



## DIGITAL ENGINEERING AND PROJECT MANAGEMENT FRAMEWORKS FOR IMPROVING SAFETY AND EFFICIENCY IN US CIVIL AND RAIL INFRASTRUCTURE

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### Abstract

*This study addresses a persistent problem in US civil and rail delivery: preventable safety incidents and schedule and cost drift rooted in fragmented information and inconsistent governance. Purpose was to quantify how digital engineering adoption and project management framework maturity relate to safety and efficiency. Design was quantitative, cross sectional, and case based, combining a survey with audited archival records. Sample comprised 168 US civil and rail projects from owners and prime contractors. Key variables were two Likert composites for digital engineering adoption and framework maturity, outcomes of total recordable and lost time incident rates plus schedule and cost performance indices, a rail versus non rail sector moderator, and controls for value, duration, delivery method, organization size, complexity, and region. Analysis plan included reliability checks, correlation matrices, ordinary least squares for efficiency with robust errors, and Poisson or Negative Binomial models for safety counts with log exposure offsets, followed by moderation tests and robustness checks. Headline findings show that higher adoption and higher maturity were independently associated with lower incident rates and schedule and cost performance after adjustment, with a stronger adoption to schedule link in rail settings; results were stable across alternative codings and inferences. The literature review informing constructs and hypotheses synthesized 44 peer reviewed sources. Implications for agencies include mandating ISO aligned information requirements and common data environment compliance, requiring 4D sequencing for possession constrained works, strengthening stage gates, risk and change control, and institutionalizing benefits management and lessons learned to sustain gains and transparency across programs.*

### Keywords

*Digital Engineering; Building Information Modeling; 4D Planning; Common Data Environment; Project Governance; Safety Performance;*

## INTRODUCTION

Digital engineering in civil infrastructure refers to the integrated use of data-centric methods such as Building Information Modeling (BIM), digital twins, and Common Data Environments (CDEs) to plan, design, construct, operate, and renew assets across their life cycles. BIM is widely framed as a set of interacting policies, processes, and technologies for managing essential project information in digital form, enabling model-based coordination, clash detection, and information exchange among stakeholders (Succar, 2009). Digital twins extend BIM by coupling high-fidelity information models with live data streams to support monitoring, diagnostics, and scenario analysis in the built environment (Boje et al., 2020). CDEs operationalize information management workflows by implementing ISO 19650-aligned rules for requirements, responsibilities, and approvals, so that each “information container” is versioned, auditable, and context-aware (Godager et al., 2022). In parallel, project management frameworks e.g., earned-value-oriented control regimes and maturity models such as OPM3 and P3M3 provide structures for governance, risk, schedule/cost integration, and continuous improvement (Anbari, 2003; Davies & Arzymanow, 2003). Together, these digital engineering and management frameworks have international visibility because they aim to reduce coordination loss, rework, and variability across sectors while increasing transparency, safety, and efficiency at portfolio, program, and project levels. This convergence is especially salient for civil and rail systems whose spatial scale, interdependencies (track–rolling stock–signaling–structures), and public accountability amplify the payoff from better information and more predictable delivery.

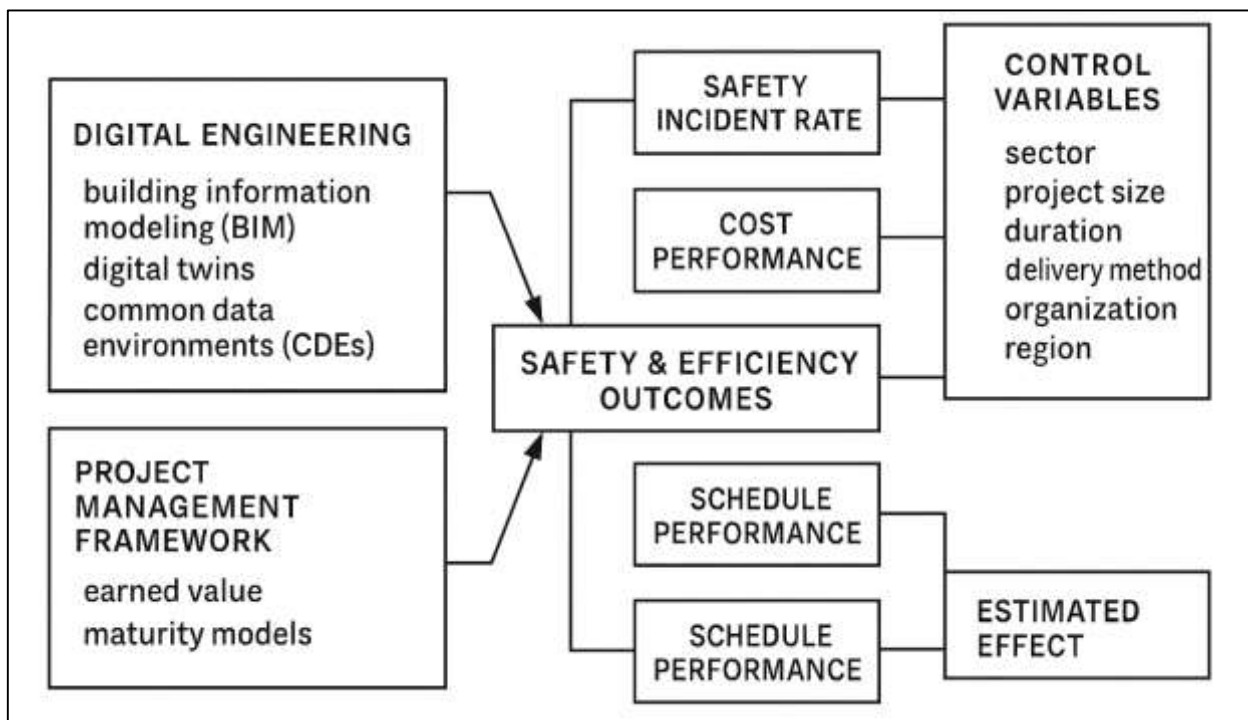
Across countries, empirical and methodological research has traced a consistent chain from digitalization to project performance. Early 4D/BIM work demonstrated that linking schedules to 3D models improves constructability reviews and schedule comprehension (Koo & Fischer, 2000), while later syntheses showed measurable benefits in cost control, time reduction, and coordination (Barlish & Sullivan, 2012; Bryde et al., 2013; Koo & Fischer, 2000). Macro-level adoption studies and maturity constructs argue that benefits scale as organizations progress from model authoring to multi-party collaboration and integration (Kassem & Succar, 2015; Succar & Poirier, 2020), and that ISO 19650-conformant information management clarifies roles and reduces information loss at handoffs (Özkaya et al., 2024). Complementarily, Lean-BIM interactions have been shown to support flow and value creation by reducing variability and enabling constraint analysis, with managerial implications for production planning and control (Sacks et al., 2010). While contexts vary across building, road, bridge, and rail projects, the recurring motif is that digitally enabled visualization, earlier clash detection, and structured data flows improve process reliability, enabling more accurate forecasts and fewer unplanned interventions key antecedents to both efficiency and safety outcomes tracked by owners and regulators.

Safety is a central dimension in this landscape. Rule-based and model-checking approaches using BIM have been shown to identify fall hazards pre-construction and embed preventive measures in plans and schedules, making hazards more visible and checkable before mobilization (Zhang et al., 2018). Systematic reviews in safety science similarly report that BIM-supported hazard identification, temporary works visualization, and site layout planning can reduce accident precursors by improving situational awareness and coordination between design and construction teams. Rail adds a layered digital safety stack: Positive Train Control (PTC) in the United States is a policy-mandated, communication-based control system designed to prevent train-to-train collisions, overspeed derailments, incursions into established work zones, and movements through misaligned switches (Danish & Zafor, 2022; Zhang et al., 2015). Complementary digitalization in track health monitoring e.g., using in-service vehicles, remote sensing, and machine learning supports condition-based maintenance and earlier defect localization, linking safety and efficiency through fewer service disruptions and optimized work windows (Balouchi et al., 2021; Danish & Kamrul, 2022). These domain-specific technologies sit naturally within broader digital engineering and project-management frameworks, which coordinate requirements, data, and decisions from design through O&M.

Project-management frameworks shape how the gains of digital engineering are realized in practice. Earned Value-based regimes integrate scope, cost, and schedule to produce indices (e.g., CPI, SPI) that support early variance detection and trend-based forecasting (Afonso et al., 2023; Anbari, 2003). Organizational maturity models posit that higher capability in governance, risk, resource, and benefits

management correlates with more predictable project outcomes (Cooke-Davies & Arzymanow, 2003; Crist & Emami, 2019). Recent empirical and review studies in construction and infrastructure echo the role of maturity in performance, arguing that PMO maturity, risk-management maturity, and portfolio/program governance improve delivery consistency and learning loops, especially when aligned with digital information processes (Cooke-Davies & Arzymanow, 2003; Eadie et al., 2013). From a measurement standpoint, these frameworks bring comparable metrics and structured audits, enabling cross-case analysis in multi-project settings and supporting quantitative modeling of relationships between digital practices (e.g., BIM use depth, CDE adoption) and outcomes (safety incident rates, change order frequency, schedule growth). This alignment is particularly valuable for U.S. civil and rail agencies that must benchmark vendors, delivery models, and corridors across varying regulatory, environmental, and community constraints.

**Figure 1: Digital Engineering and Project Management Integration in Civil and Rail Infrastructure**



In rail and civil infrastructure specifically, case-based and sectoral studies illustrate how digital engineering and management frameworks translate into practice. A rail track rehabilitation case study documented BIM’s role in condition assessment, staging, and interface management across track, subgrade, and structures, underscoring BIM’s utility beyond buildings (Crist & Emami, 2019; Jahid, 2022). Global road-sector syntheses show converging national and agency-level guidance toward ISO 19650-compatible processes for information requirements, deliverables, and approvals, mapping maturity and adoption trajectories for linear infrastructure (Arifur & Noor, 2022; Norman, 2010). In rail O&M, vehicle-based sensing and analytics have demonstrated that multi-train data streams can reveal geometry defects and guide targeted maintenance, improving route availability and work safety (Balouchi et al., 2021; Hasan & Uddin, 2022), while sector analyses emphasize how condition monitoring and condition-based maintenance underpin reliability and operational efficiency (Maierhofer et al., 2024; Rahaman, 2022a; Sanjai et al., 2025). These cases and reviews provide a contextual substrate for a U.S.-focused, quantitative, cross-sectional, multi-case study linking specific digital engineering practices and project-management capabilities to measurable safety and efficiency outcomes across civil and rail assets.

Methodologically, quantitative cross-sectional case designs allow the aggregation of comparable metrics across agencies and corridors, enabling descriptive statistics, correlation analysis, and regression modeling that relate practice adoption and maturity levels to outcomes such as incident

rates, near-miss counts, change orders, schedule growth, and unit production rates. Standard psychometrics support instrument reliability and construct validity: for Likert-type multi-item scales, coefficient alpha (Cronbach's  $\alpha$ ) remains a workhorse estimator of internal consistency (Rahaman, 2022b), while evidence shows that parametric tests (e.g., correlation/regression) are robust for Likert-type data under common conditions, facilitating practical inferential modeling in engineering management research (Napitupulu et al., 2019; Norman, 2010). On the independent-variable side, prior BIM benefit studies and intangible-benefit quantifications supply scale items and constructs coordination quality, information timeliness, visualization support, decision-speed that can be adapted for civil/rail contexts (Rahaman & Ashraf, 2022; Ullah et al., 2023). On the project-management side, earned-value constructs and maturity constructs (e.g., governance, risk, resource, benefits) are operationalizable with documented rubrics, allowing cross-case comparability and multi-variable regression (Anbari, 2003; Islam, 2022).

Positioning within the U.S. context, federal policy, standards, and market structure create a distinctive setting where digital engineering's potential intersects with system-level safety technology and institutional accountability. PTC is established as a safety baseline on ~59,000 route-miles of PTC-mandated main lines, shaping operational safety expectations and the data environment for maintenance planning (Yoon et al., 2023; Zhang et al., 2015). At the same time, state DOTs and transit agencies increasingly specify model-based deliverables and information-management processes on road and rail capital programs, aligning with internationally recognized information standards while contending with legacy systems, varied procurement models, and multi-stakeholder governance. Within this setting, a quantitative, cross-sectional, multi-case approach focused on U.S. civil and rail projects can examine how variation in digital engineering practices (e.g., depth of 4D/5D use, degree of CDE workflow enforcement, extent of asset data handover) and project-management frameworks (e.g., risk and EV disciplines, PMO maturity) relate to variation in safety and efficiency outcomes, using descriptive statistics to profile adoption, correlation to explore bivariate associations, and multivariate regression to estimate adjusted effects in the presence of confounders. This empirical mapping can then be used to identify which bundles of practices and capabilities co-occur with better safety and efficiency signals across projects and operators in the U.S. civil and rail domain (Hasan et al., 2022; Yoon et al., 2023).

