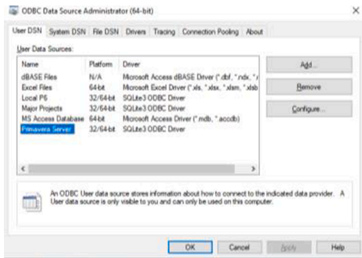


Fig. S2/1. SQLite ODBC driver.

From Figs. 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.

(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 (Fig. S2/1). This setup is called the 'Primavera Server' for better recognition.

Fig. 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": "2f641ftf-4bc4-412a-bb84-ffdb345e563c",
"metadata": {"IFC Type": "IfcBuilding",
"IFC GUID": "11tM97QqytWdIGvc4sMN3E",
"BuildingID": "n/a",
"IsPermanentID": "True",
"OccupancyType": "Project1″,
"IsLand marked": "True",
"NumberOfStoreys": 2
},
"parents": ["9ccddbd2-750d-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": {

(continued on next column)

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{"data": [
"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 Fig. 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" (Fig. 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.

(iv). Source 4 from oracle_Aconex: From Fig. 14, different API endpoints allow RealCONs to connect Aconex to Power BI to create interactive reports and dashboards. Therefore, Fig. 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 (Fig. S4/2). This data can then be used to create reports and dashboards in Power BI.

In summary, compared to the existing system (Figs. 4 and 5), RealCONs offers a significant advantage with real-time data access and circulation (Fig. 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 date for analysis. Tracking project status, including identifying delays, is crucial. Fig. 19 shows how Power BI integrates with SQL Server to update the EVM and ESM indexes through data fetched via APIs.

However, RealCONs uses Power BI queries to analyze integrated data with KPI factors from Earned Value Management (EVM) and Earned Schedule Management (ESM). Table 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,

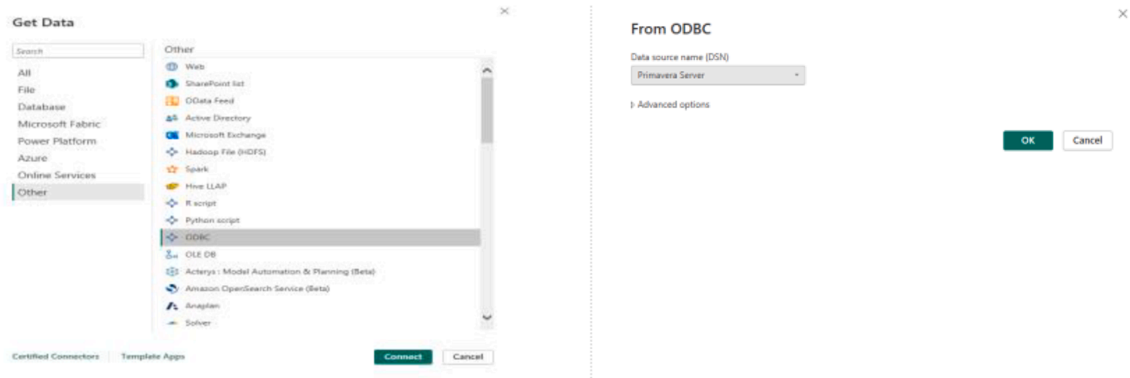


Fig. S2/2. ODBC on Power BI.

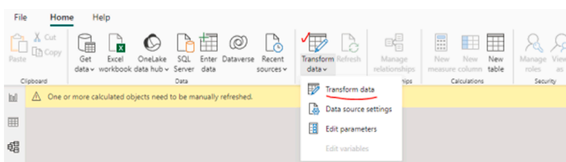


Fig. S3/1. Transform data to Power BI.

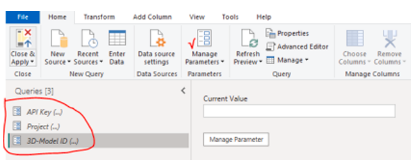


Fig. S3/2. Parameters Managing.

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.

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] (See Table 3).

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

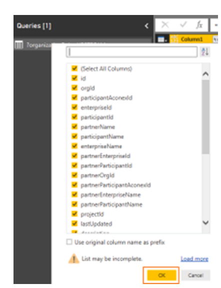


Fig. S4/2. Expand Record.

