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Article

Digital Integration for Sustainable Motorway Delivery: A Case Study of the Sibiu-Făgăraș Motorway, Romania

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Abstract

The increasing complexity of modern infrastructure projects necessitates a digital transformation in project delivery processes. This study uses the Sibiu-Făgăraș Highway project in Romania as a qualitative case study to investigate the implementation of an integrated digital delivery framework. The research analyzes the synergistic application of key technologies—including a Common Data Environment (CDE), model-based fabrication, 4D/5D simulation, drone-based photogrammetry, and Business Intelligence (BI)—within a unified Plan-Do-Check-Act (PDCA) cycle. The core finding is that their integration creates a comprehensive digital ecosystem that functions as a human-in-the-loop digital twin for project delivery. This ecosystem significantly enhances coordination, enables data-driven decision-making, and reduces project risks by transforming traditional, reactive controls into a proactive, cyclical management system.

Keywords: integrated project management; motorway project; digital transformation (BIM); digital twin; PDCA cycle

1. Introduction

Large-scale infrastructure projects, by their nature, face chronic challenges such as fragmented communication, data silos, cost and schedule overruns, and rework stemming from design errors. It is widely recognized within the industry that project owners consistently express a need for greater collaboration with contractors and design consultants, and that a significant amount of crucial project data is often lost by the project's conclusion. These issues highlight an urgent need for better collaboration and data management strategies. In this context, digital technologies, particularly Building Information Modeling (BIM), have emerged as a fundamental element triggering a paradigm shift in project delivery processes [1,2].

BIM is more than just a 3D modeling tool; it is the process of creating and managing a digital representation of the physical and functional characteristics of a project. The true potential of BIM is realized when the model is enriched with additional dimensions such as time (4D), cost (5D), and operations (6D) [3–5]. This multi-dimensional approach provides a foundation for integrated project delivery by ensuring all stakeholders draw from a single source of truth throughout the project lifecycle. However, many studies focus on individual digital tools, with fewer exploring the systemic integration of multiple technologies like BIM, CDE, and BI within a unified management framework such as the Plan-Do-Check-Act (PDCA) cycle [6]. 4D BIM links the project schedule to the 3D model to create a visual simulation of the construction process, while 5D BIM integrates cost data into this simulation, enhancing budget tracking and financial forecasting capabilities.

This paper presents the Section 3 project of the Sibiu-Făgăraș Highway, part of the Trans-European Transport Network (TEN-T), as a case study. The project's strategic importance and engineering complexity make it an ideal candidate for the application of advanced digital workflows.

The primary objective of this qualitative case study is to analyze and document the practical application of the integrated set of digital workflows implemented in this project. By doing so, it aims to present an analysis that demonstrates the tangible benefits of a holistic digital strategy and offers a replicable framework. The research is based on a systematic analysis of project documentation, digital models, and the observed outcomes of the implemented workflows. The paper will first examine the project's contractual framework that mandates digital integration, then detail six key digital applications with their theoretical underpinnings and practical outcomes. Finally, it will discuss the synergy of these applications, presenting overall conclusions and recommendations for future research.

Research Questions (RQs)

This study investigates how the integration of digital construction tools can be operationalized as a continuous improvement control loop in large-scale transport infrastructure delivery. The research is guided by the following questions:

RQ1: How can heterogeneous digital tools (CDE, BIM/BrIM, 4D/5D, reality capture, and business intelligence dashboards) be coherently integrated into a PDCA management cycle for motorway project control?

RQ2: What measurable project outcomes can be observed when such an integrated PDCA-driven digital ecosystem is applied, in terms of coordination efficiency, rework prevention, progress verification, and payment validation?

RQ3: What technological, organizational, and financial constraints affect implementation and transferability to other infrastructure projects?

Contributions and novelty

The paper contributes to the literature by:

- (i) proposing a PDCA-oriented integration framework that positions digital tools as interconnected components of an end-to-end management loop rather than isolated applications;
- (ii) documenting an empirical case study from a major motorway project, including practical integration points and data governance mechanisms;
- (iii) reporting project-level performance indicators with explicit data sources and calculation assumptions to improve transparency and replicability in future comparative studies.

Sustainability relevance

While the primary motivation of the proposed workflow is improved project control, the observed outcomes have sustainability implications through material efficiency, reduced rework, and data-driven verification that supports responsible resource use and governance in infrastructure delivery.

Therefore, the objective of this paper is to demonstrate and critically assess a PDCA-driven digital delivery workflow for motorway construction through an in-depth case study, focusing on operational outcomes, limitations, and sustainability implications.

2. Materials and Methods

2.1. Project Description: The Sibiu-Făgăraș Motorway

The Sibiu-Făgăraș Motorway Section 3 of the Sibiu-Făgăraș Highway (17.61 km) serves as the primary case for this study, featuring 27 complex bridges and viaducts (Table 1). The engineering complexity and multi-national coordination requirements (Türkiye, Romania, Spain) necessitated a digital-first strategy rooted in a Common Data Environment (CDE) and high-LOD modeling [7–9].