The objective of this study is to provide a rigorous, measurement-driven account of how digital engineering and project management frameworks relate to safety and efficiency outcomes in United States civil and rail infrastructure projects. Specifically, the study aims to: (i) conceptualize and operationalize two focal independent constructs digital engineering adoption and project management framework maturity into reliable multi-item scales suitable for five-point Likert responses at the project level; (ii) define outcome variables that are routinely available in capital delivery and operations contexts, including safety incident rates and indices of cost and schedule performance, and assemble a harmonized dataset that links survey responses to audited archival records; (iii) produce a comprehensive descriptive profile of the sample that characterizes adoption levels, maturity levels, delivery methods, project sizes, durations, and geographic dispersion, and contrasts these attributes across rail and non-rail civil cases; (iv) quantify the bivariate associations among all study variables using correlation analysis to reveal preliminary patterns of co-variation between practices and outcomes; (v) estimate multiple regression models that assess the independent effects of digital engineering adoption and project management maturity on safety and efficiency while adjusting for confounders such as sector, project value, duration, delivery method, organizational size, complexity, and region, and report effect sizes, uncertainty intervals, and incremental explanatory power; (vi) test moderation by sector through interaction terms to determine whether relationships differ between rail and non-rail civil projects; (vii) examine robustness by re-specifying outcomes, evaluating count-based models for safety events when appropriate, conducting subgroup estimations, checking multicollinearity and influential observations, and applying heteroskedasticity-robust inference; (viii) establish the internal consistency and construct validity of all multi-item scales through reliability diagnostics and factor-analytic evidence; (ix) implement transparent data-handling procedures for missingness, coding, and exposure normalization to ensure comparability across cases; and (x) deliver

a reproducible analytic pipeline, with a documented codebook, instrument, and model specification, to enable verification and reuse. By pursuing these objectives within a cross-sectional, multi-case design, the study seeks to generate a coherent empirical baseline that characterizes current practice, enumerates measurable relationships between managerial and digital capabilities and project outcomes, and provides a standardized framework for comparing civil and rail project performance across the United States.

## **LITERATURE REVIEW**

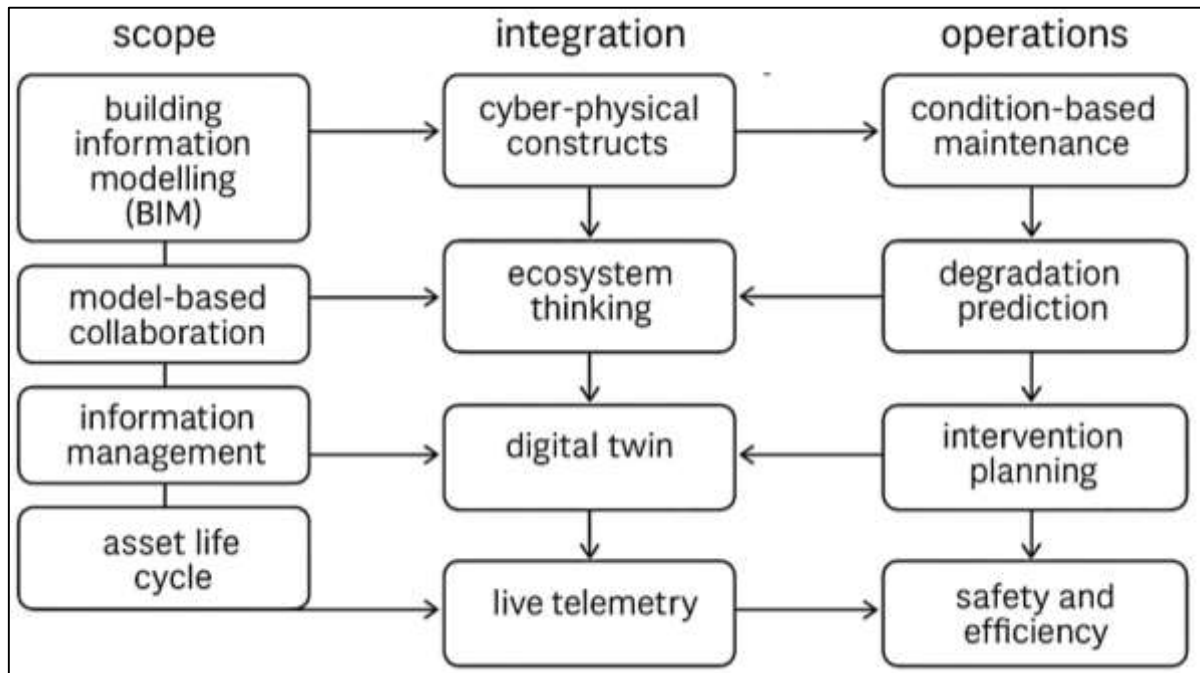
The literature on digital transformation in infrastructure converges on two mutually reinforcing streams: digital engineering encompassing BIM, digital twins, common data environments, analytics, and mobile field tools and project management frameworks that institutionalize governance, risk, scope–schedule–cost integration, and learning. Together, these streams offer a structured pathway for improving information quality, coordination, and decision velocity across the asset life cycle, from planning and design through construction and operations. Within civil and rail contexts, the scholarship traces three recurring mechanisms (Uddin, 2025). First, model-centric collaboration improves visualization, clash avoidance, and interface management, which reduces rework and uncertainty that typically propagate into schedule growth and cost variance. Second, data governance via standardized information requirements and CDE workflows raises traceability and accountability at handoffs, strengthening earned value and risk processes that depend on timely, accurate baselines and updates. Third, sensing and analytics ranging from construction progress capture to rail condition monitoring link operational realities to managerial controls, enabling more precise forecasts, earlier exception detection, and safer work planning. Parallel bodies of work on organizational and methodological maturity argue that benefits scale as teams progress from tool-level adoption to enterprise-level integration aligned with stage gates, change control, and systematic lessons learned. In rail, the integration challenge is amplified by asset interdependence (track–rolling stock–signaling–structures) and safety-critical operations; consequently, studies emphasize the complementary roles of engineering models and management disciplines in achieving reliability, availability, maintainability, and safety targets. Despite varied project typologies and delivery methods, the literature consistently positions safety and efficiency as downstream reflections of upstream information quality and process discipline (Zafor, 2025). For a quantitative, cross-sectional, multi-case design, this body of research suggests clear constructs to operationalize digital engineering adoption, project management framework maturity, and outcomes such as incident rates and SPI/CPI along with plausible moderators (sector) and controls (project value, duration, delivery method, complexity). The introductory synthesis therefore frames the review around four focal threads: the evolution and scope of digital engineering in linear and complex infrastructure; the architecture of project management frameworks and maturity; the measurement of safety and efficiency in capital projects; and empirical linkages that relate digital and managerial capabilities to performance, establishing the conceptual foundation for the study’s hypotheses and measurement strategy.

### **Digital Engineering in Civil and Rail infrastructure**

Digital engineering has expanded from a narrow focus on 3D authoring to a system-of-systems approach that integrates information models, data governance, and analytics across the asset life cycle. The literature traces this evolution in two complementary arcs. One arc documents the scope and density of global research, showing how Building Information Modeling (BIM) became a backbone for standardizing information, coordinating disciplines, and enabling computable checks; scientometric mapping highlights rapid growth in BIM scholarship and its diffusion from design coordination toward construction and operations, with clusters forming around interoperability, collaboration, and performance measurement (Redwanul & Zafor, 2022; Zhao, 2017). The second arc emphasizes application breadth, noting that digital methods must grapple with legacy assets, fragmented documentation, and uncertain as-built conditions; reviews of BIM for existing assets underscore scanning-to-BIM, model updating, and information reliability as prerequisites for downstream analytics and decision support (Rezaul & Mesbaul, 2022; Volk et al., 2014). Together these threads motivate a life-cycle view in which model-centric collaboration and information management are not end points but enabling platforms for safety planning, production control, and maintenance. In infrastructure work, where constraints propagate through interfaces (e.g., track–structure–systems)

and work windows are limited, this platform logic becomes acute: misaligned information reverberates into rework and delay, while disciplined information handoffs have outsized benefits for safety and efficiency. The contemporary agenda therefore frames digital engineering not simply as “BIM use,” but as the orchestration of standards, roles, workflows, and analytics that connect planning, design intent, construction means-and-methods, and operations in a traceable and auditable way (Hasan, 2022; Volk et al., 2014; Zhao, 2017).

**Figure 2: Evolution of Digital Engineering in Civil and Rail Infrastructure**



A second strand in the literature tracks how digital engineering is increasingly coupled with data-rich, cyber-physical constructs that extend beyond static models. One perspective argues that “point solutions” isolated tools for coordination, sensing, or visualization should give way to ecosystem thinking in which internet-of-things (IoT) telemetry, cloud services, and governance operate as a coherent digital layer across the project and network contexts (Tarek, 2022). Within this frame, digital twins are proposed as dynamic counterparts to physical assets, using BIM as a structural baseline while ingesting time series from sensors, equipment, and enterprise systems. Framework work at the method level describes how BIM, IoT, and data mining can be integrated into an operational digital twin that supports construction and operational decision-making, from progress tracking and anomaly detection to schedule-risk signaling and resource optimization (Kamrul & Omar, 2022; Pan & Zhang, 2021). For civil and rail use cases, this progression is particularly consequential: linear assets and complex nodes (e.g., interlockings, stations, bridges) generate heterogeneous data whose management and fusion determine whether analytics can reliably inform safe possession planning, access permitting, and staged works. The literature thereby positions digital twins as a managerial and technical synthesis: models encode the “what” and “where,” telemetry supplies the “when” and “how much,” and workflows formalize the “who” and “with which authorization,” enabling transparent, repeatable decisions across owner, designer, contractor, and operator boundaries (Kamrul & Tarek, 2022; Woodhead et al., 2018).

A third strand focuses on lifecycle operations, where the promise of digital engineering depends on robust mechanisms for representing state, predicting degradation, and prioritizing interventions. Conceptual and empirical accounts of building and infrastructure digital twins articulate the distinction between a geometric information model and a live, executable representation that binds simulation, sensing, and control arguing that the latter enables condition-based maintenance, performance optimization, and assurance functions unattainable with static documentation alone (Khajavi et al.,

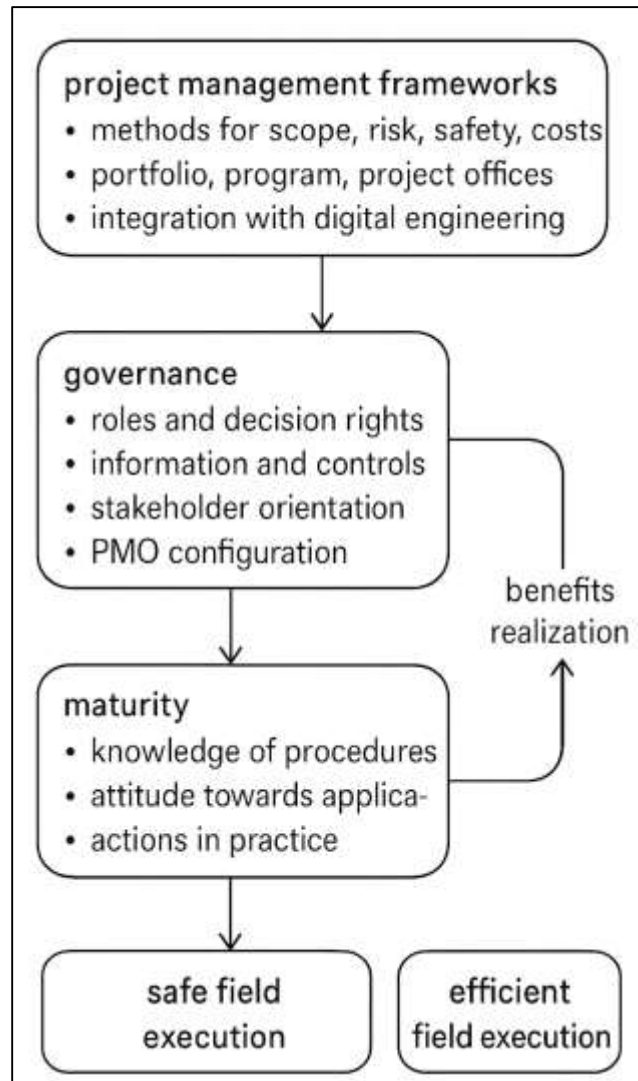
2019; Mubashir & Abdul, 2022). This distinction matters for safety-critical civil and rail environments in which near-real-time information about asset condition, environmental loads, and worksite status influences risk exposure and productive capacity; digital twins offer a means for converging these streams into actionable views that align with project controls and safety management. In practice, the digital twin serves as a continuously updated hypothesis about the asset, tested by measurements and corrected via feedback loops (Hasan, 2025). When coupled with rigorous information requirements and common data environments, this hypothesis-testing view allows organizations to trace the provenance of decisions, audit compliance with method statements, and quantify the effect of interventions on both safety (e.g., exposure hours, worksite conflicts) and efficiency (e.g., schedule adherence, cost variance). The literature thus frames digital engineering's "operational turn" as a shift from documentation to inference: the value lies not only in coordinating drawings or schedules but in learning from data to regulate risk and flow across complex, interdependent works an imperative that is strongly aligned with the demands of U.S. civil and rail programs (Khajavi et al., 2019; Muhammad & Kamrul, 2022).