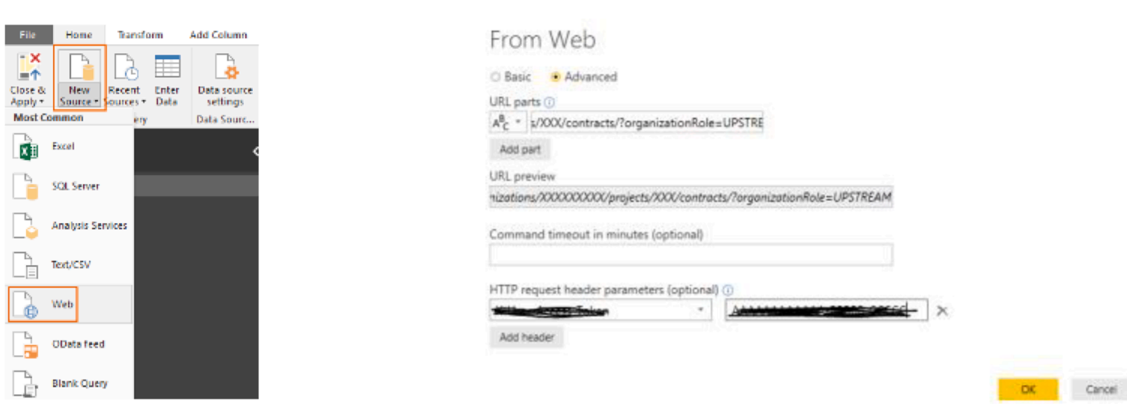


Fig. S4/1. New Source and WEB and URL Views.

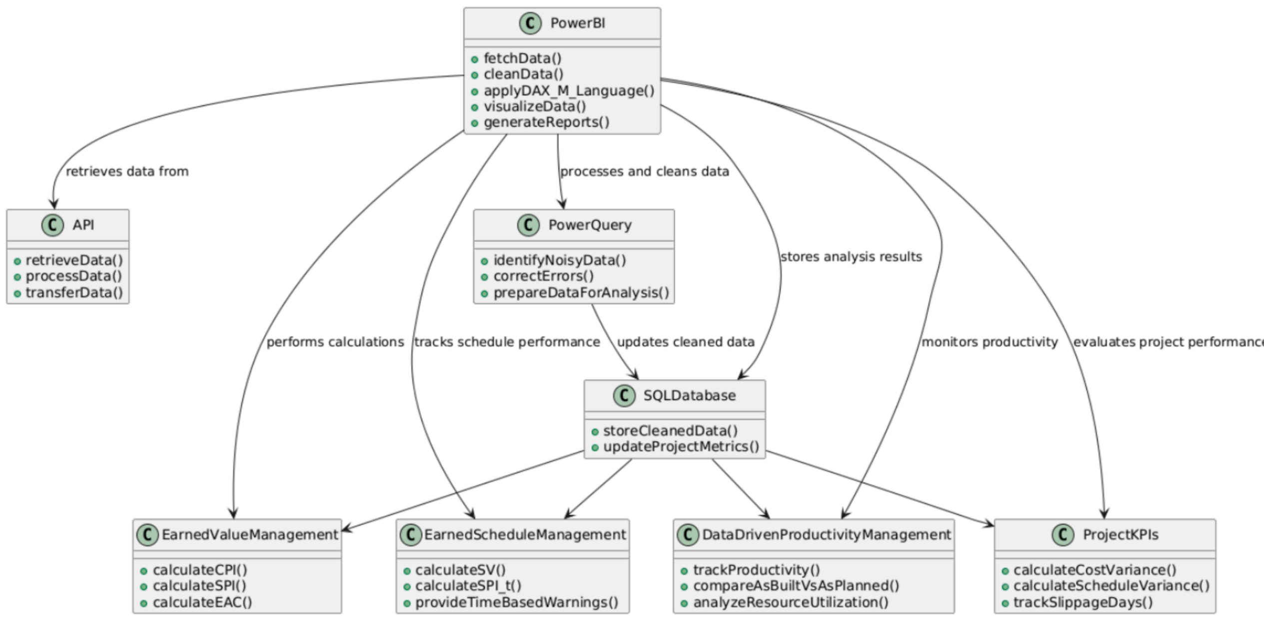


Fig. 19. Data Analysis and Visualisation Mapping.