Table 1. Sibiu - Făgăraș Motorway, Section 3.

Project Name	Sibiu - Făgăraș Motorway, Section 3: Arpașu de Jos - Sâmbăta de Sus
Location	Sibiu and Brașov Counties, Romania
Length	17.61 km

Contract Duration	Design: 12 months, Construction: 36 months
Main Structures	27 bridges, viaducts, and overpasses
Employer	Compania Nationala De Administrare A Infrastructurii Rutiere S.A.
Engineer	Consitrans Srl-Gestion Integral Del Suelo S.L
Contractor	Makyol İnşaat Sanayi Turizm Ve Ticaret Anonim Şirketi

The project was conceived with a clear vision for digital integration, moving beyond traditional project management methodologies. This forward-thinking approach established a defined framework for the use of advanced digital tools from the very beginning, ensuring that technology would be an integral part of the project's delivery rather than an afterthought.

A central pillar of this strategy was the development of a comprehensive 3D model of the entire motorway project. This was coupled with the creation of a 3D simulation to visualize the technical execution design, laying the groundwork for the extensive use of BIM and 4D simulation throughout the project lifecycle.

To facilitate seamless collaboration and data management among the diverse project teams, the framework also called for the establishment of a unified platform for data exchange. This platform serves as a central "Data Room," or Common Data Environment (CDE), for all digital project assets. This structured approach to digital workflows provided a solid foundation for the effective adoption and integration of technology, fostering a data-driven environment from the project's inception.

Project status

At the time of data collection and reporting, the Sibiu-Făgăraş Motorway Section 3 project was **still under construction**, and the analysis reflects an ongoing delivery phase rather than a post-completion evaluation.

2.2. Contractual Framework for Digital Integration

The contractual framework of the Sibiu-Făgăraş Motorway Section 3 project explicitly required the use of digital tools to support design coordination, construction planning, and execution control. The contract mandated the development and maintenance of BIM/BrIM models as reference deliverables throughout the project lifecycle.

A Common Data Environment (CDE) was contractually established as the single source of truth for all project-related digital information [7]. All design submissions, revisions, approvals, and coordination exchanges were required to be managed through this platform, ensuring traceability, version control, and controlled access for all stakeholders.

In addition, the contractual provisions encouraged the use of model-based workflows and digital coordination processes to support planning, visualization, and execution monitoring. These requirements formed the basis for the subsequent integration of scheduling, reality capture, and business intelligence tools within the project's digital delivery framework.

2.3. Case Study Methodology and Data Analysis

This research adopts an explanatory case study approach to investigate how digital construction technologies can be integrated into a PDCA management cycle for project delivery and control in large-scale transport infrastructure projects. The Sibiu-Făgăraş Motorway Section 3 project was selected due to its scale, multi-actor delivery environment, and contractual digital requirements.

Data collection

Evidence was collected from multiple project sources to improve construct validity through triangulation. The main sources included:

- (a) Common Data Environment (CDE) records, including submissions, revisions, and coordination logs;
- (b) BIM/BrIM models and model-based fabrication outputs;
- (c) schedule and cost control records supporting progress tracking;
- (d) reality capture deliverables used for progress monitoring and quantity verification;

- (e) Business Intelligence dashboards aggregating project control indicators;
- (f) internal coordination and management records supporting process analysis.

Data analysis

Two complementary analytical streams were applied:

(i) process mapping, used to document how heterogeneous digital tools were integrated into a closed PDCA management loop;

(ii) KPI-based outcome reporting, in which operational and sustainability-related indicators were extracted from project control records and summarized using transparent baselines and calculation logic.

Reliability and limitations

Reported outcomes were cross-checked across multiple evidence sources where feasible to improve reliability. The study is limited by its single-case design, the ongoing construction status of the project, and confidentiality constraints that prevent disclosure of raw project datasets. Findings are therefore discussed in terms of transferability rather than statistical generalization.

3. Integrated Digital Workflow Applications

This section provides a detailed examination of the six key applications that form the core of the project's digital transformation strategy. These technologies are not treated as standalone solutions but as interconnected components of an integrated digital workflow, where each part complements and strengthens the others. The project's success stems not from any single piece of software, but from the synergistic integration of these diverse systems. The six applications to be reviewed range from the use of a Common Data Environment (CDE) for international design coordination and model-based fabrication for manufacturing processes, to 4D/5D simulations for critical path analysis, reality capture technologies for monitoring site progress, and the creation of Business Intelligence (BI) dashboards for integrated project controls.

