

Article

A Closed-Loop Digital QA/QC Framework for Mega Construction Projects: Integrating BIM, Reality Capture, AI and Enterprise Systems

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Abstract

Quality management in mega construction projects is increasingly supported by digital technologies, yet quality information often remains fragmented across inspection systems, reality-capture platforms, Building Information Modelling (BIM) environments and enterprise systems. This fragmentation limits traceability, delays corrective actions and weakens the connection between quality performance, contractual obligations and financial accountability. This study develops a closed-loop digital QA/QC framework that integrates BIM, mobile field inspection, reality capture, artificial intelligence (AI) augmentation and enterprise resource planning (ERP) within a unified governance architecture. Following a Design Science Research approach, the study proposes a seven-layer framework linking quality events to procurement, financial control, and project-management processes while supporting role-based decision-making through data democratisation mechanisms. The framework extends conventional ERP-enabled quality management by explicitly incorporating procurement (MM) and financial-control (FI/CO) functions, including supplier-quality management, cost-of-poor-quality tracking and quality-linked payment governance. An illustrative project scenario and sensitivity analysis are used to demonstrate the application of the proposed KPI and evaluation structure. By treating integration as the primary design objective, the framework provides a foundation for enterprise-wide digital quality management, lifecycle information continuity and digital-twin readiness in mega construction projects. The contribution itself is evaluated through an illustrative Design Science Research demonstration and an assumption-bounded sensitivity analysis rather than through field data, with future empirical validation specified through a controlled before-and-after case-study protocol.

Keywords: building information modelling (BIM); construction quality management; digital twin; enterprise resource planning (ERP); reality capture



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1. Introduction

Mega construction projects—including large shopping malls, hospitals, airports, mixed-use developments and industrial facilities—are characterised by highly interdependent architectural, structural, mechanical, electrical, plumbing (MEP), fire-safety, façade, vertical transportation and commissioning activities executed under compressed delivery schedules. Within such environments, a single unresolved quality issue can propagate far beyond its technical origin, delaying subsequent trades, postponing tenant handover, triggering rework, affecting payment certification, generating contractual disputes and increasing project costs. Previous studies have reported that direct rework alone may account

for 5–12% of total project contract value, while indirect consequences such as disruption, prolongation and claims can produce comparable or even greater economic impacts [1,2].

Recent advances in digital construction technologies have created significant opportunities to improve quality management practices. Building Information Modelling (BIM) facilitates the integration of design information, construction activities and quality verification processes [3]. Mobile field inspection platforms digitise inspections, punch lists and non-conformance reporting, while reality-capture technologies such as 360-degree imagery, photogrammetry and laser scanning provide persistent visual records of as-built conditions and support remote verification [4–7]. Artificial intelligence (AI) techniques increasingly enable automated detection of selected defect categories and comparison between as-designed and as-built states [8,9]. At the enterprise level, ERP systems formalise quality workflows, connect quality events to projects and cost structures, and support supplier-performance monitoring and payment governance.

Despite this technological progress, digital quality management in construction remains largely fragmented. Information generated by BIM platforms, field inspection systems, reality-capture applications, AI tools and enterprise systems is frequently stored and managed in separate environments. As a result, quality-related information often follows disconnected reporting paths: defects may be photographed on-site, discussed during coordination meetings, recorded in spreadsheets, summarised in periodic reports and only later documented through formal non-conformance procedures. Links between quality events, schedule activities, contractual responsibilities, material traceability, cost allocation and payment certification are therefore often established retrospectively through manual effort, if they are established at all. Consequently, many construction organisations operate quality systems that are digitally enabled but only partially integrated.

This study argues that the principal challenge of contemporary digital construction quality management is no longer the availability of digital tools, but the absence of an integrated information architecture capable of connecting them. From this perspective, quality management extends beyond technical inspection and compliance verification and can be understood as an enterprise-wide information system linking field evidence, contractual obligations, financial accountability and stakeholder decision-making within a single auditable environment.

To address this gap, the study develops a closed-loop digital QA/QC framework that integrates BIM, mobile field inspection, reality capture, AI-assisted analytics and enterprise resource planning (ERP) processes into a unified governance architecture. The framework further extends conventional quality-management integration by explicitly incorporating procurement, supplier-quality management, cost-of-poor-quality accounting and quality-linked payment governance. In addition, it introduces a role-based data-democratisation approach and a KPI framework designed to support transparent evaluation across time, quality and cost dimensions.