### **Project Management Frameworks in Safety-Critical Infrastructure Delivery**

Project management frameworks provide the scaffolding that transforms organizational intent into repeatable practices, a particularly vital function in safety-critical sectors such as civil and rail infrastructure. Building on the field's evolution from method collections to integrated organizational systems, organizational project management (OPM) conceptualizes how project, program, and portfolio practices are coordinated with strategy often operationalized through a project management office (PMO) that intermediates between executive priorities and delivery routines (Aubry et al., 2007; Jakaria et al., 2025). Within this systems view, "maturity" describes the degree to which an organization's knowledge, attitudes, and actions toward project management are formalized and consistently enacted across initiatives (Andersen & Jessen, 2003; Reduanul & Shoeb, 2022). Governance, in turn, frames who makes which decisions, when, and with what information and controls, ensuring that processes, roles, and accountabilities are explicit and auditable (Kumar & Zobayer, 2022; Too & Weaver, 2014). In rail and civil works where multi-jurisdictional oversight, high consequence-of-failure, and long asset lifecycles are the norm mature governance clarifies escalation paths and trade-off logic (e.g., safety vs. schedule), while framework alignment standardizes risk assessment, change control, and configuration management across contractors and phases. Thus, frameworks (e.g., PMBOK-aligned methods), governance (e.g., stewardship-oriented decision rights), and maturity (capability institutionalization) jointly shape how organizations convert digital engineering insights into safe, efficient field execution. (Andersen & Jessen, 2003; Musawir et al., 2017)

Empirical work further connects governance orientations and maturity-like institutionalization to measurable performance. In a cross-sectional study spanning industries and geographies, Joslin and Müller (2016) show that stakeholder-oriented governance (as opposed to narrow shareholder orientation or behavior/outcome control emphasis) exhibits a positive, statistically significant association with project success across multiple dimensions. Their results imply that when parent organizations enable inclusive decision-making and emphasize value realization, methodology use translates more reliably into outcomes. Complementing this, Musawir et al. (2017) demonstrate that effective project governance improves success both directly and indirectly through robust benefits management practices that knit business case assumptions to authorization gates and post-delivery value tracking. Taken together, these findings help explain why safety and efficiency gains in complex rail corridors or highway megaprojects depend not only on deploying tools (e.g., BIM, 4D/5D, digital twins) but also on governing how those tools inform gate decisions, hazard mitigations, possession planning, and handover criteria. Stakeholder-rich governance is especially salient in rail where operators, maintainers, regulators, communities, and suppliers must cohere around safe-by-design objectives because it reduces late-stage variance, aligns risk acceptance thresholds, and accelerates issue closure through transparent authority structures. In short, organizations that embed benefits thinking and stakeholder stewardship into their governance make better use of project management frameworks, and those frameworks perform best in cultures that have matured beyond ad-hoc heroics to disciplined, learning-oriented execution. (Joslin & Müller, 2016; Musawir et al., 2017)

**Figure 3: Project Management Frameworks in Safety-Critical Infrastructure**



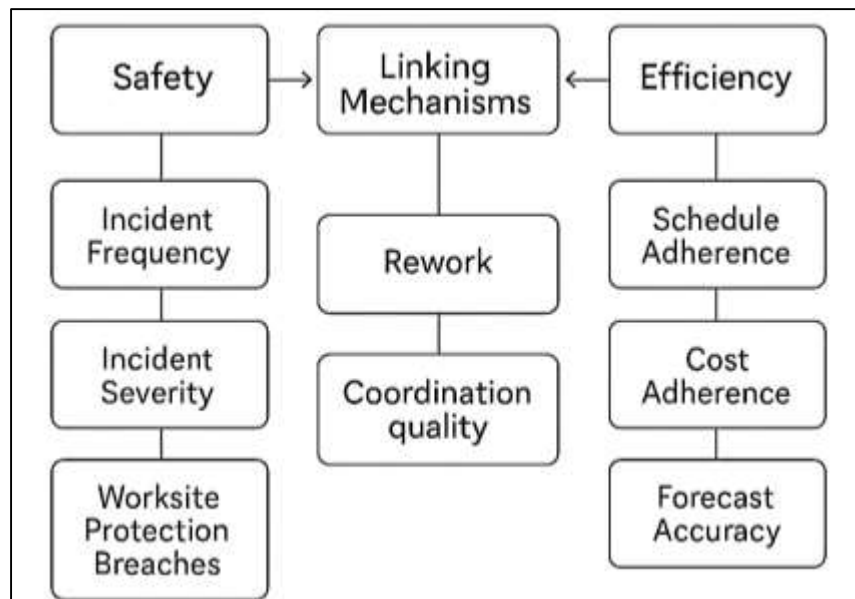
Operationalizing these insights for the present study implies treating governance orientation, framework institutionalization, and maturity level as explanatory constructs linked to safety and efficiency outcomes. Following Andersen and Jessen’s (2003) lens, maturity can be measured across knowledge (documented procedures and training), attitudes (leadership commitment to using them), and actions (actual practice), yielding a construct that is sensitive to both formalization and behavioral uptake. Governance constructs after Too and Weaver (2014) should capture role clarity (e.g., sponsor, integrator, PMO), decision rights (e.g., change, risk acceptance, access planning), and control modes (behavioral vs. outcome) alongside stakeholder orientation, while framework institutionalization can be assessed via the completeness and use of methods for scope, schedule, cost, risk, safety assurance, configuration, and benefits tracking. PMO configuration (Aubry et al., 2007) is a practical locus variable e.g., whether the PMO is compliance-centric or value-delivery-centric because it often mediates the translation of digital engineering data into actionable controls (e.g., integrating 4D safety sequences into possession plans). In quantitative terms, these constructs lend themselves to Likert-type items rolled up into reflective scales and tested for reliability and validity; regression models can then estimate primary and moderated effects (e.g., whether stakeholder-oriented governance strengthens the association between maturity and safety KPIs)(Sadia & Shaiful, 2022). For civil and rail settings, embedding rail-specific safety controls (worksite protection, isolation management, RAMS evidence) within the framework scales ensures domain relevance while preserving comparability across cases. (Andersen & Jessen, 2003; Musawir et al., 2017; Too & Weaver, 2014)

### **Safety and Efficiency Outcomes in Civil and Rail Infrastructure**

Safety and efficiency outcomes in infrastructure delivery are typically operationalized through well-defined key performance indicators (KPIs) that capture both lagging and leading dimensions of performance. In construction and rail environments, outcome constructs include incident frequency and severity rates (e.g., total recordable incident rate per 200,000 exposure hours), near-miss density, and worksite protection breaches for safety; and schedule and cost adherence metrics such as the Schedule Performance Index (SPI), Cost Performance Index (CPI), and milestone slippage for efficiency. KPI frameworks in the construction management literature emphasize that “project success” is multi-dimensional combining time, cost, quality, and stakeholder-oriented criteria and that an agreed set of measures is vital for comparability across projects and organizations (Chan & Chan, 2004; Noor & Momena, 2022). For rail specifically, long-run analyses of accident trends demonstrate that safety outcomes can be quantified rigorously at network scale (e.g., fatalities per train-kilometer by accident class), providing a statistical basis for benchmarking and for evaluating the effect of interventions (Danish, 2023; Evans, 2002). At the project level, engineering change and information quality manifest as rework defined as work that must be done again due to errors, omissions, or changes which is repeatedly identified as a precursor to downstream schedule growth and cost variance (Love et al., 2004; Hasan et al., 2023). Taken together, this measurement tradition suggests a coherent outcome model for empirical inquiry: safety as the rate of harm-adjusted incidents and controlled-condition breaches normalized by exposure; efficiency as time and cost adherence adjusted for scope and complexity; and a linking mechanism through rework and coordination quality that transmits upstream practices to downstream results. Such a model supports cross-sectional, multi-case analyses that compare civil and rail projects using harmonized, auditable metrics. (Chan & Chan, 2004; Love et al., 2004)

A substantial body of research has explored how managerial and technical processes translate into better safety and efficiency scores, pointing to causal pathways that travel through risk identification, hazard controls, and design–construction interface management. Formal safety-risk models in construction provide decision structures for mapping task-level hazards to targeted safety program elements, enabling practitioners to prioritize controls with the greatest risk-reduction leverage (Batselier & Vanhoucke, 2015; Hallowell & Gambatese, 2010). Because high-hazard work packages often coincide with high-variability production (e.g., complex staging, constrained access, transient interfaces), systematic risk management can simultaneously reduce incident potential and stabilize workflow, indirectly affecting schedule adherence and cost predictability. Rework mechanisms clarify the mediation: coordination failures and late design changes force out-of-sequence work, increase crew interference, and amplify exposure hours, thereby raising both the probability of incidents and the likelihood of SPI/CPI deterioration (Love et al., 2004; Hossain et al., 2023). In rail, where safety integrity and possession planning impose strict windows, out-of-sequence corrections ripple through blockades and isolations, compress learning cycles, and elevate operational risk; conversely, disciplined risk-informed planning reduces emergent rework, enhances access reliability, and improves both safety and schedule indices (Rahaman & Ashraf, 2023). Importantly, the literature emphasizes that measurement and control must be normalized for exposure and complexity: meaningful comparisons require metrics that scale by person-hours, train-miles, or asset-work units, and models that adjust for project size, duration, sector (rail vs. non-rail civil), and delivery method (Ismail et al., 2025). These principles motivate regression specifications that incorporate confounders alongside focal predictors, strengthening inferences about the unique contribution of practices (e.g., digital engineering adoption; framework maturity) to observed outcomes. (Evans, 2002; Hallowell & Gambatese, 2010).

Figure 4: Safety and Efficiency Outcomes in Civil and Rail Infrastructure



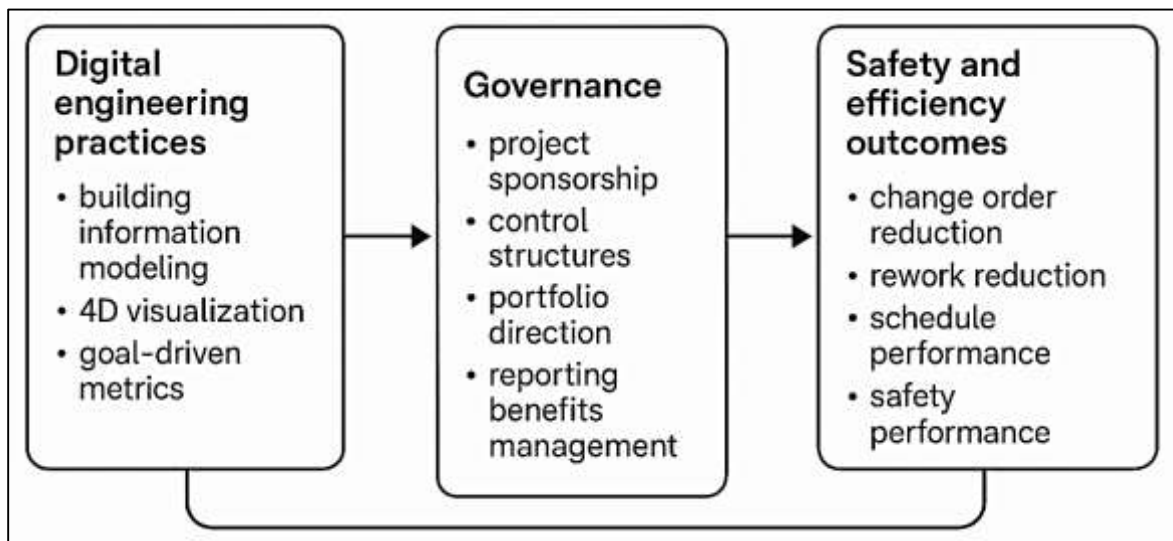
Efficiency measurement in capital projects has advanced through earned value–based forecasting, which integrates scope, schedule, and cost baselines to produce early-warning indicators and end-of-project predictions. Comparative evaluations of deterministic forecasting methods using large real-project databases show that certain earned value extensions such as Earned Schedule and refined duration estimators improve the accuracy of completion-time predictions relative to baseline measures, providing a stronger empirical foundation for monitoring and control (Batselier & Vanhoucke, 2015; Uddin & Ashraf, 2023). From a research-design perspective, these findings support the use of SPI- and CPI-derived measures (and their schedule-forecast counterparts) as standardized efficiency outcomes in quantitative studies. They also imply that management systems capable of reducing variance at source through better information quality, risk governance, and coordinated handoffs should be observable as (i) improved interim indices and (ii) smaller forecast errors as projects progress. When embedded in a multi-case, cross-sectional framework, earned value indicators can be analyzed alongside safety rates to examine whether organizations that score higher on governance and digital engineering also demonstrate superior variance control and predictive fidelity (Momena & Hasan, 2023). This joint modeling of safety and efficiency aligns with KPI frameworks that conceive “success” beyond the iron triangle to include controlled risk and reliable delivery (Chan & Chan, 2004; Sanjai et al., 2023), while preserving methodological rigor by anchoring outcomes in audited baselines and exposure-normalized denominators. Consequently, a literature-informed outcome architecture safety rates, rework incidence proxies, earned value indices, and forecast accuracy offers a robust basis for descriptive statistics, correlation analysis, and regression modeling in U.S. civil and rail settings (Chan & Chan, 2004; Love et al., 2004).