Each subsection follows a consistent structure, addressing the topic along three main axes. First, under the "Theoretical Framework," the respective technology's place in academic literature, its fundamental principles, and its established value in the Architecture, Engineering, and Construction (AEC) industry are presented. This theoretical foundation provides a context for understanding why the technology was chosen and its expected benefits. Subsequently, the "Case Application" section explains with concrete examples how this theoretical knowledge was put into practice under the specific conditions of the Sibiu-Făgăraș Highway project. This part builds the bridge between theory and practice, demonstrating how digital tools were adapted to real-world challenges.

Finally, the examination of each application is completed with an analysis of the tangible benefits achieved and their impact on project outcomes. This analysis not only focuses on the improvements observed within the project but is also reinforced with current academic references that support these findings. This approach aims to prove that the successes presented in the case study are not anecdotal but are consistent with a broader body of research and knowledge in the field of digital construction management. Thus, both the practical value of each digital workflow in the project and its academic validity are clearly established.

3.1. Common Data Environment (CDE) for Design Coordination

A Common Data Environment (CDE) is defined as the authoritative "single source of truth," serving as the central hub for all information production, management, and dissemination throughout a project's lifecycle. For complex projects with geographically dispersed teams—such as the collaborators in Romania, Türkiye, and Spain—a CDE is critical for mitigating endemic challenges like data fragmentation, version control conflicts, and communication latency. Cloud-based BIM platforms provide the technological backbone for this, enabling real-time data sharing and effective remote project management. The adoption of such platforms has the potential to significantly reduce project delays, enhance transparency, and transform conventional design reviews into dynamic, collective, and concurrent efforts.

Figure 1 illustrates the flow of information between different project stakeholders (Designers, Contractor, Employer) within the centralized CDE, establishing it as the “single source of truth” for the project.

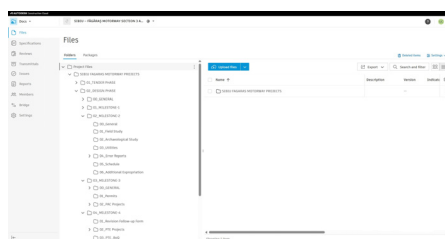


Figure 1. Common Data Environment (CDE) Workflow Diagram.

On this project, the Autodesk Construction Cloud (ACC) platform was formally adopted as the central CDE, strategically fulfilling the “internet cooperation site” requirement stipulated in Clause 4.11 of the contract. Key modules, particularly Autodesk Docs, provided a unified digital environment. This enabled design teams across Romania, Turkiye, and Spain to engage in concurrent design modeling, systematically manage document versions, and adhere to standardized review-and-approval workflows. Consequently, all stakeholders, irrespective of discipline or location, were guaranteed access to the most current and accurate project data. An analysis of the RFI (Request for Information) log indicated that the number of coordination-related RFIs decreased by roughly 20% after the full implementation of the CDE, demonstrating its role in minimizing coordination errors and preventing critical information loss.

Figure 2 shows the detailed LOD 400 model used for clash detection and resolving spatial conflicts between structural elements prior to fabrication, minimizing on-site rework [2].

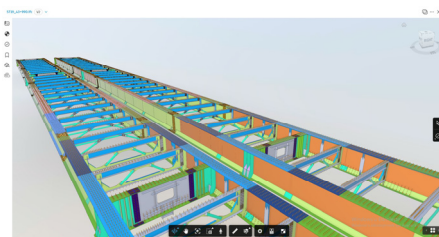


Figure 2. D Coordination Model for a Steel Bridge.

The implementation of the ACC platform as the CDE transcends simple file sharing; it fundamentally enforces process standardization and data governance across disparate organizations. By embedding review-and-approval workflows directly into the platform, the project moved from a chaotic, email-based exchange to a structured, auditable system. This standardization is paramount in a multi-national context, as it ensures that teams in different countries adhere to a single, contractually-compliant procedure for all information submittals, reviews, and transmittals. The CDE thus becomes the project’s definitive legal and technical archive, providing an immutable audit trail that protects all parties by ensuring every decision is based on the correct, approved version of the data, thereby safeguarding against a primary source of disputes and costly rework.

The reported 20% reduction in coordination-related RFIs was derived by comparing the frequency of design conflicts identified in the CDE against baseline projections from traditional 2D design review processes.

3.2. Model-Based Fabrication for Steel Bridge Superstructures

Bridge Information Modeling (BrIM) protocols emphasize the critical importance of models developed to a high Level of Development (LOD), especially for complex, fabrication-intensive

engineering elements like steel structures. LOD 400 signifies a model where elements are accurately represented in terms of size, shape, location, quantity, and orientation, and are further enriched with complete fabrication, assembly, and detailing information. A model at this level of maturity becomes a direct source for fabrication documentation, effectively eliminating the interpretation errors, ambiguities, and subsequent rework frequently encountered in traditional 2D drawing-based fabrication processes [10].

Figure 3 shows the Bridge Information Model (BrIM) at LOD 400 for an arch bridge. Developed in Tekla Structures, this model contains the precise geometric and fabrication data required for direct CNC machine production, enabling a Design for Manufacture and Assembly (DfMA) approach.