Research Contributions

This study makes five specific contributions. First, it proposes a closed-loop architecture that connects field inspection, reality capture, AI-assisted augmentation, enterprise integration and analytics within a single information loop, rather than treating these as separate technological add-ons. Second, it extends ERP-enabled quality management beyond conventional quality-notification workflows into procurement (MM) and financial control (FI/CO) processes. Third, it introduces a five-gate payment governance mechanism that links demonstrated quality performance to payment certification. Fourth, it treats data democratisation and role-based analytics as a formal architectural requirement rather than a reporting feature. Fifth, it operationalises the framework through a Design Science

Research demonstration together with a KPI structure and cost–benefit evaluation logic, while explicitly specifying an empirical validation protocol for future research.

2. Literature Review and Research Gap

2.1. Construction QA/QC, Rework and Project Performance

Quality management in construction encompasses both quality assurance (the design of processes intended to prevent defects) and quality control (the inspection and verification activities used to detect them), consistent with the definitions established in ISO 9001:2015 [10]. Rework is widely recognised as the most visible manifestation of QA/QC failure. Previous studies have shown that rework originates from design errors, late design changes, inadequate coordination, deficient supervision and supply-chain quality failures, while its indirect consequences—including disruption, delay, productivity loss and contractual claims—often exceed direct repair costs [1,2]. Hegazy et al. [11] further argue that rework must be considered within schedule analysis because its impact depends not only on magnitude but also on timing and interaction with downstream activities. A more recent synthesis by Love et al. [12] confirms that rework remains a chronic and costly problem across project types and geographies, and argues that its mitigation requires not only technical solutions but also governance structures that make quality performance visible and accountable across the supply chain—a premise that directly motivates the present framework.

In mega projects, quality failures frequently emerge at interfaces between disciplines, trades and contractual packages. Consequently, QA/QC performance should be evaluated not only through defect counts but also through detection speed, accountability, closure efficiency, recurrence rates and the downstream effects of quality events on project schedule and cost performance.

2.2. Digital Construction Quality Technologies

The digitalisation of construction quality management has accelerated through the adoption of BIM, mobile inspection platforms, reality-capture technologies and artificial intelligence. Chen and Luo [3] demonstrated that BIM can function as a quality information backbone linking product, process and organisational information. Subsequent research extended this concept through model-based inspections, rule-based compliance checking and integration of inspection records with digital model objects [13]. More recently, Ghosh and Karmakar [14] developed and validated a BIM-integrated quality document management system (QMS-BIM) on a national highway project, demonstrating that BIM-enabled quality workflows can substantially improve traceability and transparency compared with conventional document-based systems.

Mobile inspection platforms have transformed field-based quality management by enabling digital forms, issue tracking, responsibility assignment and photographic documentation. However, their effectiveness depends heavily on integration with drawings, BIM models, locations and enterprise information systems. Demirkesen and Tezel [15] observed that fragmented deployment of digital tools often reproduces the information silos that such technologies were intended to eliminate.

Reality-capture technologies—including laser scanning, photogrammetry, image-based monitoring and 360-degree imagery—have emerged as important mechanisms for documenting and validating site conditions. Research has demonstrated their value for progress monitoring, as-built verification and construction-performance assessment [4,6,7]. More recent reviews identify 360-degree imaging and laser scanning as mature technologies suitable for routine deployment in construction projects [5].

Artificial intelligence has become an increasingly important component of construction informatics. Existing applications include Scan-to-BIM workflows, automated comparison between design intent and observed conditions, defect classification, progress monitoring and predictive analytics [8,9]. Pan and Zhang [16] identify defect detection, safety management and progress monitoring as the most mature AI application domains, while Akinosho et al. [17] emphasise the continuing dependence of AI performance on the availability and quality of training data.

Although these technologies have matured considerably, the majority of studies continue to examine them individually or in limited combinations. As a result, digital quality management remains technologically sophisticated but organisationally fragmented.

2.3. ERP Integration and Enterprise Quality Management

Enterprise Resource Planning (ERP) systems provide the organisational infrastructure necessary to connect quality management with procurement, project controls, cost management and supplier-performance monitoring. In practice, however, most construction QA/QC implementations utilise ERP systems primarily for non-conformance management and quality notifications.

Prior research suggests that this narrow scope limits the strategic value of ERP-enabled quality management. Tatari et al. [18] demonstrated that ERP performance in construction depends on integration across procurement, finance and project-management functions. Galagali et al. [19] similarly observed that BIM and ERP systems frequently operate as parallel rather than integrated environments, limiting the visibility of the financial and contractual consequences of quality events.