Table 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 > PV
	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= 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>= BCWS	I= $(EV\text{-}PV_C)/(PV_{C+1} - PV_C)$	
	I: is increment index and uses PV and EV from EVM		
	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

Fig. 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 [54,45]. 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.

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.

Table 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

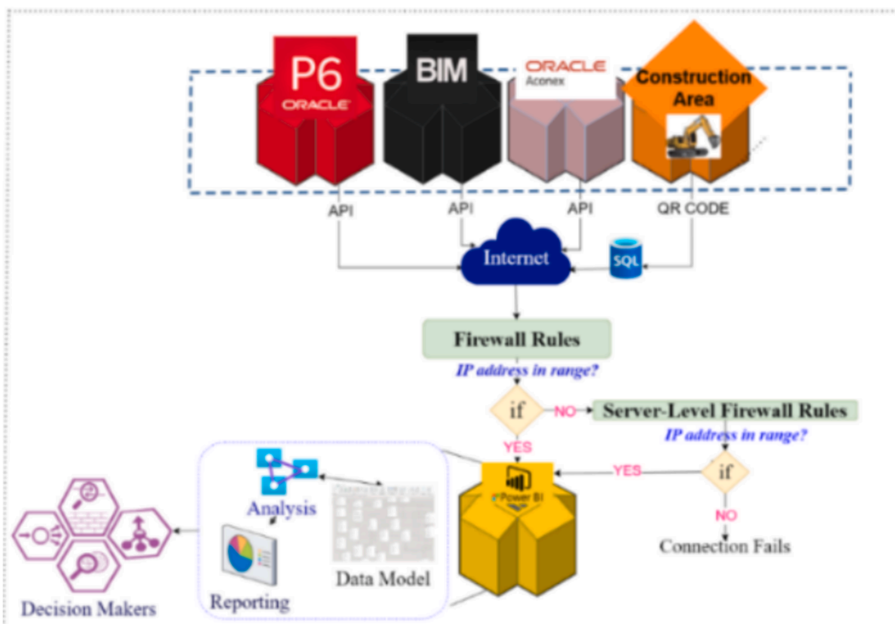


Fig. 20. Data-Driven Architecture of Real-Time Decision-Making.

5.3. Improving the existing process using the RealCONs framework

In comparison with the RealCONs approach (via Fig. 17) and existing approach (via Figs. 4 and 5), Fig. 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.

6. 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 Fig. 21, a traceable workflow comparison demonstrates the operational differences between the two approaches using real-world scenarios.

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 h 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. Fig. 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