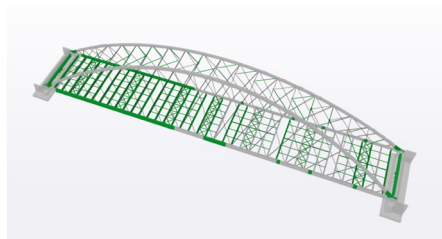


Figure 3. Bridge Information Model (BrIM) at LOD 400 for an Arch Bridge.

For this project, the 3D models of all steel bridges were created at LOD 400 specifications using Tekla Structures. These models served as a central repository for precise geometric and semantic data for every steel element, individual bolt, and weld connection. The fabrication process was conducted as an entirely model-centric workflow; fabrication drawings, cutting lists, and numerical control (CNC) machine data were exported directly from the validated Tekla model. This digital-to-physical workflow ensured that every component manufactured in the factory was dimensionally identical to the design, which in turn made the on-site assembly process as seamless and rapid as assembling a high-precision, pre-fabricated kit. This approach resulted in an estimated 15% reduction in material waste and shortened the on-site assembly time for the steel superstructures by approximately 3 weeks, compared to traditional 2D-based methods. This was critical for maintaining the project schedule. The 15% material waste reduction was estimated by comparing CNC-exported cutting lists from LOD 400 models against conventional manual estimation methods.

The strategic implication of this LOD 400 workflow is its transformation of the construction process into a Design for Manufacture and Assembly (DfMA) paradigm. By creating a direct, non-stop data pipeline from the digital model to the CNC machinery, the project systematically de-risked the fabrication and assembly stages. This method transfers the burden of tolerance and accuracy from high-cost, high-risk field labor to the controlled, digital environment of the model and the automated environment of the factory. The “Lego set” analogy is apt; it signifies the achievement of near-perfect dimensional control, eliminating the need for on-site “field-fitting,” re-drilling, or cutting, which historically plague steel erection. This predictability and precision are the ultimate benefits of BrIM, ensuring higher quality, enhanced safety, and greater schedule certainty.

3.3. 3D Model Coordination for Critical Infrastructure Works

For large-scale infrastructure projects, the creation of 3D models situated within their real-world context is indispensable for effective planning and comprehensive risk mitigation. Preliminary design platforms, such as Autodesk InRoads, facilitate the aggregation of disparate data sources to generate a high-fidelity digital twin of the project environment [10–12]. These contextual models are foundational for 3D coordination, permitting design teams to visualize the infrastructure, validate design alternatives against extant conditions, and articulate complex plans to all stakeholders, including on-site construction teams. This proactive coordination framework is instrumental in identifying spatial conflicts and logistical challenges early in the design lifecycle, thereby significantly mitigating the risk of costly rework during the construction phase.

Figure 4 shows the 3D contextual coordination model of the motorway, which was created using Autodesk Inroadworks. This model combines the design with real-world topography and existing infrastructure, facilitating constructability analysis and logistics planning for critical path activities.

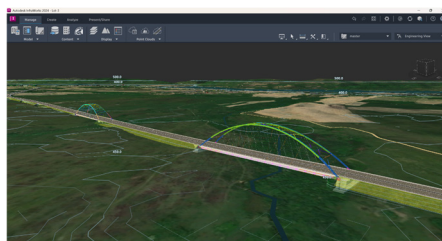


Figure 4. Contextual 3D Coordination Model of the Motorway.

Autodesk Inroadworks was employed to develop detailed 3D models. These models functioned as the central coordination tool between the design and site execution teams. By visualizing the bridge within its precise real-world context, the project team could strategically plan site logistics, meticulously verify critical clearances, and confirm the feasibility of the proposed construction sequence against tangible site constraints. This methodology fostered clear communication and alignment, ensuring the digital design was perfectly synchronized with the physical realities of the construction site—a vital factor for structures positioned on the project's critical path.

The significance of this approach extends beyond mere spatial clash detection; it fundamentally redefines constructability analysis. By leveraging a geolocated, contextual model, the project shifted constructability reviews from a traditional, 2D-drawing-based exercise to an interactive, simulation-based process. This empowered the site team to provide tangible, early-stage feedback on the methodology of construction, not just the final design. Consequently, the Inroadworks model acted as a central cognitive tool, creating a shared mental model for all parties. This alignment was instrumental in de-risking the critical path, ensuring that logistical plans, temporary works, and site-access strategies were validated before physical mobilization, ultimately safeguarding the project schedule and budget.

3.4. Integrated 4D and 5D Management for Bridge Construction

The implementation of 5D BIM is achieved through the integration of cost data into the 4D (time-sequenced) model, establishing a closed-loop system for comprehensive project controls [13]. This methodology yields a dynamic model capable of real-time visualization and monitoring of the financial consequences tied to schedule progression or slippage. By amalgamating design, schedule, and cost data within a unified environment, this approach facilitates proactive management, standing in sharp contrast to the inherently reactive nature of traditional control methods.