On the procurement side, Neuman et al. [20] and AlMaian et al. [21] demonstrated that supplier-quality surveillance, goods-receipt inspection and vendor-performance monitoring can significantly reduce quality failures attributable to supplied components. Bryde et al. [22] further reported that BIM delivers its greatest measurable benefits when linked to contractual and cost-management processes. Collectively, these findings suggest that effective digital QA/QC requires integration not only with quality-management modules but also with procurement, financial-control and project-management functions.

2.4. Data Democratisation and Construction Analytics

The growing availability of digital project data has increased interest in data democratisation, defined as the ability of stakeholders across organisational levels to access, understand and act upon relevant information while operating within appropriate governance structures [23]. Although related concepts appear in lean-construction and collaborative-planning research, data democratisation has rarely been treated as a formal design objective within digital QA/QC architectures.

This limitation is important because quality outcomes are ultimately produced at the point of work rather than within central QA/QC departments. Effective democratisation, therefore, requires more than dashboard visibility. It also depends on self-service analytical capability, mobile-first information delivery, structured feedback mechanisms and governance frameworks that balance transparency with commercial confidentiality. These requirements suggest that data democratisation should be considered an architectural component of digital QA/QC systems rather than merely a reporting function.

2.5. Research Gap

The reviewed literature provides strong foundations for BIM-enabled quality management, mobile inspection technologies, reality capture, artificial intelligence and ERP-supported quality workflows. Nevertheless, three important gaps remain insufficiently addressed.

First, existing studies generally focus on individual technologies or limited combinations of technologies, while integrated architectures spanning BIM, field inspection, reality capture, AI and ERP systems remain rare. Second, ERP integration is typically confined to quality-notification processes, with limited attention given to procurement, supplier-quality management and financial-control functions. Third, data democratisation has received little systematic consideration as an explicit design requirement of construction QA/QC information architectures.

These gaps are particularly important because quality failures generate consequences that extend beyond inspection activities and propagate through procurement, scheduling, contractual administration and financial management processes. Addressing such complexity requires an integrated perspective that treats quality management as an enterprise-wide information architecture rather than an isolated inspection function.

Prior studies typically integrate two or three of these technological components but do not define construction quality as an enterprise-wide governance loop that connects field evidence, supplier qualification, payment certification, cost allocation and role-based analytics within a single closed-loop architecture. This distinction, rather than the number of technologies combined, is the central argument developed in Table 1 below.

Table 1 compares representative studies against the dimensions considered in this research and demonstrates that no prior study simultaneously addresses BIM, reality capture, artificial intelligence, ERP-MM, ERP-FI/CO and data democratisation within a unified closed-loop QA/QC framework.

Table 1. Comparison of selected prior studies against the dimensions addressed by the proposed framework.

Study	BIM QA/QC	Mobile Insp.	Reality Cap.	AI/CV	ERP QM	ERP MM	ERP FI/CO	Data Democr.
Chen & Luo [3]	•	●	—	—	●	—	—	—
Turkan et al. [4]	•	—	•	●	—	—	—	—
Golparvar-Fard [6]	●	—	•	●	—	—	—	—
Fobiri et al. [5]	●	—	•	—	—	—	—	—
Hegazy et al. [11]	—	—	—	—	●	—	—	—
Bosché [8]	•	—	•	•	—	—	—	—
Son et al. [9]	•	—	•	•	—	—	—	—
Pan & Zhang [16]	●	●	●	•	●	—	—	—
Akinosho et al. [17]	●	—	●	•	—	—	—	—
Dave et al. [23]	●	●	—	—	—	—	—	•

Note: • Fully addressed; ● Partially addressed; — Not addressed. AI/CV = artificial intelligence/computer vision; ERP QM = ERP quality management module; ERP MM = procurement and supplier qualification module; ERP FI/CO = finance/controllership, including COPQ accounting and payment gates. Coverage for this study refers to architectural and framework-level integration; empirical validation is planned as future work.