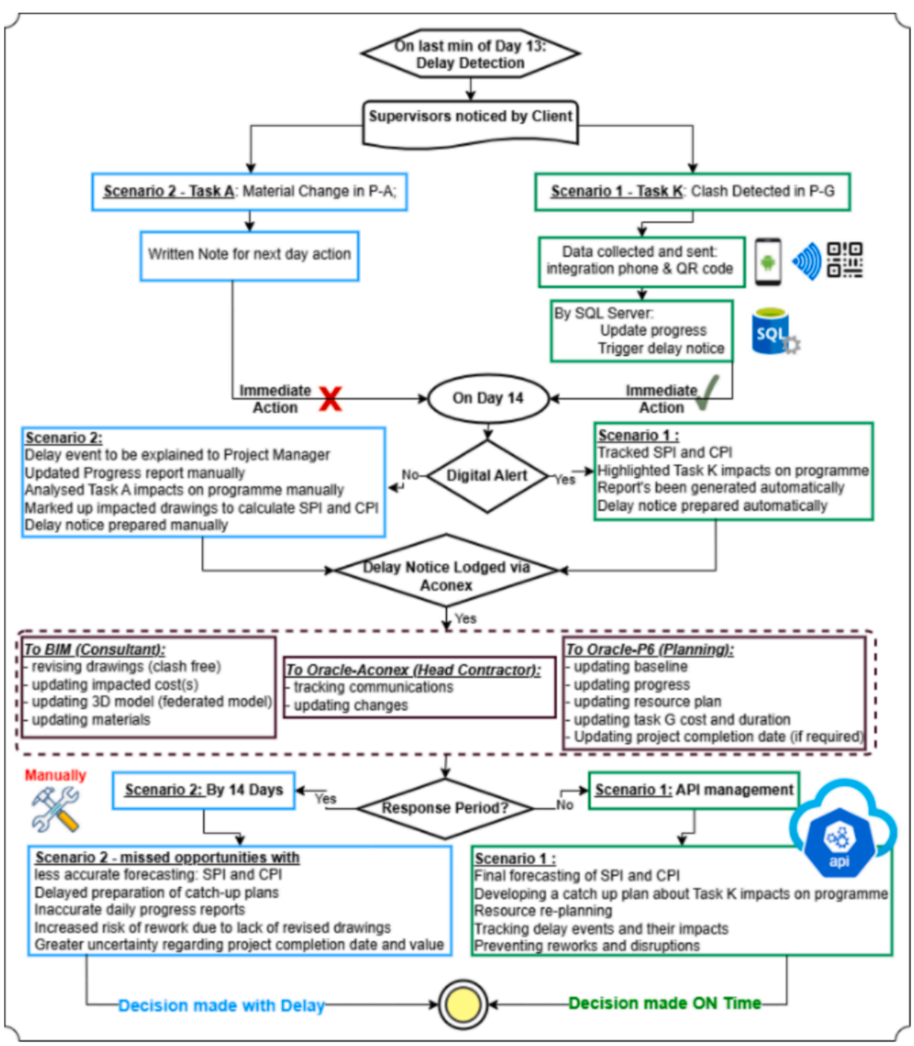


Fig. 21. A Simple View of Data Flow Via Existing and RealCONs Approaches.

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:

6.1. 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.

Additionally, Fig. 22 presents a bar chart based on Table 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.

Fig. 22 reveals that the proposed framework missed one report on days 5,12,17, and 23 due to internet issues, not data noise. Fig. 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.

Fig. 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	4.46×1^{-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}	

$W = \frac{\left(\sum_{i=1}^{n} a_i x_i\right)^2}{\sum_{i=1}^{n} (x_i - \overline{x})^2}$ Where: x_i is the ordered sample values (sorted from smallest to largest), $\overline{x}$ 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.

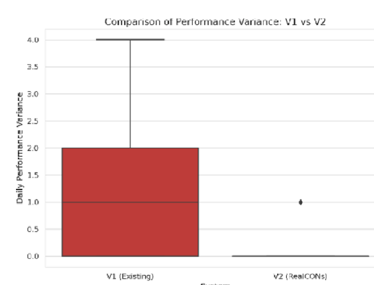
The Wilcoxon test compares two related variances: V1) The difference between the planned target and existing actuals, and V2) the difference between the planned target and proposed (RealCONs) actuals. The hypotheses tested were:

- 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.



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

Table 4
Daily Data Collection Status: A Snapshot of 30 Days Received Reports.

Project	Day	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15
Planned		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
RealCONs		4	4	4	4	3	4	4	4	4	4	4	3	4	4	4
Existing	P-A	N	N	Y	N	Y	N	Y	Y	Y	Y	Y	N	Y	N	N
	P-C	N	Y	Y	Y	N	Y	Y	N	Y	Y	N	Y	Y	N	Y
	P-E	Y	N	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y	N	Y
	P-F	Y	N	Y	Y	Y	N	Y	Y	Y	Y	N	Y	Y	N	N
RealCON	P-B	Y	Y	Y	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
	P-G	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
	P-H	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

Project	Day	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
Existing		0	2	4	3	2	3	4	2	2	2	1	1	1	1	0
RealCONs		4	3	4	4	4	4	4	3	4	4	4	4	4	4	4
Existing	P-A	N	N	Y	Y	Y	N	Y	N	Y	N	N	N	Y	N	N
	P-C	N	Y	Y	Y	N	Y	Y	Y	Y	N	N	Y	N	N	N
	P-E	N	N	Y	N	Y	Y	Y	Y	N	Y	Y	N	N	N	N
	P-F	N	Y	Y	Y	N	Y	Y	N	N	Y	N	N	N	Y	N
RealCON	P-B	Y	N	Y	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	Y	Y	Y	Y
	P-G	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	Y	Y	Y	Y	Y
	P-H	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