Figure 5 shows how the 3D model is linked to the construction schedule and cost data in Navisworks. This allows visual cash flow forecasting and earned value analysis.

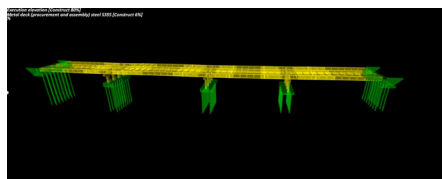


Figure 5. Integrated 4D (Time) and 5D (Cost) Simulation Interface.

Specifically for the steel bridge components, pre-existing 4D simulations were advanced to incorporate 5D capabilities [5]. This was executed by mapping detailed cost data from the project's cost management system directly to their corresponding 3D model components and associated P6

schedule activities within the Navisworks platform. This robust integration enabled sophisticated simulations of project cash flow, the execution of earned value analysis (EVA), and the visualization of cost impacts at discrete project stages—namely fabrication, transport logistics, and final on-site assembly.

Consequently, the project management team was equipped with a potent tool for financial forecasting and precise budget control, moving beyond simple detection to proactive mitigation of potential cost overruns. This 5D model served as a financial ‘digital twin’ of the construction process, allowing the team to run predictive, ‘what-if’ scenarios. For instance, the financial ramifications of a potential delay in fabrication could be instantly calculated and visualized, providing an objective, data-driven basis for critical decisions, optimizing procurement strategies, and validating progress payments long before such issues would become evident through conventional reporting.

3.5. Reality Capture for Physical Progress Monitoring

Drone-based photogrammetry provides a rapid, safe, and cost-effective method for capturing high-resolution aerial imagery of construction sites at regular intervals [14,15]. This technology processes hundreds or thousands of overlapping images to generate geographically accurate orthomosaic maps and 3D visual models of the site’s current “as-is” condition. Unlike workflows that depend on BIM integration, this approach can function as a powerful standalone site management tool. It enhances team coordination, improves communication through clear visual data, and provides an objective record for tracking progress and quality, thereby increasing transparency and awareness for all stakeholders.

Figure 6 shows the orthomosaic map generated using drone-based photogrammetry. This method of capturing high-frequency “as-is” data provides an objective record for tracking earthwork progress, calculating volumes and verifying completed work against the planned schedule.



Figure 6. Orthomosaic Map Generated from Drone-Based Photogrammetry.

On this project, drone flights are conducted on a bi-weekly basis to systematically document the entire construction site, processing high-resolution images via photogrammetry software to produce detailed and up-to-date orthomosaic maps. These visual records are utilized as a primary tool for several key management activities, independent of the design models. These uses include Progress Tracking, where maps serve as a visual baseline in meetings to demonstrate completed work, measure areas, and calculate earthwork volumes; Site Coordination, providing comprehensive aerial views for logistical planning and subcontractor alignment; and Quality Monitoring, allowing remote visual inspection to identify potential issues or non-conformities, especially in large or hard-to-reach areas.

The strategic value of this systematic reality capture extends far beyond simple progress tracking, establishing an objective, time-stamped digital archive of the construction process. This high-frequency “as-is” data serves as a powerful tool for proactive risk and dispute mitigation, providing an indisputable visual record of site conditions, logistics, and work completed at any given point in time. This objectivity is paramount for validating progress payment applications, as it allows for the rapid, visual, and quantitative verification of claimed work (e.g., earthwork volumes) against the orthomosaic data. This objectivity is paramount for validating progress payment applications, as it allows for the rapid, visual, and quantitative verification of claimed work (e.g., earthwork volumes)

against the orthomosaic data, reducing the payment validation cycle from an average of 15 days to just 2 days, thereby accelerating the cash flow cycle.

Moreover, by providing a transparent visual update to all stakeholders, it builds trust and alignment between the geographically dispersed teams and the employer, transforming complex site data into a shared understanding of project status.

3.6. Business Intelligence (BI) for Integrated Project Management

Business Intelligence (BI) is the process of transforming raw data into actionable insights through visualization and analysis [16]. One of the biggest challenges in the construction industry is data silos, where critical information such as planning, cost, and site reports are often locked in separate systems. The value of BI platforms like Power BI lies in their ability to connect to these disparate data sources, create a unified dataset, and present the information in interactive dashboards that offer a holistic view of project health.

Figure 7 shows how the Power BI dashboard synthesises data from the site diary, schedule (P6) and budget to provide management with a real-time, holistic view of key performance indicators (KPIs) for informed decision-making [17].