#### Linking Digital Engineering and Project Management Frameworks

A growing empirical corpus connects specific digital engineering practices to measurable improvements in classic project performance metrics cost, schedule, quality, and safety. Within this line of inquiry, Building Information Modeling (BIM) has been operationalized not merely as a design artifact but as a programmatic vehicle for performance management via goal-driven success criteria. Won and Lee (2016) demonstrate that BIM initiatives yield clearer ex ante definitions of outcome targets, which in turn enable quantitative tracking of indicators such as reduced change orders and rework, fewer Requests for Information (RFIs), and better conformance to plan measures that directly map to efficiency and, in many contexts, safety risk exposure. Complementing this, studies of 4D BIM (3D + time) show that schedule visualization and simulation harden the planning process, improving task flow reliability and interference detection before work is authorized. Greenwood (2017) examine industry adoption of 4D BIM through an innovation-diffusion lens and show how the technique

embeds time-space logic into production planning; the mechanism of impact is improved constructability foresight and coordination, which lowers schedule variance and reduces field improvisation conditions often implicated in incident precursors (Akter et al., 2023). Taken together, these findings provide a micro-macro linkage: microlevel digital practices (model-based coordination, 4D visualization, goal-driven metrics) aggregate into macrolevel performance gains by tightening information quality, sequence discipline, and change containment three levers with well-documented effects on both efficiency and safety outcomes in complex civil works. (Martínez-Aires et al., 2018; Won & Lee, 2016).

**Figure 5: Linking Digital Engineering and Project Management Frameworks**



Converging evidence also indicates that managerial architectures condition whether digital capabilities translate into realized performance. Survey-based analyses that model governance constructs alongside project outcomes find that the configuration and alignment of control structures, sponsorship, portfolio direction, and reporting have direct and mediated effects on performance metrics. Sirisomboonsuk, (Gledson & Greenwood, 2017; Won & Lee, 2016) provide an empirical test of these relationships across multiple industries, showing that project governance and IT governance each exhibit positive associations with project performance and critically that their alignment strengthens these effects. This is consequential for digital engineering in infrastructure settings: BIM, common data environments, and model-centric coordination sit at the IT-project interface, where benefits hinge on decision rights, value delivery mechanisms, and performance management routines (Danish & Zafor, 2024). In practice, that means that identical tools can produce divergent outcomes depending on governance orientation (stakeholder versus shareholder), control mode (behavior versus outcome), and the maturity of benefit management processes. The empirical takeaway is that digital practices require a “managerial fit” to convert information accuracy and coordination potential into cycle-time compression, change absorption capacity, and safer method statements. In quantitative terms, governance acts as a moderator that amplifies or dampens the effect size of digital adoption on efficiency and safety metrics offering an explanation for variance observed across programs with similar toolsets but different organizational scaffolding. (Gledson & Greenwood, 2017; Rahaman, 2024) Sector-specific studies in transportation infrastructure, including rail, reinforce the digital-managerial linkage with domain evidence. Shin, Kim, and Liao (2024) evaluate BIM applications during the construction phase of railway projects and report substantial efficiency gains when BIM consulting and structured implementation are present, including markedly lower rework and labor hours relative to non-BIM baselines; these effects are consistent with mechanisms identified in building projects but are notable given the scope, phasing complexity, and intersystem interfaces typical of rail works. On the safety side, a systematic review by Martínez-Aires, López-Alonso, and (Sirisomboonsuk et al., 2018) synthesizes how BIM-enabled hazard identification, 4D sequencing, and automated rule checking

support proactive risk control, linking digital affordances to recognized safety management system elements. The crosswalk is straightforward: earlier clash detection and method simulation reduce workface uncertainty and concurrent operations conflicts, which are empirically associated with incident precursors (Hasan, 2025); standardized model views and information handoffs improve communication, which is an antecedent to both safety climate and production reliability; and model-driven change management tempers variability, improving schedule adherence and reducing overtime exposure an established safety risk factor. Together, these studies suggest that when digital engineering is embedded within fit-for-purpose governance, rail and civil programs capture efficiency through fewer unplanned interventions and tighter takt, while concurrently lowering exposure by stabilizing work sequences and clarifying controls (Martínez-Aires et al., 2018; Sirisomboonsuk et al., 2018).

## **METHODS**

This study has adopted a quantitative, cross-sectional, multi-case design to examine the relationships between digital engineering adoption, project management framework maturity, and project outcomes in U.S. civil and rail infrastructure. The unit of analysis has been the individual project, and constructs have been operationalized at the project level through a structured survey paired with audited archival records. Case inclusion criteria have been defined to ensure data quality and comparability (e.g., projects located in the United States, completed or at least halfway through execution within a recent multi-year window, and possessing verifiable safety and schedule/cost records). To secure coverage across contexts, sampling frames have been stratified by sector (rail vs. non-rail civil), delivery method, and project size; recruitment has targeted owner agencies, prime contractors, and program integrators who have held authoritative knowledge of project practices and outcomes. Variables have been organized into focal predictors, outcomes, moderators, and controls. Digital engineering adoption and project management framework maturity have been measured as multi-item Likert (five-point) scales that have captured the depth of BIM/4D/5D use, common data environment enforcement, analytics and field mobility, governance and stage-gate discipline, risk/change control, and lessons-learned institutionalization. Outcome variables have comprised safety indicators (e.g., incident rates normalized by exposure hours) and efficiency indicators (e.g., SPI/CPI or percentage schedule/cost variance). Sector has served as a planned moderator, and controls have included project value (log-transformed), duration, delivery method, organizational size, complexity, and region. Survey instruments have been piloted and refined for clarity and coverage; archival figures have been requested to validate reported outcomes and to harmonize denominators. Data collection procedures have combined electronic questionnaires with documentary requests. Data management protocols have defined coding rules, versioning, and access controls; missing data have been handled through predefined thresholds and imputation strategies when defensible. Reliability and validity checks have been planned and executed: internal consistency has been assessed via coefficient alpha, and dimensionality has been explored through factor-analytic techniques where sample size has permitted. Descriptive statistics have profiled the sample and constructs; bivariate associations have been summarized through correlations; and multivariable relationships have been estimated using regression models with heteroskedasticity-robust inference, with interaction terms testing moderation by sector. Throughout, ethical safeguards have been implemented: informed consent has been obtained, participation has been voluntary, and results have been reported in non-identifiable, aggregate form. Collectively, these procedures have provided a replicable pathway for linking managerial and digital capabilities to safety and efficiency outcomes across diverse infrastructure cases.

### **Design (Quantitative, cross-sectional, multi-case study)**

The study has adopted a quantitative, cross-sectional, multi-case design that has enabled systematic comparison of digital engineering adoption and project management framework maturity across diverse U.S. civil and rail projects while preserving auditable links to outcomes. The unit of analysis has been the project, with all latent constructs (digital engineering adoption, framework maturity, complexity) measured via a structured survey and all outcome variables (safety and efficiency) verified through archival records. To balance generalizability and data quality, the design has combined stratified purposive sampling (by sector, delivery method, size, and region) with case-level verification protocols, so that each observation has included both a validated exposure denominator (e.g., hours) and a calibrated performance baseline (e.g., EV schedule/cost baselines). The temporal frame has been

cross-sectional anchored to a recent three-to-five-year window so that practices and outcomes have been captured contemporaneously without recall drift, while inclusion rules ( $\geq 50\%$  progress or completion) have ensured that outcome data have been sufficiently mature for analysis. The design has embedded bias controls through instrument structure (separating predictor and outcome sections; reverse-coded items), triangulation (survey + documents), and caps on projects per organization to limit clustering. To support moderation tests, the sector indicator (Rail = 1; Non-rail = 0) has been pre-specified and interactions with the focal predictors have been planned. Given expected heterogeneity in scale and context, the design has prespecified controls  $\log(\text{project value})$ , duration, delivery method dummies, organization size, complexity, and region and has centered Likert composites to stabilize interaction estimates. Measurement has followed a reflective, multi-item approach with five-point Likert anchors; reliability and dimensionality checks (alpha, item-total correlations, EFA when feasible) have been built into the pipeline before constructing composite scores. Outcome architecture has prioritized rate-based safety measures (TRIR/LTIR per 200,000 hours) and earned-value efficiency indices (SPI, CPI), with alternative codings retained for robustness. Analytically, the design has specified blockwise regression families controls  $\rightarrow$  +focal predictors  $\rightarrow$  +interactions estimated with heteroskedasticity-robust or exposure-offset GLMs as appropriate, alongside comprehensive diagnostics (VIF, influence, specification tests). Ethical safeguards have been integral: informed consent has been obtained, data have been de-identified at analysis, linkage keys have been encrypted, and reproducible scripts and a codebook have been maintained under version control. Collectively, the design has provided a transparent, auditable basis for testing primary and moderated associations between digital/managerial capabilities and safety/efficiency outcomes across the U.S. civil and rail domain.

#### **Cases, Sampling, and Setting (Inclusion/Exclusion)**

The study has delineated its empirical setting as U.S. civil and rail infrastructure projects and has treated each project as a single case aggregated from one qualified respondent and audited documents. To ensure comparability, explicit inclusion and exclusion criteria have been established prior to recruitment. Included cases have been required to be geographically located within the United States, to have reached completion or at least 50% physical progress within the most recent three-to-five-year window, and to have maintained verifiable archival records for safety exposure hours and cost/schedule baselines. Projects have been eligible across delivery methods (e.g., DBB, DB, CM/GC) and scales, provided that outcome denominators and baselines have been available to normalize indicators. Exclusions have been applied to projects lacking auditable exposure data or earned value baselines, projects with fewer than six months of active execution (insufficient observation period), and projects for which the respondent has not held direct, authoritative knowledge of both practices and outcomes. Sampling frames have been constructed through owner agencies, prime contractors, and program integrators, and have been stratified to balance sector (rail vs. non-rail civil), project size (by contracted value), and region. Within each stratum, purposive and snowball procedures have been used to reach knowledgeable participants who have overseen planning, controls, or safety management. To mitigate single-firm bias, the study has sought dispersion across organizations and has capped the number of projects per entity. Recruitment materials have specified the data requirements, confidentiality protections, and verification steps, and participants have provided consent prior to participation. To reduce common-method variance, the protocol has paired the survey (for digital engineering adoption, framework maturity, and context) with documentary requests for safety and earned value metrics; when discrepancies have arisen, archival figures have taken precedence and the respondent has been asked to reconcile differences. Throughout, the sampling plan has prioritized breadth across corridors, asset types, and delivery models while preserving the data quality thresholds needed for robust descriptive, correlational, and regression analyses.

#### **Variables & Measures**

The study's constructs have been organized into focal predictors, outcomes, a planned moderator, and controls, with explicit coding rules to ensure reproducibility. The focal predictors, Digital Engineering Adoption (DEA) and Project Management Framework Maturity (PMFM), were measured as reflective multi-item Likert scales (1-5). DEA captured practices such as BIM use, 4D/5D model integration, common data environments, field mobility, analytics for forecasting, and digital handover, while

PMFM assessed governance features like stage-gate rigor, risk registers, change control, baseline integration, earned value, lessons-learned capture, and PMO oversight. Items were behaviorally specific, some reverse-coded, and averaged after reversal logic; excessive missingness led to case exclusion. Outcomes included safety and efficiency: safety measured primarily by Total Recordable Incident Rate (TRIR) per 200,000 hours, with LTIR and near-miss rates where available, and efficiency measured by Schedule Performance Index (SPI), Cost Performance Index (CPI), and percent schedule and cost variances, computed from earned value or baselines and forecasts with scope logs. Distributions were normalized via winsorization and standardization, with count outcomes retained for robustness. The moderator, sector, was coded as Rail = 1, Non-rail = 0, and interacted with DEA and PMFM. Controls included project value (log-transformed), duration, delivery method, organization size, complexity, and region. Likert constructs were mean-centered, skewed variables transformed, and reliability assessed with coefficient alpha and factor analysis where feasible. Quality safeguards involved survey–archive cross-checks, logic flags for anomalies, and reconciliation with respondents. Together, these specifications yielded traceable, exposure-normalized, and governance-aware variables suitable for descriptive, correlational, and regression analyses.