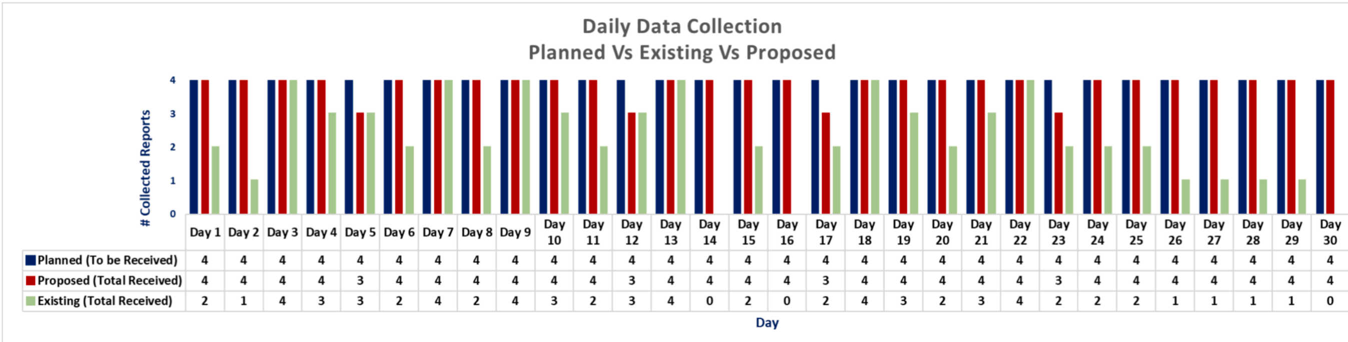


Fig. 22. Daily Data Collection: Planned Vs Existing Vs Proposed.

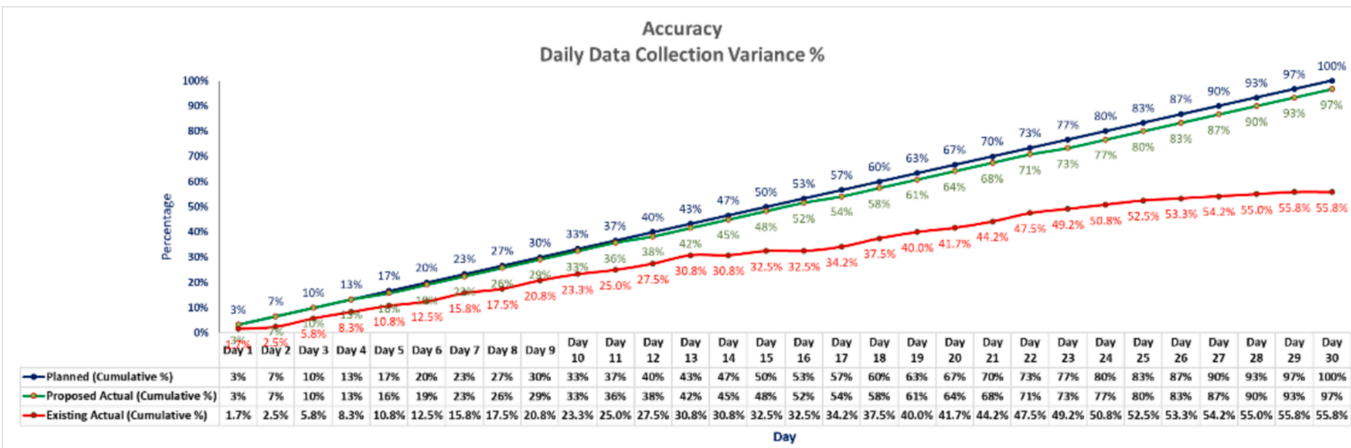


Fig. 23. Daily Variance Percentage in Data Collection.

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.

6.2. 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 (Fig. 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 Fig. 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 5 highlights the difference in data trends, underscoring how early delay notifications significantly enhance managerial responsiveness and predictive reliability.