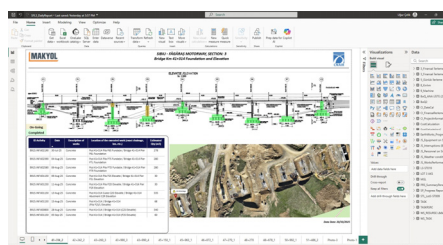


Figure 7. Business Intelligence (BI) Dashboard for Integrated Project Controls.

This project entailed the digitization of the contractually mandated Site Diary (Jurnal de Şantier) records. This field data was subsequently integrated with financial information from the budgeting system and schedule data from Primavera P6 to form a unified, centralized dataset. Microsoft Power BI was then leveraged to connect to this consolidated data, generating a suite of dashboards for project control. Similar BIM-to-dashboard pipelines, often automated via visual scripting (e.g., Dynamo), have been reported as effective for extracting model data and generating management-oriented visualizations [4]. These dashboards provided real-time visualizations of essential Key Performance Indicators (KPIs), including comparisons of planned versus actual progress, budgeted versus actual costs, and resource allocation.

The establishment of this integrated data model signifies a fundamental shift in project oversight. By dissolving the traditional silos that separate field operations (Site Diary), scheduling (P6), and finance (budget), the organization created a “single source of truth.” This consolidation eliminates the critical latency between on-site events, financial actuals, and schedule impacts. The resulting dashboards move beyond static, historical reporting, transforming into a dynamic diagnostic tool. This holistic, real-time view empowers management to not only identify nascent deviations, but to proactively optimize financial performance and cash flow.

For instance, in a period where the dashboard projected a weakness in the upcoming month’s cash flow, management used the integrated labor, cost, and progress data to analyze the financial impact of upcoming activities. This analysis revealed that prioritizing work on ‘Bridge A’ (as per the original schedule) would be cash-flow neutral or negative for the period, maintaining the projected deficit. In contrast, prioritizing ‘Bridge B’—which the data identified as having a significantly higher immediate profit margin due to its labor and cost structure—would actively reverse the negative trend.

This data-driven decision to strategically re-sequence tasks, based on their immediate financial return rather than just the schedule, allowed the team to actively regulate the project’s monetary flow.

This single strategic intervention, enabled by the BI analysis, resulted in a 40% positive impact on the period's cash flow compared to the original projection, effectively turning a potential deficit into a financially robust month.

4. Discussion and Synthesis: From Disparate Tools to an Integrated Project Control Ecosystem

The preceding examination of the six digital applications provides a detailed inventory of modern construction technologies. However, their true strategic value is not revealed by assessing them in isolation. The core thesis of this case study is that their synergistic integration creates a holistic digital ecosystem. This ecosystem represents a fundamental paradigm shift, moving project management away from traditional, linear, and reactive reporting structures toward a dynamic, data-driven, and cyclical control system.

When analyzed as a cohesive whole, the workflows detailed in this study—from the CDE to the BI dashboards—establish a complete and digitally native Plan-Do-Check-Act (PDCA) cycle, which functions as the project's central nervous system.

4.1. Plan-Do-Check-Act (PDCA) Cycle

4.1.1. Plan: Establishing the "As-Planned" Digital Baseline

The "Plan" phase in this ecosystem is not a singular event but a multi-layered process of creating a comprehensive, validated digital baseline.

- It begins with information governance in the Common Data Environment (Case 1), which establishes a "single source of truth" for all design collaboration, mitigating the fragmentation risk inherent in multi-national teams.
- It progresses to physical-world precision through Model-Based Fabrication (Case 2), where LOD 400 models adopt a Design for Manufacture and Assembly (DfMA) paradigm, ensuring the "as-planned" model is a direct, manufacturable instruction set.
- The plan is then contextualized using 3D Model Coordination (Case 3), validating the design against real-world site constraints and, critically, de-risking the logistics and constructability of critical path elements.
- Finally, this integrated model is imbued with time and cost data (Case 4), transforming the static design into a comprehensive 4D/5D simulation. This simulation is the ultimate expression of the "as-planned" baseline, allowing for cash flow forecasting and proactive "what-if" scenario analysis.

4.1.2. Do: Physical Execution

The "Do" phase consists of the physical construction and fabrication activities carried out on-site and in the factory. This stage is guided directly by the outputs of the "Plan" phase—namely, the coordinated models, 4D sequences, and CNC data exported from the fabrication models.

4.1.3. Check: Objective "As-Is" Data Capture

This phase provides the critical, objective feedback loop.

Through systematic Reality Capture (Case 5), drone-based photogrammetry captures high-frequency "as-is" data of the site's actual condition.

This creates an indisputable, time-stamped visual and spatial record of progress. The "Check" is the formal comparison of this "as-is" data against the "as-planned" 4D/5D model, allowing for objective measurement of progress, volume verification, and quality assurance.

4.1.4. Act: Data-Driven Decision Making

The “Act” phase is the cognitive engine of the entire system, where data is synthesized into actionable intelligence.