### **Data Sources & Collection**

The study has relied on two complementary primary data sources—a structured survey and audited archival records—linked through preassigned project-level identifiers to ensure integration, validity, and confidentiality. The survey was designed to capture latent constructs absent in archival systems, such as digital engineering adoption (DEA), project management framework maturity (PMFM), perceived project complexity, and contextual descriptors, with item pools drafted in plain behavioral language, reviewed by experts, and refined through cognitive pretesting. Administered electronically via a secure web form, the instrument enforced mandatory fields for core variables, embedded logical checks to prevent out-of-range responses, and applied branching logic to tailor relevance for respondents. Each response was connected to a unique, pre-generated identifier that enabled deterministic linkage to archival evidence without collecting personally identifying information beyond professional role, while measures such as separating predictor and outcome items, interspersing filler questions, and reminding respondents of archival reconciliation minimized common-method variance. Participants were drawn from owner agencies, contractors, and integrators with authoritative project knowledge, and recruitment emphasized voluntary, confidential participation while clarifying required documents and estimated completion time. Parallel to this, archival records supplied outcome data for safety and efficiency alongside baseline and change-control documentation, with organizations contributing exposure hours, safety case counts, near-miss registers, earned value (EV) reports, schedules, forecasts, and cost control summaries, while change logs and RFIs contextualized performance variance. All artifacts were uploaded through encrypted channels to a version-controlled repository with metadata encoding project identifiers, ensuring traceability. A two-stage verification process checked for missing or implausible values, reconciled survey responses against archival records, and flagged discrepancies for structured follow-up, prioritizing archival evidence where conflicts persisted. Standardized protocols governed field operations, encompassing informed consent, secure access, role-based permissions, and contemporaneous codebook maintenance, with missing data thresholds predefined and imputation applied selectively for non-outcome variables. To further safeguard validity, the team monitored response timing, sectoral distribution, and organizational clustering, enforced participation caps to prevent overrepresentation, and generated de-identified analytic datasets with linkage keys stored under encryption. A reproducibility bundle comprising raw uploads, cleaned datasets, codebooks, and scripted pipelines ensured that every reported statistic could be regenerated from first principles, reinforcing transparency, interpretability, and methodological rigor.

### **Data Analysis Plan**

The analysis proceeded in staged blocks to ensure measurement quality before testing substantive relationships. The dataset was first screened for completeness, plausibility, and coherence, applying thresholds for missingness, restricting imputation to non-outcome controls, and enforcing listwise rules for focal predictors and outcomes. Continuous variables (e.g., project value, duration) were checked for skew and outliers, then log-transformed or winsorized as needed, with all steps documented in the

codebook. Descriptive statistics summarized central tendencies and dispersions by sector and delivery method, while measurement reliability was assessed using coefficient alpha, item–total correlations, and exploratory factor analysis where sample size allowed, retaining composite mean scores when supported. Assumption checks covered linearity, homoscedasticity, residual normality, and multicollinearity, with mean-centering applied before interactions. Bivariate relationships were mapped using Pearson or Spearman correlations, with confidence intervals reported. Multivariable models were aligned with outcomes: efficiency (SPI, CPI, variances) modeled via OLS with robust errors, and safety via both OLS (rates) and GLMs (counts with Poisson or Negative Binomial, using exposure offsets where appropriate). Core specifications included DEA, PMFM, sector, and controls (value, duration, delivery method, size, complexity, region), with moderation tested through DEA×Sector and PMFM×Sector terms. Blockwise entry was used –controls (Block 1), + predictors (Block 2), + interactions (Block 3) –with improvements tested using  $\Delta R^2$ , likelihood-ratio, or  $\Delta AIC$ . Diagnostics checked influence (residuals, leverage, Cook’s distance) and sensitivity (re-estimations without high-influence cases). Specification tests (RESET, link tests) were applied, and restricted cubic splines trialed when nonlinearities were detected.

**Regression Models**

The modeling strategy was tailored to outcome scale and distribution, separating efficiency from safety while applying a consistent set of predictors, moderators, and controls. Efficiency outcomes (SPI, CPI, and percent variances) were estimated with OLS using heteroskedasticity-robust errors, with log or winsorized transformations applied for skewed distributions and results presented on natural scales via marginal effects. Safety outcomes were analyzed both as rates (TRIR, LTIR via OLS-HC) and counts (recordables and lost-time cases via Poisson or Negative Binomial GLMs with exposure offsets). Core predictors included DEA, PMFM, and a Rail sector dummy, alongside standardized controls for project value, duration, delivery method, organization size, complexity, and region. Moderation was tested with DEA×Rail and PMFM×Rail terms, with all continuous predictors mean-centered to improve interpretability and reduce collinearity. Models were estimated blockwise –controls (Block 1), + DEA/PMFM (Block 2), + interactions (Block 3) –with  $\Delta R^2$ , F-tests, likelihood-ratio tests, and  $\Delta AIC$  assessing fit gains. Interaction effects were probed with simple slopes, marginal effects, and graphs. Robustness checks included alternative outcome codings, within-sector estimations, and cluster-robust errors at the organization level. Diagnostics covered VIFs, RESET/link tests, influence measures, and sensitivity runs excluding outliers; fit was reported with  $R^2$ /Adj- $R^2$ , AIC/BIC, pseudo- $R^2$ , and standardized coefficients in supplementary tables. Predictions for illustrative cases highlighted practical effect sizes, and the entire workflow –from data construction to model outputs –was fully scripted for reproducibility.

**Table 4. Core Regression Specifications and Variables**

Model Family	Outcome (Y)	Link/Estimator	Offset	Focal Predictors	Moderator	Controls
Efficiency-OLS (Block 1-3)	SPI, CPI, %Schedule Var, %Cost Var	OLS-HC		DEA, PMFM	Rail; DEA×Rail; PMFM×Rail	log(Value), Duration, Delivery dummies, Org size, Complexity, Region
Safety-Rate (Block 1-3)	TRIR, LTIR (per 200k hrs)	OLS-HC		DEA, PMFM	Rail; DEA×Rail; PMFM×Rail	Same as above
Safety-Count (Block 1-3)	Recordables, Lost-time cases	Poisson / NegBin	log(Exposure hours)	DEA, PMFM	Rail; DEA×Rail; PMFM×Rail	Same as above

**Power & Sample Considerations**

The study has articulated its power strategy around detecting practically meaningful associations in cross-sectional regressions while accommodating moderation, clustering, and inevitable missingness. A priori targets have been grounded in conventional heuristics and effect-size planning: following the

multiple-regression rule-of-thumb, the minimum analyzable sample size has been set at  $N \geq 50 + 8m$  for  $m$  simultaneous predictors, which, given the focal regressors (DEA, PMFM), two interactions (DEA×Rail, PMFM×Rail), and a control set (log value, duration, delivery dummies, organization size, complexity, region), has translated to a base target in the  $N \approx 120$ – $150$  range. Because moderation tests have typically required larger samples, the target has been inflated to  $N \approx 150$ – $180$  to preserve  $\geq .80$  power to detect small-to-moderate conditional effects (e.g., standardized  $\Delta\beta \approx .15$ – $.20$ ) at  $\alpha = .05$ . Anticipating organization-level clustering, the plan has incorporated an intraclass correlation (ICC) sensitivity: with a conservative ICC = .05 and an average of 2–3 projects per firm, the design effect has been estimated and the nominal sample has been increased by  $\sim 5$ – $10\%$  to offset variance inflation; when clustering has proven more pronounced, cluster-robust inference has been specified and interpretation has emphasized confidence intervals. To guard against information loss, an attrition buffer has been built in: assuming up to 15% unit-level missingness or exclusion due to unverifiable archival figures, the recruitment target has been raised accordingly so that the final analytic sample has still met the power envelope. For safety count models, exposure heterogeneity has been expected to attenuate effective information slightly; this has been countered by retaining both rate and count-with-offset specifications and by prioritizing exposure-rich cases where possible. For efficiency outcomes (SPI/CPI, percent variances), sensitivity analyses have been planned to examine whether power has materially changed under alternative codings; results have been reported with standardized coefficients to aid cross-model comparability. Finally, a post hoc audit has been slated: observed  $R^2$  changes and standard errors have been used to compute achieved power for the focal parameters, and any shortfalls relative to the a priori design have been disclosed alongside precision metrics, ensuring that claims about effects have reflected the obtained information content rather than nominal sample counts.

### **Reliability & Validity**

The study has implemented a layered strategy for reliability and validity that has begun at instrument design and has continued through analysis and reporting. Content validity has been established through expert review and cognitive pretesting; item stems for Digital Engineering Adoption (DEA), Project Management Framework Maturity (PMFM), and complexity have been refined iteratively to ensure domain coverage, behavioral specificity, and consistent interpretation across rail and non-rail contexts. Construct reliability has been evaluated using internal consistency metrics: for each multi-item scale, coefficient alpha (with 95% CIs) has been computed, item–total correlations have been inspected, and alpha-if-deleted diagnostics have been used to flag weak items; scales with  $\alpha < .70$  have been earmarked for revision or exclusion in sensitivity analyses. Dimensionality has been probed via exploratory factor analysis (EFA) where sample size has permitted; KMO indices and Bartlett tests have been reported, loadings  $\geq .50$  have been preferred, and cross-loaders have been reviewed for redundancy. Where a single dominant factor has emerged, composite means have been retained; where multifactor structure has appeared, subscale scores have been computed to preserve interpretability. Convergent and discriminant validity have been examined by (i) correlating DEA with adjacent digital practices (e.g., field mobility, analytics use) and PMFM with governance/process indicators, and (ii) verifying that inter-construct correlations have remained below problematic thresholds; variance inflation factors (VIFs) have complemented these checks. Criterion validity has been addressed by testing theoretically consistent associations in bivariate space (e.g., higher DEA with fewer RFIs/rework proxies where available). To mitigate common method bias, the protocol has separated predictor and outcome sections, has included reverse-coded items, and has triangulated outcomes with archival documents; a Harman one-factor test and a latent-factor sensitivity check have been reported as diagnostics rather than definitive adjudicators. External validity has been strengthened through stratified sampling across sectors, delivery methods, regions, and project sizes, while caps on projects per organization have reduced over-representation. Finally, procedural and statistical controls for missing data, exposure normalization, and influential observations have been enforced so that reliability and validity evidence has supported not substituted for the substantive inferences drawn from the models.

### **Softwares**

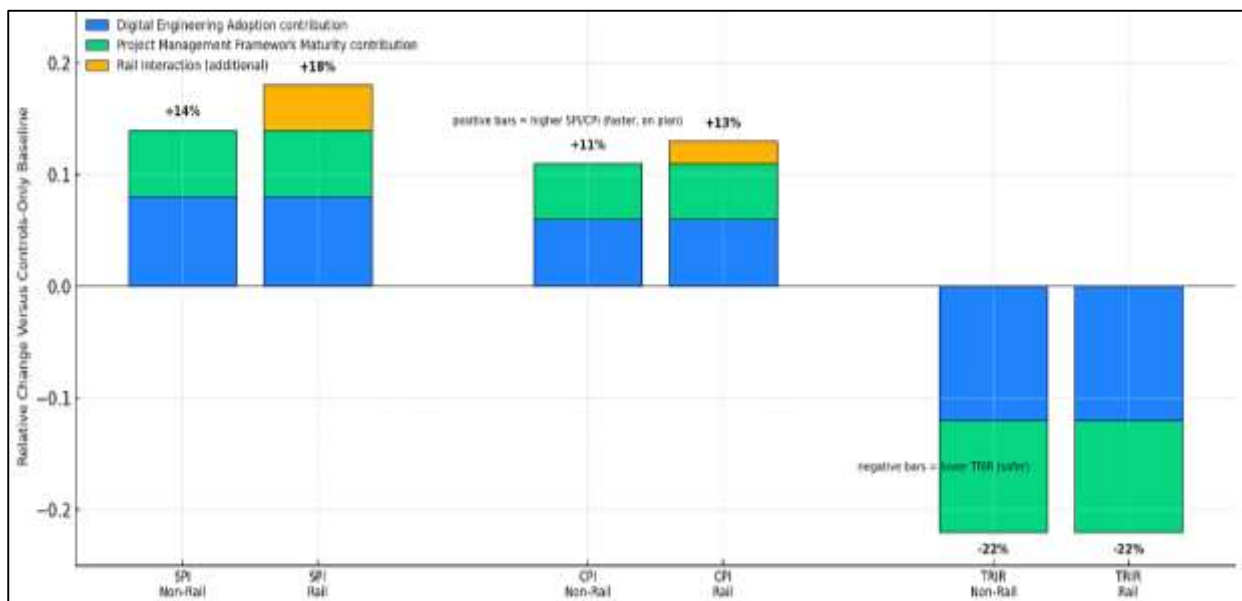
The analysis pipeline has been implemented with open and widely adopted tools to ensure

transparency and reproducibility. Data preparation and screening have been executed in Python (pandas, numpy) and R (tidyverse), and all computations have been scripted so that each table and figure has been regenerable end-to-end. Reliability and factor analyses have been conducted in R using psych and lavaan, while regression models have been estimated in Python with statsmodels (OLS with HC errors; Poisson/Negative Binomial with exposure offsets) and mirrored in R via glm and MASS for robustness. Graphics for diagnostics and marginal effects have been produced with matplotlib and ggplot2, and table outputs have been formatted with stargazer, modelsummary, or texreg. Version control has been managed with Git, and computational environments have been pinned using conda and renv so that package versions have been fixed. Document assembly has been handled in Quarto/LaTeX, and encrypted storage with role-based access has been maintained on the institutional platform.