Between Days 14 and 17, Table 5 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 Fig. 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 Fig. 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)

Table 5
A Snapshot of Table 4.

Project \ Day		D13	D14	D15	D16	D17	D18	D19	D20
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

Table 6
Earned Value Management (ESM) Matrix.

	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	
Day	**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	$0.43	−$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

impact on the $20 K Day-18 payment milestone; 2) trends in CPI and SPI; 3) variance comparisons (SV and CV); and 4) maintaining performance thresholds. Table 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.

- **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 $20 K 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, loos 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.

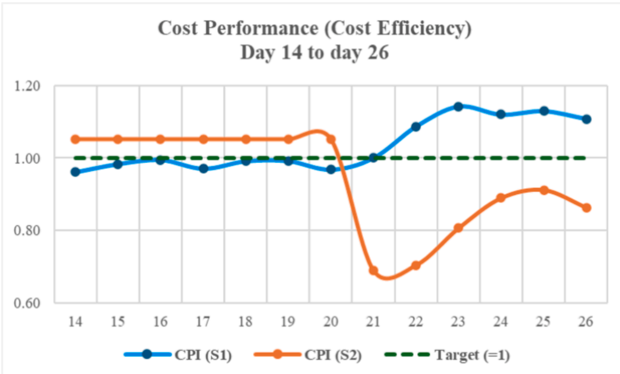


Fig. 24. Cost Efficiency.

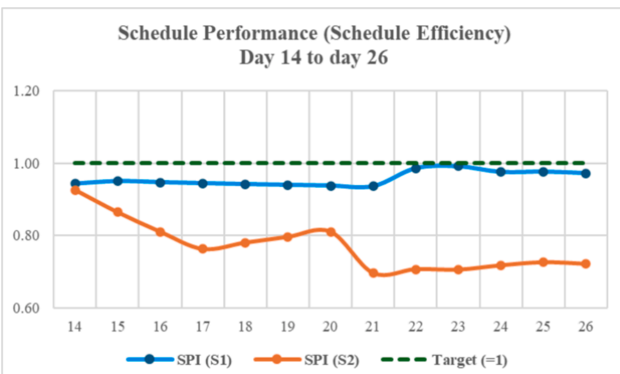


Fig. 25. Schedule Efficiency.

- **Goal-2) monitoring EVM index trends (CPI, SPI):** Figs. 24 and 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 $\geq$ 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.

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.

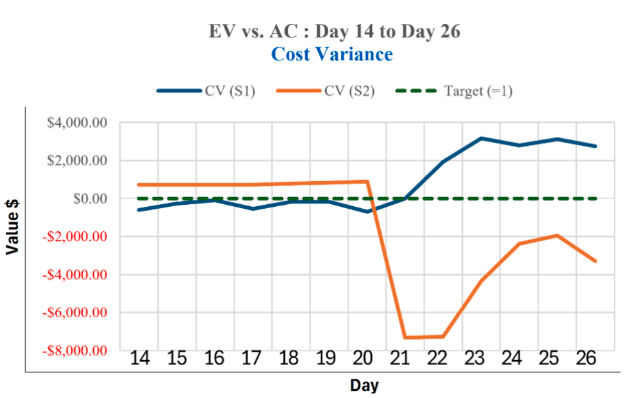


Fig. 26. Cost Variance.

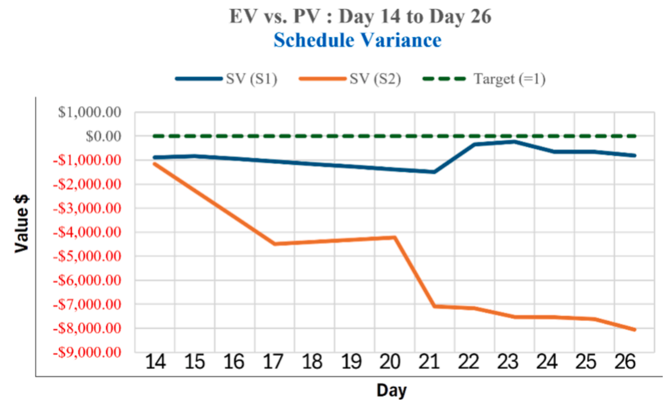


Fig. 27. Schedule Variance.