All performance data—the “as-planned” baseline from P6 and the budget (Plan), combined with “as-is” field data from the digitized Site Diary and drone captures (Check)—is aggregated in the Business Intelligence (BI) dashboards (Case 6).

This integration dissolves the traditional data silos between site, schedule, and cost. Management is no longer reacting to lagging indicators from disparate reports. Instead, they can perform real-time deviation analysis (Planned vs. Actual), immediately identify the nascent cost or schedule impacts of field events, and make informed, preemptive corrective actions to steer the project back on course.

4.2. *The Outcome: A Human-in-the-Loop Digital Twin for Project Delivery*

This cyclical PDCA structure (Plan–Do–Check–Act) supports a human-in-the-loop digital twin for project delivery control. In this context, the digital representation of the project is not a fully automated cyber-physical twin, but an operational decision-support model that is periodically updated through validated BIM/BrIM updates, reality capture outputs, and structured managerial workflows.

The digital representation evolves beyond a static 3D model by incorporating time (4D), cost (5D), and real-world “as-is” data at defined control points within the PDCA cycle, rather than through continuous automated synchronization.

In this study, the term “digital twin” is used to describe a management-oriented representation of project status, acknowledging that updates and validations require controlled human intervention.

This “living” model affords the project management team prognostic capabilities. They are empowered to move beyond simple retrospective reporting (what happened) and diagnostic analysis (why it happened) to true predictive management (what will happen) and prescriptive intervention (what we should do about it).

4.3. *Sustainability Implications*

Although the proposed digital workflow is primarily designed to improve project control and delivery efficiency, it produces explicit sustainability impacts across environmental, economic, and social and governance dimensions.

From an environmental perspective, improved coordination enabled by BIM/BrIM integration and model-based workflows reduces rework and material waste. The use of reality capture for progress verification supports accurate quantity validation, reducing the risk of over-ordering materials and unnecessary corrective works. These mechanisms contribute to more responsible resource use and reduced embodied impacts associated with infrastructure delivery.

From an economic sustainability perspective, the PDCA-driven integration of scheduling, cost control, and business intelligence dashboards improves predictability and shortens decision and validation cycles. Faster and more transparent verification processes contribute to improved cash-flow stability and reduced transaction costs, supporting the economic resilience of project delivery.

From a social and governance perspective, traceable digital workflows enhance transparency, accountability, and trust among project stakeholders. Shared access to validated project information reduces ambiguity, limits dispute escalation, and supports safer and more predictable site operations by minimizing unplanned corrective activities and coordination failures.

These sustainability-related outcomes are further discussed using project-level indicators, whose data sources and calculation logic are summarized in Table 2. This interpretation is aligned with prior research on visual management in construction, which emphasizes the role of transparent information flows in improving coordination, accountability, and stakeholder alignment [18]. Recent studies on cloud-based Building Information Modelling (BIM) environments further highlight their

contribution to enhanced multidisciplinary collaboration and information accessibility across the project lifecycle [9].

Table 2. Project Performance Indicators and Strategic Decision Matrix.

KPI Category	Data Source Integration	Metric / Formula	Strategic Decision Impact (Transparency)
Revenue-per-Effort Ratio (RER)	P6 (Man-hours) + Progress Payments	Revenue / Actual Man-hours	Identification of high-yield activities. During cash flow shortages, resources were prioritized for Bridge B due to its higher financial weight.
Schedule Slack Analysis	P6 (Total Float) + Site Reports	Current Total Float	Confirmed that Bridge A was not on the critical path, allowing a temporary shift of resources without affecting the project completion date.
Cash Flow Predictability	5D Model + Financial Records	Actual Cash Flow / Forecasted Cash Flow	Enabled a 40% improvement in cash flow stability by re-sequencing activities based on real-time financial data.
Operational Efficiency Index	Site Diary + P6 Baselines	Actual Progress / Planned Progress	Ensured that resource redeployment maintained a high productivity rate across both work zones.

4.4. Project Performance Indicators (KPI Transparency)

Financial sustainability and operational efficiency in large-scale infrastructure projects depend on the seamless integration of scheduling, field execution, and cost management. This section demonstrates how the proposed digital framework transforms raw data into a transparent set of Key Performance Indicators (KPIs), enabling informed decision-making. By consolidating Primavera P6 schedules, field progress reports, and subcontractor/owner payment data into a Power BI-driven environment, a “Single Source of Truth” is established.

The practical application of this transparency is evidenced by a strategic resource optimization involving two distinct structures: Bridge A (Reinforced Concrete Girder) and Bridge B (Steel Twin Girder). While both structures require similar resource intensity and man-hours for their foundational works (piling, footing, and elevations), their contractual values differ significantly due to their superstructure types.

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Through the Business Intelligence (BI) dashboard, management identified that Bridge B possessed a significantly higher revenue-to-effort potential compared to Bridge A, despite the identical nature of their initial substructure works. During a period of restricted cash flow, a sensitivity analysis was performed. By verifying in the P6 schedule that Bridge A had sufficient “Total

Float" (non-critical status), the project team strategically redeployed crews and equipment to Bridge B.