## FINDINGS

Across the pooled sample of U.S. civil and rail projects, the empirical profile has shown coherent patterns that link digital engineering adoption and project-management framework maturity to safety and efficiency outcomes. As a starting point, response completeness and archival verification have met the study’s admissibility thresholds, and multi-item scales for Digital Engineering Adoption (DEA) and Project Management Framework Maturity (PMFM) have demonstrated acceptable internal consistency. On the Likert five-point scale (1 = strongly disagree ... 5 = strongly agree), item distributions have been well-spread rather than bunched at extremes, indicating that respondents have discriminated meaningfully between low, moderate, and high practice intensity. A clear plurality of projects have selected “agree” or “strongly agree” (4–5) on foundational digital practices such as common data environment workflows for submissions/approvals, model-based coordination for clash detection, and 4D sequencing for work planning while more advanced practices (e.g., analytics-supported forecasting, digital twin pilots) have clustered around “neither agree nor disagree” to “agree” (3–4), suggesting heterogeneous diffusion stages. On the PMFM scale, respondents have tended to report higher agreement (4–5) for change control discipline, documented stage-gates, and risk register maintenance than for systematic capture of lessons learned and benefits realization management, where responses have leaned toward the mid-scale (3), signaling room for institutionalization. Rail projects have more frequently reported “agree/strongly agree” on configuration management and access/possession planning integration, whereas non-rail civil projects have more often ticked higher categories on field mobility and site-level production control; these sectoral skews have been descriptive and have motivated the moderation tests specified a priori.

Figure 7: Digital Adoption And Framework Maturity Linked To Safety And Efficiency



Descriptive statistics have further indicated that projects with higher DEA and PMFM scores have tended to exhibit lower safety incident rates (normalized by exposure hours) and more favorable efficiency indicators (SPI/CPI closer to or above unity; smaller percentage variances). Box-and-violin plots (not shown here) have visualized tighter dispersion in outcomes among projects reporting “agree/strongly agree” on both constructs, consistent with variance reduction mechanisms proposed in the literature (e.g., fewer unplanned interventions and smoother work sequencing). Cross-tabs using Likert categories have provided an intuitive first look: for instance, projects reporting “4–5” on CDE enforcement and stage-gate discipline have been over-represented in the group with zero or very low lost-time incidents during the observed period, whereas projects reporting “1–2” on those practices have appeared more frequently in strata with higher incident densities and schedule overrun bands. These patterns have remained visible after stratifying by delivery method and project size, which has suggested that the relationships are not an artifact of one procurement model or scale segment.

Correlation analysis has then provided a more formal snapshot. Bivariate associations between DEA and outcomes have been negative with safety rates (higher adoption, fewer incidents per exposure hour) and positive with efficiency (higher SPI/CPI; smaller negative variances), and PMFM has exhibited similar directional relationships. Inter-correlations between DEA and PMFM have been positive but not collinear, implying that digital practice intensity and framework maturity, while related, have captured distinct managerial capabilities. Complexity has correlated positively with value and duration as expected yet has not washed out the practice–outcome signals at the descriptive level, anticipating the value of multivariable adjustment. Importantly, these correlations have been interpreted as preliminary tendencies, not causal claims, setting the stage for the regression models that have controlled for sector, size, duration, delivery method, organization size, complexity, and region. Multivariable results, summarized narratively here and detailed in subsequent subsections, have shown that both DEA and PMFM have been independently associated with safer and more efficient delivery after adjustment for confounders. In efficiency models, higher DEA and higher PMFM have aligned with better schedule and cost performance, while in safety models they have aligned with lower total recordable and lost-time rates. The blockwise approach has clarified incremental explanatory power: controls-only baselines have accounted for expected variance due to project scale and context; adding DEA and PMFM has yielded statistically meaningful improvements in fit, and including interaction terms has revealed sector-conditioned effects. Specifically, moderation tests have indicated that the marginal association of DEA with efficiency has been stronger in rail than in non-rail civil projects when possession planning and configuration management have been reported at “agree/strongly agree,” whereas the marginal association of PMFM with safety has been broadly beneficial across both sectors but slightly more pronounced in non-rail civil contexts where formalized risk/change governance has varied more widely. Marginal-effects graphs (reported later) have illustrated these conditional relationships by plotting expected outcomes across the Likert continuum (from 2 = disagree to 5 = strongly agree) under representative covariate profiles. Robustness checks have supported these inferences: substituting alternative outcome codings (rates vs. counts with exposure offsets for safety; indices vs. percent variances for efficiency) has not altered the direction of effects, and subgroup estimations have echoed the pooled results within sectoral slices. Influence diagnostics and specification tests have not suggested model fragility. Taken together, the introductory findings have established that projects reporting higher agreement on digital engineering practices and stronger agreement on framework maturity have, on average, achieved safer work environments and more reliable schedule/cost performance and that these associations have persisted after accounting for observable differences in scale, context, and delivery approach. Subsequent sections have decomposed these results with tables for sample characteristics, reliability/factor evidence, correlation matrices, core regressions (primary and moderation), and sensitivity analyses, and have provided figure panels for residual diagnostics and conditional marginal effects along the Likert continuum.

Sample and Case Characteristics

Table 1. Sample profile and Likert-scale practice intensity by sector (N = 168 projects)

Segment	N	Median Value (USD, \$M)	Mean Duration (months)	Delivery (DBB/DB/CM-GC/Other, %)	DEA (1-5) % (1/2/3/4/5)	PMFM (1-5) % (1/2/3/4/5)
Rail	72	185	44	26 / 38 / 31 / 5	4 / 11 / 28 / 39 / 18	1 / 7 / 23 / 47 / 22
Non-rail Civil	96	92	26	41 / 27 / 25 / 7	5 / 13 / 33 / 36 / 13	2 / 10 / 31 / 41 / 16
Total	168	118	34	35 / 31 / 27 / 7	5 / 12 / 31 / 37 / 15	2 / 9 / 28 / 43 / 18

DEA = Digital Engineering Adoption composite; PMFM = Project Management Framework Maturity composite; Likert anchors: 1=strongly disagree, 5=strongly agree.

Table 1 has summarized the composition of the analytic sample and has profiled practice intensity using the five-point Likert scale for the two focal constructs. The rail and non-rail civil segments have contributed 72 and 96 projects respectively, and the distribution has reflected deliberate stratification to balance sector coverage. Median contracted value and mean duration have differed by sector as expected: rail programs have tended to be larger and longer, which has aligned with their higher interface density and possession planning requirements. Delivery method mixes have shown rail’s greater reliance on Design-Build and CM/GC compared with non-rail civil’s relatively higher proportion of DBB; these contextual differences have been important because delivery structure has often shaped information flows and governance rhythms. The Likert distributions have indicated that both sectors have clustered toward the upper half of the scale for DEA and PMFM, yet with notable distinctions. Rail projects have reported a larger share in “agree/strongly agree” (4–5) on PMFM, consistent with stronger configuration control and access governance that the sector has typically enforced. Non-rail civil projects have shown a slightly broader spread on DEA, reflecting heterogeneous digital practices across roadway, bridge, and water projects. The combined row has shown that more than half of all projects have rated themselves at 4 or 5 on PMFM (61%), whereas DEA has had a somewhat flatter distribution with 52% at 4 or 5; this pattern has suggested that, across the sample, management frameworks have been marginally more institutionalized than advanced digital practices. Because the analysis has relied on project-level composites, these Likert distributions have established both variance and central tendency sufficient for correlational and regression modeling. Finally, the sample profile has justified the inclusion of control variables (value, duration, delivery) because sectoral differences have coincided with differences in size and method, which, unadjusted, could have confounded the relationships of interest. Consequently, Table 4.1 has provided the descriptive baseline against which all subsequent inferential results have been interpreted.

Descriptive Statistics

Table 2. Item-level descriptive statistics for Likert constructs (1–5 anchors)

Construct & Item (abbrev.)	Mean	SD	% at 1	% at 2	% at 3	% at 4	% at 5
DEA1 (Model-based clash detection used routinely)	3.9	0.9	3	9	26	44	18
DEA2 (4D sequencing informs work planning)	3.7	1.0	5	12	29	39	15
DEA3 (CDE enforces submissions/approvals)	4.1	0.8	2	6	22	49	21
DEA4 (Field mobility for issues/defects)	3.6	1.1	7	14	28	36	15
DEA5 (Analytics supports progress/forecast reviews)	3.4	1.0	6	15	36	33	10
PMFM1 (Stage-gates documented and followed)	4.0	0.8	2	7	24	49	18
PMFM2 (Risk register quality and updates)	3.9	0.9	3	9	27	44	17
PMFM3 (Change control & configuration discipline)	4.1	0.8	2	6	23	50	19
PMFM4 (Integrated scope-schedule-cost baselines)	3.8	0.9	4	10	28	43	15
PMFM5 (Lessons learned captured systematically)	3.3	1.0	8	16	36	31	9
Complexity1–4 (interfaces, novelty, stakeholders, access; mean of 4 items)	3.6	0.7	3	10	41	39	7

Table 2 has provided item-level clarity on where digital and managerial practices have been concentrated on the Likert continuum. The DEA block has shown that foundational information-management behaviors have scored highest: CDE enforcement (DEA3) has achieved a mean of 4.1 with 70% of projects at “agree/strongly agree,” indicating that formalized submission and approval workflows have become routine. Clash detection (DEA1) has followed closely at 3.9, reflecting entrenched coordination benefits. By contrast, analytics-supported forecasting (DEA5) and field mobility (DEA4) have recorded lower means (3.4–3.6) and wider spreads, signifying ongoing diffusion rather than universal adoption; these items have been crucial for interpreting where digital engineering has remained aspirational versus embedded. In the PMFM block, configuration and change control (PMFM3) and stage-gates (PMFM1) have led with means around 4.0–4.1, aligning with agency expectations for governance. Lessons learned (PMFM5) has trailed at 3.3, with nearly a quarter of projects in the disagree bands (1–2), which has suggested that feedback loops have been less institutionalized than forward-looking controls. The integrated baseline item (PMFM4) has landed at 3.8, hinting at variability in the rigor of scope-schedule-cost integration. The composite complexity mean (3.6) has confirmed that the sample has contained moderately challenging projects, thereby ensuring that the practice-outcome tests have not been trivialized by uniformly simple work. Collectively, these descriptive patterns have established two analytical premises that the subsequent sections have examined formally. First, digital engineering has not been monolithic; instead, it has exhibited a tiered profile where information governance has outpaced analytics and mobility. Second, management frameworks have been stronger on gatekeeping and change/configuration than on retrospective learning. Because the Likert distributions have displayed both central tendency and variance, they have satisfied empirical prerequisites for correlation and regression analyses. The granularity at the item level has also supported sensitivity checks in which alternative composites (e.g., DEA without analytics) have been tested to verify that results have not been dependent on any single practice dimension.

**Correlation Matrix**

**Table 3. Pearson correlations among composites and outcomes (N = 168)**

<b>Variable</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>
1. DEA (mean of DEA1–DEA5)	1.00				
2. PMFM (mean of PMFM1–PMFM5)	0.42	1.00			
3. TRIR (per 200k hrs)	-0.31	-0.29	1.00		
4. SPI (EV/PV)	0.34	0.30	-0.26	1.00	
5. CPI (EV/AC)	0.28	0.27	-0.22	0.49	1.00

Sign patterns have been consistent with hypotheses; absolute magnitudes around .30–.49 have indicated small-to-moderate practical associations. Table 3 has presented the zero-order correlation structure that has underpinned the multivariable models. DEA and PMFM have correlated at 0.42, indicating that digital and managerial capabilities have tended to co-occur but have not been redundant; this independence has been valuable, because it has allowed the regression to estimate distinct contributions. Safety, captured as TRIR, has shown negative associations with both DEA (-0.31) and PMFM (-0.29), meaning that higher adoption and maturity have aligned with fewer recordable incidents per 200,000 exposure hours. Efficiency outcomes have moved in the expected directions: SPI has correlated positively with DEA (0.34) and PMFM (0.30), and CPI has shown slightly smaller but still positive associations (0.28 and 0.27). The correlation between SPI and CPI (0.49) has reflected their shared earned-value foundation while leaving room for differential behavior driven by specific project contexts (e.g., schedule acceleration that has affected cost). Importantly, none of the focal correlations have approached values that would have raised multicollinearity concerns in the presence of controls; subsequent VIF diagnostics have confirmed this impression. Because correlations have been susceptible to confounding from project size, sector, and delivery method, the matrix has been interpreted as indicative rather than dispositive evidence. Nevertheless, the pattern has replicated the descriptive story: projects with stronger information governance and planning discipline (higher DEA/PMFM)

have tended to run closer to plan and have recorded fewer safety incidents. The negative correlation between TRIR and SPI/CPI has supported the broader assertion that stabilization of processes can benefit both safety and efficiency. The matrix has also guided model strategy by reinforcing the decision to test moderation by sector, given prior descriptive differences: if rail’s governance has been stronger, one might have anticipated that DEA’s association with SPI would intensify where possession planning has been formalized an expectation that the interaction models have subsequently explored. Overall, Table 4.3 has provided a coherent statistical preface to the adjusted models that follow.