- **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. Figs. 26 and 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.

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, Fig. 21 and Table 7 present an Earned Schedule Management (ESM) analysis to assess the impact of early-stage delay identification between Days 14–26. Table 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).

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).

Behaviour analysis across three phases reveals distinct patterns (Table 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.

Fig. 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

Table 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

Table 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 ≈ C (SVc ≈ 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.

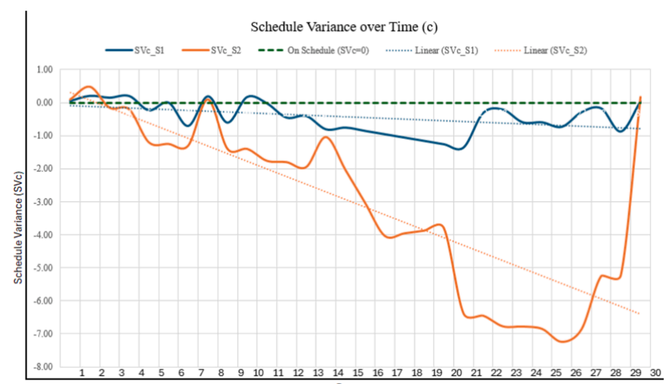


Fig. 28. Schedule Variance (SVc).

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.

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 9. using the time extension (TS) formula, provides one approach for calculating additional days required:

$$TimeExtension(TE) = \frac{PlannedRemainingDuration(Totalplanneddays - Currentday)}{SPI}$$

Additionally, Table 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:

Table 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

Table 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

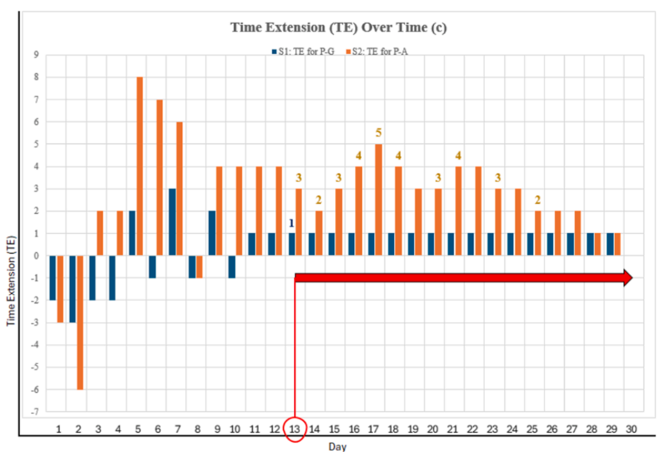


Fig. 29. Time Extension: RealCONs Vs Existing Approach.

$$NewProjectDuration = OriginalDuration + ActualTime - ES$$

Fig. 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.

7. 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 [29], 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) [42,59], Digital Twin technologies [47,60,61], 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 11 provides a comparative evaluation of RealCONs and these established frameworks across key project management attributes.

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

Table 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

Table 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
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

shown in Table 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.

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.

8. Conclusions

Advanced tools and technologies are increasingly applied to construction projects to enhance project management [34]. 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 [29,64]. 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.

9. Declaration of AI Assistance

The authors acknowledge the use of artificial intelligence (AI) tools, specifically ChatGPT by OpenAI, to assist in refining and enhancing the clarity and readability of some paragraphs in this manuscript. The AI was employed to smooth out and improve the English, while the authors maintained full responsibility for the content, accuracy, and interpretation of the text. All final revisions were thoroughly reviewed and approved by the authors to ensure alignment with the intended meaning and scientific integrity of the work. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Kambiz Radman: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mostafa Babaeian Jelodar:** Writing – review & editing, Validation, Supervision, Methodology. **Ruggiero Lovreglio:** Writing – review & editing, Supervision, Software, Investigation, Data curation, Conceptualization. **Eghbal Ghazizadeh:** Visualization, Validation, Supervision. **Suzanne Wilkinson:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aei.2025.103511.

Data availability

Data will be made available on request.

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