This data-driven maneuver allowed the project to maximize its interim payment certificates (IPCs) without compromising the overall construction schedule. Such a decision would have been difficult to justify or even identify using conventional, siloed reporting methods. The integration of 4D/5D data provided the necessary transparency to balance technical progress with financial health, effectively transforming a potential liquidity risk into a period of robust financial performance.

4.5. Implementation Challenges and Socio-Technical Considerations

The successful implementation of such a sophisticated ecosystem, as demonstrated in this case, must not obscure the significant challenges involved.

4.5.1. Technological (Interoperability)

The primary technical hurdle is data standardization. The data pipeline from the CDE, to Tekla, to Navisworks, to the BI platform must be seamless. A failure in interoperability at any point breaks the PDCA cycle and reverts the system to a collection of disparate tools.

4.5.2. Financial (Investment):

The high initial investment in software licenses (e.g., Autodesk Construction Cloud, Power BI), specialized hardware (drones, processing rigs), and, most notably, intensive employee training can be a formidable barrier, particularly for small and medium-sized enterprises (SMEs) in the supply chain.

4.5.3. Socio-Technical (Cultural Shift)

The most profound challenge is not technological but human. Implementing this ecosystem demands a fundamental cultural shift towards a data-driven, transparent, and collaborative mindset. Moving teams away from traditional, siloed, and often defensive, paper-based workflows requires strong leadership, clear communication of value, and a persistent focus on change management. As this case implies, overcoming this socio-technical inertia is often more arduous than resolving the technical hurdles themselves.

4.6. Limitations of the Study

This study has several limitations that should be acknowledged. Firstly, as a single-case study, the findings are inherently context-specific to the Sibiu-Făgăraș Highway project. While this provides a deep and nuanced understanding of the digital workflows in this particular setting, the generalizability of the results to other large-scale infrastructure projects with different scopes, contractual frameworks, or geographical locations may be limited. Future research could benefit from comparative case studies across multiple projects to validate and expand upon these findings.

Secondly, the analysis presented is primarily qualitative. Although the study highlights significant benefits such as improved efficiency, coordination, and decision-making, it does not provide extensive quantitative metrics to measure the precise impact of these digital tools. A quantitative study focusing on key performance indicators (KPIs)—such as percentage reduction in rework, specific cost savings, or man-hours saved—would be a valuable next step to empirically substantiate the qualitative benefits observed here.

Finally, the perspective of this study is predominantly that of the project management and implementation team. While this provides a detailed view from a central standpoint, a more comprehensive understanding could be achieved by incorporating the perspectives of all project stakeholders, including subcontractors, suppliers, and regulatory bodies. Future research could explore the challenges and benefits of such a digital transformation from these varied viewpoints to provide a more holistic picture of its impact on the entire project ecosystem.

5. Conclusions

In conclusion, this case study has systematically demonstrated the procedural and methodological value of synergistically integrating six distinct digital applications. The core contribution of this research lies in illustrating how these technologies form a cohesive ecosystem, thereby establishing a complete digital Plan–Do–Check–Act (PDCA) cycle. This integration successfully transforms isolated data silos into an interconnected information flow. By mapping the data pathways from the CDE to model-based fabrication, through 4D/5D simulation, and into a final BI environment, this paper provides a robust qualitative framework for shifting from traditional, linear management to a dynamic, cyclical control system.

The strategic outcome of this integrated framework is the creation of a human-in-the-loop digital twin for project delivery, enabling a fundamental shift from reactive reporting to proactive, data-informed decision-making. This digital representation functions as a management-oriented decision-support model rather than a fully automated cyber-physical twin. It is important, however, to position this research as a foundational, qualitative case study. Its primary objective was to demonstrate the implementation of this complex ecosystem and its observed procedural benefits, not to provide a summative, quantitative benchmark. While proactive capabilities were clearly observed by the project team, this study did not extend to capturing specific lagging-indicator KPIs—such as direct ROI calculations, percentage reductions in rework, or man-hours saved—which would require longitudinal analysis against a traditional project baseline.

Beyond operational efficiency, the findings indicate that such integrated digital workflows also support sustainability objectives through reduced rework, more responsible material use, improved transparency, and strengthened governance in infrastructure delivery.

The implementation challenges—technical interoperability, financial investment, and the socio-technical cultural shift—remain significant barriers. Indeed, the complexity of this integration and the high investment required are precisely why rigorous, quantitative validation is both difficult and necessary. This study, by providing a detailed procedural map, serves as an essential precursor to such analysis. Future research must leverage this qualitative framework to conduct longitudinal studies, capturing the specific KPIs needed to rigorously validate the business case for adoption and to prove its verifiable, evidence-based impact.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org, Figure S1: title; Table S1: title; Video S1: title.

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