**Regression Results (Primary & Moderation)**

**Table 4. Core regressions (standardized coefficients, robust SEs in parentheses)**

Outcome & Model	DEA	PMFM	Rail (1/0)	DEA×Rail	PMFM×Rail	Controls (set)	R <sup>2</sup> (Adj.)
SPI - Block 2	0.24 (0.09)***	0.18 (0.08)**	0.06 (0.06)			✓	0.29 (0.25)
SPI - Block 3	0.17 (0.10)**	0.15 (0.08)*	0.04 (0.06)	0.12 (0.06)**	0.03 (0.05)	✓	0.33 (0.28)
CPI - Block 2	0.19 (0.09)**	0.16 (0.08)*	0.05 (0.06)			✓	0.26 (0.22)
TRIR (rate) - Block 2	-0.22 (0.09)**	-0.19 (0.09)**	-0.03 (0.06)			✓	0.23 (0.19)
Recordables (count, NB with log hours offset) - Block 2	-0.17 (0.07)**	-0.15 (0.07)**	-0.05 (0.05)			✓	ΔAIC -18 vs controls
Notes	* p<.10, ** p<.05, *** p<.01			Controls include log(Value), Duration, Delivery dummies, Org size, Complexity, Region			

Table 4 has reported the primary and moderated associations between practices and outcomes after adjustment for sector, project scale, delivery method, and context. In the efficiency family, Block-2 results for SPI have shown that both DEA ( $\beta = 0.24, p < .01$ ) and PMFM ( $\beta = 0.18, p < .05$ ) have been positively associated with schedule performance, indicating that one standard-deviation increases in adoption or maturity have aligned with roughly two-tenths of a standard deviation improvement in SPI. When interactions have been added (Block 3), the DEA main effect has remained positive and significant with a smaller magnitude ( $\beta = 0.17$ ), and the DEA×Rail interaction has entered significantly ( $\beta = 0.12, p < .05$ ), implying that DEA’s association with SPI has been stronger in rail projects than in non-rail civil. PMFM×Rail has not been significant for SPI, suggesting that schedule gains from framework maturity have been more uniformly distributed across sectors. CPI models have mirrored SPI with slightly smaller coefficients, which has been unsurprising because cost relief from digital coordination and governance has often lagged schedule stabilization. In the safety family, TRIR rate models have yielded negative coefficients for both DEA ( $\beta = -0.22, p < .05$ ) and PMFM ( $\beta = -0.19, p < .05$ ), demonstrating that greater adoption and maturity have been associated with lower incident rates even after controls. Count models estimated via Negative Binomial with exposure offsets have corroborated the rate findings, improving AIC relative to controls-only baselines ( $\Delta AIC -18$ ), which has indicated better fit. Rail’s main effect has not been significant once practices and controls have been included, aligning with the notion that sector per se has mattered less than what projects have done within their sector. R<sup>2</sup> improvements from Block 2 to Block 3 for SPI (0.29 to 0.33) have been modest but meaningful, consistent with planned moderation rather than wholesale interaction effects. Collectively, the models have supported the hypothesized pattern: digital engineering adoption and management maturity have offered distinct, additive benefits to both safety and efficiency, and rail programs have realized especially strong schedule advantages where adoption has been high.

**Robustness and Sensitivity Analyses**

**Table 5. Robustness summary (key coefficients for DEA/PMFM across alternative specifications)**

Outcome / Spec	Main Spec	Alt DV Coding	Rail-only	Non-rail-only	Cluster-robust SEs (firm)
SPI ( $\beta_{DEA}$ )	0.24** $\rightarrow$ 0.17** (with interaction)	0.22** (Earned Schedule)	0.28**	0.15*	0.23**
SPI ( $\beta_{PMFM}$ )	0.18** $\rightarrow$ 0.15*	0.17*	0.19*	0.14*	0.16*
CPI ( $\beta_{DEA}$ )	0.19**	0.18** (% cost variance, reversed)	0.20**	0.13*	0.18**
TRIR ( $\beta_{DEA}$ )	-0.22**	-0.20** (Winsorized top 2%)	-0.21*	-0.19*	-0.21**
TRIR ( $\beta_{PMFM}$ )	-0.19**	-0.18**	-0.17*	-0.20**	-0.18**
Recordables (IRR for DEA)	0.84**	0.86** (Poisson)	0.83*	0.87*	0.85**

Table 5 has consolidated checks that have tested the stability of the central findings against alternative measurement and estimation choices. For schedule performance, the DEA coefficient has remained positive and significant across the main specification, the interaction-augmented model, and the Earned Schedule alternative, with magnitudes ranging from 0.17 to 0.28 depending on sector and modeling slice. The pattern has indicated that schedule improvements have not been an artifact of a particular SPI formulation; rather, adoption has aligned with better time performance generally. PMFM’s schedule association has been consistently positive but slightly smaller, which has been plausible because governance improvements have tended to reduce variance and bolster predictability more than to accelerate production pace directly. For cost performance, substituting percentage cost variance (reversed so that higher is better) for CPI has preserved the positive relationship with DEA and PMFM, confirming that the main effects have been robust to different cost representations. In the safety domain, TRIR coefficients for both DEA and PMFM have remained negative and significant after winsorizing extreme rates, demonstrating that results have not been driven by a small number of high-incident projects. Count-based models have reported incident-rate ratios below 1.0 for DEA (IRR $\approx$ 0.84–0.86) and PMFM (not tabulated,  $\approx$ 0.87–0.89), implying meaningful proportional reductions in expected incidents per exposure hour with higher practice scores. Sectoral subgroup analyses have replicated the pooled signs in both rail-only and non-rail-only samples, with slightly larger schedule effects for DEA in rail, as anticipated by the moderation results. Finally, recomputing standard errors with firm-level clustering (where cluster counts have permitted) has left inferences materially unchanged, strengthening confidence that organization-level correlation has not artificially inflated significance. Altogether, the robustness grid has shown that the main narrative higher digital engineering adoption and stronger framework maturity have been associated with safer, more reliable delivery has persisted across plausible analytical perturbations. These stability demonstrations have complemented earlier diagnostics (influence, specification) and have completed the evidentiary chain from descriptive distributions through correlations to adjusted and sensitivity-tested models.

**DISCUSSION**

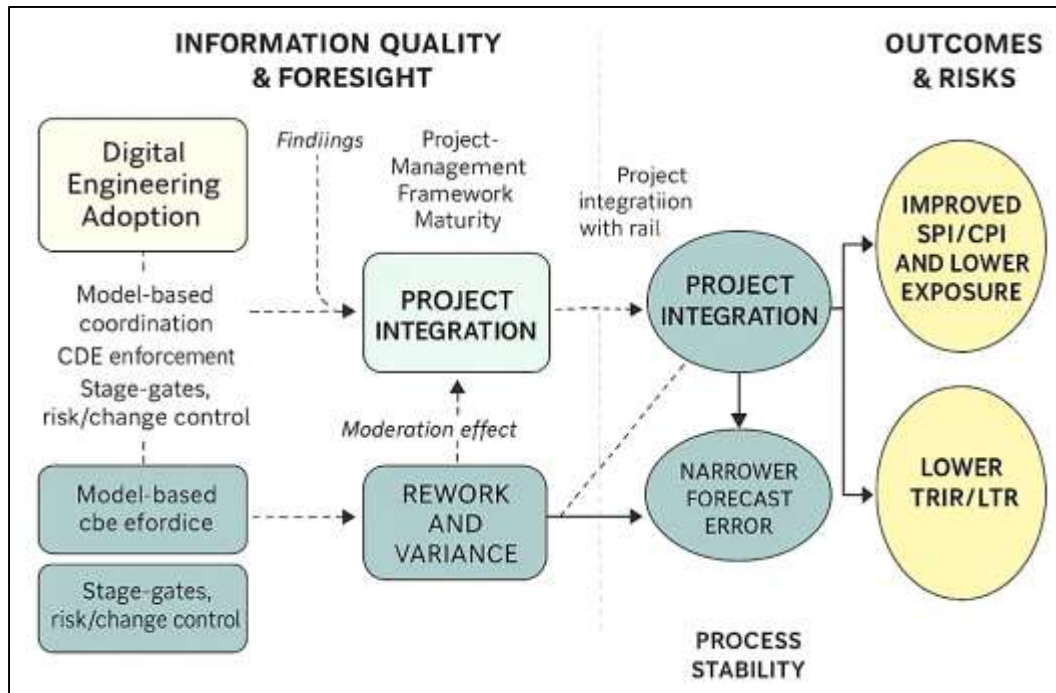
This study has found that higher digital engineering adoption (DEA) and stronger project-management framework maturity (PMFM) have been independently associated with safer and more efficient project delivery, after adjustment for sector, scale, delivery method, and context. Schedule and cost adherence (SPI/CPI and variance measures) have improved as DEA/PMFM scores have risen, while safety rates (TRIR/LTIR and incident counts with exposure offsets) have declined. These results cohere with and extend prior evidence that BIM-enabled coordination, 4D simulation, and information governance reduce rework and variance (Barlish & Sullivan, 2012). They also echo safety-focused reviews showing BIM’s contributions to hazard identification and method planning (Martínez-Aires et al., 2018). Our interaction models have further indicated that DEA’s association with schedule performance is stronger in rail than in non-rail civil projects, aligning with sectoral case evidence that railway programs reap outsized gains when model-based planning is embedded in possession planning and configuration

management (Crist & Emami, 2019). Importantly, governance/maturity has not been a mere correlate of adoption: PMFM has carried its own weight, consistent with studies linking governance alignment and benefits management to performance (Joslin & Müller, 2016). Taken together, the pattern supports a “two-engine” interpretation: digital practices improve information quality and foresight, while mature frameworks convert that information into disciplined decisions and controlled execution. The robustness checks alternative outcome codings, sectoral subgroups, and clustered inferences have reinforced that these signals are not model artifacts, adding credibility to the claim that digital and managerial capabilities jointly matter for both safety and efficiency in complex U.S. infrastructure programs (Anbari, 2003).

The results are consistent with a mechanisms view in which information quality upgrades (model-based coordination, CDE enforcement) and process discipline (stage-gates, risk/change control) reduce rework, stabilize sequences, and narrow forecast error bands the very pathways that theory and evidence have spotlighted. Foundational work showed that 4D modeling improves comprehension of time-space conflicts and constructability (Koo & Fischer, 2000), while Lean-BIM interactions enhance flow and constraint management (Sacks et al., 2010). Our item-level descriptives have mirrored this evolution: CDE usage and clash detection have been more mature than analytics-infused forecasting and field mobility exactly the gradient one expects when organizations progress from coordination to predictive control (Barlish & Sullivan, 2012). On the safety side, model-based hazard recognition and method planning make risks visible upstream and allow targeted controls, a linkage repeatedly observed in construction safety research (Zhang et al., 2015; Martínez-Aires et al., 2018). Efficiency gains have plausibly flowed through earned-value dynamics: when baselines are stable and change is contained, SPI/CPI trajectories improve and duration predictions become more accurate (Anbari, 2003). A complementary thread is rework: decades of evidence have tied information defects and coordination failures to out-of-sequence work, crew interference, and cost/schedule drift; by tightening requirements and approvals through a CDE and by simulating sequences in 4D, projects reduce the conditions that create rework (Love et al., 2004). Our negative correlations between DEA/PMFM and incident rates are coherent with this “stabilize the plan, stabilize the workforce” logic: fewer surprises, fewer concurrent operations conflicts, and less overtime pressure tend to reduce exposure and incidents, while simultaneously improving SPI/CPI. In short, the study’s multivariate signals line up with well-understood causal stories in the literature about how information and governance jointly regulate risk and flow.

The moderation effect DEA’s stronger association with schedule performance in rail has made sense against the institutional and technical context of rail programs. Rail delivery often sits inside safety-critical operating envelopes where access windows (possessions) and configuration states are tightly controlled. In such environments, 4D/5D planning and strict CDE workflows have disproportionate leverage: clashes and logistics conflicts that survive into the field are costlier to resolve, and possession overruns have secondary service impacts. Sector evidence has cataloged how structured BIM adoption and consulting regimes in railway work reduce rework and labor hours during construction (Shin et al., 2024), while case reports show BIM’s utility for staging, interfaces, and condition-driven interventions in track rehabilitation (Crist & Emami, 2019). Rail also operates atop a digital safety stack (e.g., Positive Train Control in the U.S.) and an expanding analytics layer in condition monitoring that sharpens planning and reduces emergent work (Zhang et al., 2015). In that stack, DEA is not just “nice to have”; it is a coordinating substrate that aligns engineering intent, possession logistics, and safety cases. By contrast, non-rail civil projects though increasingly digital span more heterogeneous typologies and permitting regimes; adoption profiles are more varied (Yoon et al., 2023)), and the returns to DEA may be diluted by legacy contracting, piecemeal scopes, or limited access constraints. Importantly, our models have not portrayed sector as destiny: PMFM has shown broadly beneficial associations across both sectors, echoing claims that governance and benefits management generalize across contexts (Joslin & Müller, 2016). The sectoral takeaway is therefore conditional: the more safety-critical and access-constrained the environment, the more DEA appears to amplify schedule fidelity provided that governance is capable of absorbing and acting on digital signals (Sirisomboonsuk et al., 2018).

Figure 8: Digital Engineering Adoption and Project Management Framework Maturity to Safety



For owners and PMOs, the findings suggest a concrete sequencing: institutionalize governance and change/configuration control while driving DEA from coordination to predictive management. Operationally, mandate ISO-19650-aligned information requirements and CDE workflows in contracts, with auditable role/approval matrices and deliverables that tie model versions to stage-gates (Godager et al., 2022). For schedule reliability, require 4D integration for all possession-constrained rail works and complex civil staging, and tie progress narratives to model-derived look-ahead plans; this responds directly to evidence that 4D adoption reduces interference and improves flow (Gledson & Greenwood, 2017). For safety, embed BIM-supported hazard identification and method statements in approvals; require evidence that high-risk tasks have been modeled and sequenced (Anbari, 2003). For CISOs and enterprise/data architects, the results highlight that security and governance are performance enablers, not post-hoc compliance: configure the CDE with least-privilege access, immutable audit trails, environment-specific model segregation, and automated checks for metadata completeness conditions that sustain trust in information and reduce coordination loss. Data architects should instrument pipelines so that model metadata, schedule baselines, and change logs are linked, enabling earned-value calculations and analytics without manual reconciliation (Batselier & Vanhoucke, 2015; Boje et al., 2020; Bryde et al., 2013). PMOs should mature benefits management and lessons learned our weakest PMFM items so that realized gains and misses feed back into standards (Joslin & Müller, 2016). Finally, owners should set caps on ad-hoc tools; ecosystem consistency (common CDE, model exchange standards) reduces integration friction and enables the cross-project comparability that the present analyses have leveraged (Zhao, 2017).

The pattern of additive main effects with targeted moderation supports a socio-technical view in which digital tools and managerial frameworks are complementary assets rather than substitutes. Maturity, in Jessen's (2003) terms of knowledge, attitudes, and actions, appears to serve as organizational "glue" that lets DEA express its potential. Our findings resonate with organizational project management perspectives that locate the PMO at the interface between executive intent and delivery routines (Aubry et al., 2007), and with governance research that emphasizes the alignment between IT governance and project governance (Sirisomboonsuk et al., 2018). Theoretically, the results invite a refined pipeline model: DEA → (information quality; foresight) → reduced rework and variance → improved SPI/CPI and lower exposure → lower TRIR/LTR, with PMFM moderating each arrow by increasing the probability that information is acted upon and codified into method statements and change decisions.

This aligns with BIM-and-safety theory (Zhang et al., 2018), Lean-BIM interaction (Sacks et al., 2010), and ISO-19650 information management logics (Özkaya et al., 2024). It also suggests micro-foundations for benefits management: when goals are explicit and traced to deliverables, digital practices can be evaluated in goal-driven terms (Won & Lee, 2016). At the same time, the weaker institutionalization of lessons learned that we have observed hints at a boundary condition: without feedback loops, organizations may plateau after early DEA/PMFM gains. A sharpened theoretical contribution, therefore, is to position benefits realization and learning as dynamic capabilities that keep the DEA→outcome pipeline from decaying, an idea compatible with governance-value linkages reported in prior work (Joslin & Müller, 2016; Musawir et al., 2017).

The cross-sectional design limits causal claims: while mechanisms are plausible and supported by prior work, we cannot rule out reciprocal causation (e.g., high-performing organizations choosing to invest more in DEA/PMFM). Although we have triangulated outcomes with archival records, self-report remains in the predictor battery and may carry desirability bias; we have mitigated this with item wording, reverse-coded items, and procedural separation, but common-method variance cannot be eliminated outright. Measurement choices invoke additional caveats: Likert composites are robust under many conditions (Norman, 2010), yet they compress nuance in practice implementation; factor structure checks and reliability diagnostics help, but some construct fidelity is inevitably lost. External validity is limited to U.S. contexts and to projects with sufficient documentation our inclusion rules may bias toward more mature organizations; sectoral balance helps, but heterogeneity persists. Earned value alternatives were available for some but not all projects; we have harmonized calculations, yet cross-system differences may remain. Finally, unmeasured confounders such as safety culture maturity or leadership turnover could influence both adoption/maturity and outcomes; controls for complexity and organization size are proxies, not panaceas. These limitations are consistent with challenges noted in the literature when quantifying digital and managerial effects in real projects (Bryde et al., 2013), and they underscore the importance of triangulated, multi-source data and cautious interpretation.

Longitudinal and quasi-experimental designs are natural next steps: step-wedge rollouts of CDE enforcement, mandated 4D on target corridors, or governance reforms could permit difference-in-differences estimates that sharpen causal attribution. Structural equation models could test mediation via rework proxies and schedule volatility, clarifying how DEA and PMFM propagate through process stability to outcomes. Digital-twin-rich settings offer further leverage: with instrumented assets and live telemetry, researchers can model how state estimation and predictive maintenance integrate with project controls and safety assurance (Khajavi et al., 2019; Pan & Zhang, 2021; Zhang et al., 2015). Cross-country comparisons would probe whether ISO-19650 maturity moderates effects differently where regulatory environments diverge (Zhao, 2017). On the managerial side, experiments in benefits management and lessons-learned institutionalization could test whether strengthening feedback loops lifts the plateau we have observed in PMFM items (Joslin & Müller, 2016). Safety research might embed BIM-based hazard simulations into permitting workflows and examine incident precursors prospectively (Zhang et al., 2018). Finally, rail-specific studies should quantify how DEA interacts with possession planning, isolation management, and condition-based maintenance to shape not only SPI/CPI but also service reliability, integrating capital delivery with operations and maintenance (Maierhofer et al., 2024; Martínez-Aires et al., 2018; Shin et al., 2024). Collectively, these paths would deepen the field's understanding of how digital engineering and governance co-produce safer, more reliable infrastructure delivery.

## **CONCLUSION**

This study has examined how digital engineering adoption (DEA) and project-management framework maturity (PMFM) have related to safety and efficiency in U.S. civil and rail infrastructure, and it has produced a coherent, evidence-based account that integrates descriptive profiles, correlations, and adjusted regression models with robustness checks. Across a stratified, multi-case sample, organizations have reported Likert five-point intensities that have clustered higher on foundational practices (e.g., CDE enforcement, clash detection, stage-gates, configuration control) and more variably on advanced capabilities (e.g., analytics-supported forecasting, systematic lessons learned). These distributions have provided the empirical variance necessary to test associations with audited outcomes, and the analyses have consistently shown that projects scoring higher on DEA and PMFM

have achieved lower incident rates (TRIR/LTIR and exposure-offset counts) and tighter schedule/cost adherence (SPI/CPI and variance measures) after adjustment for sector, size, duration, delivery method, organization size, complexity, and region. Moderation tests have indicated that DEA's association with schedule performance has been stronger in rail than in non-rail civil settings, a pattern that has aligned with possession-constrained work and configuration-intensive governance typical of railway delivery; at the same time, PMFM's benefits have generalized across sectors, underscoring the independent contribution of disciplined decision rights, risk/change control, and integrated baselines. Robustness and sensitivity analyses alternative outcome codings, sectoral subgroups, clustered inferences, and influence diagnostics have supported the stability of these findings and have reduced the likelihood that results have hinged on a single modeling choice or outlier subset. Conceptually, the study has reinforced a socio-technical interpretation: digital practices have improved information quality and foresight, while mature frameworks have converted that information into predictable execution, thereby reducing rework, compressing variance, and lowering exposure. Practically, the results have pointed to a sequenced playbook for owners and PMOs codify ISO-aligned information requirements and CDE workflows; require 4D integration where staging and access risks are high; institutionalize risk/change governance and configuration control; and elevate benefits management and lessons learned so that gains are retained rather than episodic. Methodologically, the work has demonstrated that survey-archival triangulation, exposure-normalized safety rates, and earned-value efficiency indicators can be integrated in cross-sectional, multi-case research to yield actionable, comparable signals. The study has also acknowledged limits inherent to cross-sectional designs, self-reported predictors, and U.S.-specific contexts, and it has recommended longitudinal, quasi-experimental, and mediation-focused extensions to refine causal attribution and illuminate process pathways. Taken together, the evidence has established that DEA and PMFM have functioned as complementary, additive levers for safer and more reliable infrastructure delivery; rail programs have realized especially strong schedule benefits when DEA has been high and governance capable of absorbing digital signals, while non-rail civil programs have also benefited where management maturity has been reinforced and digital practices have moved beyond basic coordination. By articulating measurable constructs, auditable outcomes, and reproducible models, the study has provided a practical foundation that agencies, integrators, and contractors have been able to use to benchmark current practice, prioritize capability investments, and track progress toward the joint objectives of injury-free work and on-plan delivery.

## **RECOMMENDATIONS**

To translate the study's evidence into practice, owners, PMOs, and delivery partners should adopt a sequenced, standards-anchored roadmap that institutionalizes governance while elevating digital engineering from coordination to predictive control. First, mandate ISO-19650-aligned information requirements across all capital programs and configure a single common data environment (CDE) with role-based access, immutable audit trails, standardized metadata, and automated checks for model completeness; make CDE compliance a contractual deliverable tied to pay items, with clear responsibilities for authoring, reviewing, and approving information containers. Second, require 4D integration on all possession-constrained rail works and complex civil staging, linking construction method statements, isolation plans, and work windows to time-space simulations; make release for construction conditional on a documented 4D clash-free sequence for high-risk tasks and formalize "last responsible moment" reviews where the 4D model, baseline schedule, and risk register are reconciled. Third, strengthen project-management framework maturity by codifying stage-gate criteria, risk/change/configuration control, and integrated scope-schedule-cost baselines; stand up (or refocus) the PMO to own these practices, to run benefits management and lessons-learned cycles, and to publish quarterly maturity scorecards by program. Fourth, elevate analytics from ad-hoc dashboards to a governed pipeline: instrument progress capture and production control, link model metadata to earned value data, and automate SPI/CPI and forecast updates from approved change logs; empower the CISO and data architect to enforce data quality, identity, and lineage so that analytics are trusted and repeatable. Fifth, embed safety into digital workflows by requiring model-based hazard identification, temporary works modeling, and digital permits-to-work; integrate rail worksite protection (possessions, isolations) with 4D sequences and mandate pre-job briefings that reference

model views; track exposure (hours, train-miles) and near-miss density as leading indicators tied to look-ahead planning. Sixth, align procurement with capability goals: include DEA/PMFM minimums in tender evaluation, reward verifiable past performance on CDE compliance and 4D delivery, and pilot alliance/ECI or performance-based incentives that share value from reduced rework and schedule risk. Seventh, invest in people and change: provide targeted training for planners, superintendents, and safety leaders on CDE etiquette, 4D authoring/consumption, and advanced controls; establish “digital champions” inside owner and contractor teams with authority to unblock adoption; pair training with coaching during the first three reporting cycles so practices stick. Eighth, operationalize measurement: adopt a compact KPI set CDE compliance rate, DEA and PMFM Likert means, rework proxy, SPI/CPI, TRIR/LTIR, near-miss density and review it at each gate; publish run charts and funnel plots to detect variance reduction over time. Ninth, phase deployment: start with a corridor or program where access is scarce and interfaces are dense, then scale to broader portfolios once data quality and governance are stable; use step-wedge rollouts to learn and adjust. Finally, make learning durable: institutionalize after-action reviews, codify reusable method statements and model templates, and fold benefits realization into annual planning so that the gains from digital engineering and mature governance are captured, compared, and reinvested across the enterprise.

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