2.6. Theoretical Positioning of the Framework

The present study is positioned as an enterprise-architecture and governance-design contribution rather than as a software-implementation paper or an empirical performance-measurement study. Consistent with Design Science Research, it develops and demonstrates an artefact intended to address an identified organisational problem; it does not report results from a deployed system. Theoretically, the framework's novelty does not rest solely on combining a larger number of technologies than prior studies, but on reframing quality management as a governance mechanism capable of reducing information asym-

metry between contracting parties. Building on Aben et al. [24], who argue that digital transformation in complex contractual environments requires mechanisms that reduce both information asymmetry and interpretive ambiguity, this study extends that logic from information governance into financial and contractual governance through the five-gate payment mechanism described in Section 4. This reframes ERP integration, supplier accountability and payment certification as expressions of a single underlying theoretical mechanism rather than as a list of incrementally combined features.

3. Methodology

This study adopts a Design Science Research (DSR) approach. DSR is a problem-solving research paradigm concerned with the development and evaluation of artefacts intended to address identified organisational problems [25]. The methodology is particularly appropriate when the research objective is not to explain an existing phenomenon but to design and justify a transferable solution. In the present study, the artefact is a closed-loop digital QA/QC framework intended to address the fragmentation of quality information across BIM, field inspection, reality capture, artificial intelligence and enterprise resource planning systems.

The research process follows the six-stage Design Science Research Methodology proposed by Peffers et al. [26]: problem identification and motivation, definition of objectives, design and development, demonstration, evaluation and communication. The first four stages are completed within the scope of this paper. Problem identification and objective definition are addressed through the literature review and research-gap analysis presented in Sections 1 and 2. Design and development are represented by the framework architecture and KPI structure proposed in Sections 4 and 5, while demonstration is undertaken through the illustrative application presented in Section 6. The evaluation stage is identified as the next phase of research and its proposed protocol is described in Section 8.

The study is further aligned with the relevance, design and rigour cycles proposed by Hevner et al. [25]. Relevance is established through the documented fragmentation of digital quality-management processes in mega construction projects. Rigour is provided through systematic engagement with the construction informatics, ERP integration and data-democratisation literature. The design cycle is represented by the iterative development of the framework architecture, KPI structure and demonstration scenario. Table S1 in the Supplementary Materials summarises the mapping between the DSR stages and the components of the present study.

Consistent with the demonstration stage of DSR, the numerical values presented in Section 6 are illustrative rather than empirical. They are derived from transparent assumptions informed by publicly reported industry benchmarks and are used solely to demonstrate how the proposed framework and KPI structure can be operationalised and evaluated. Empirical assessment of framework performance is reserved for the controlled before-and-after case study proposed in Section 8. The absence of full empirical evaluation at this stage is not presented as evidence of the framework's effectiveness; rather, it defines the explicit boundary of the current Design Science Research cycle, with empirical evaluation constituting the subsequent cycle described in Section 8.

Design Requirements

Table 2 summarises the design requirements underlying the proposed framework and the literature streams from which they were derived, together with the architectural layer that addresses each requirement.

Table 2. Design requirements derived from literature synthesis.

Design Requirement	Source of Requirement	Framework Response
Traceability of quality evidence	BIM/Common Data Environment literature	L1–L3
Evidence-based issue closure	Reality-capture literature	L3
AI-assisted classification and prioritisation	AI/NLP literature	L4
Supplier and subcontractor accountability	ERP/procurement (MM) literature	L5
Financial accountability and COPQ allocation	ERP finance/controlling (FI/CO) literature	L5
Role-based, auditable decision support	Data democratisation literature	L6–L7

These requirements were derived from systematic literature synthesis rather than from expert workshops or field piloting; this constitutes an explicit boundary of the present Design Science Research cycle and is revisited in Section 8.

4. The Closed-Loop Digital QA/QC Framework

4.1. Framework Architecture

The proposed framework conceptualises digital construction quality management as a closed-loop information architecture rather than a sequence of isolated inspection activities. As illustrated in Figure 1 and summarised in Table 3, the framework consists of seven interconnected layers organised around the continuous creation, verification, enrichment, governance and utilisation of quality information.

The framework conceptualises quality management as an integrated information architecture spanning project information, field execution, evidence management, AI-assisted augmentation, enterprise governance, analytics and data democratisation. Information flows downward through the layers as inspection records, evidence and performance indicators accumulate, while corrective-action and governance decisions flow back toward field execution, creating a continuous feedback loop. The Enterprise Integration Layer (L5) represents the framework's principal contribution by extending quality management beyond conventional QA/QC workflows into procurement, supplier-quality and financial-control processes. The resulting architecture enables lifecycle traceability from field observations to contractual, financial and operational outcomes.

The first four layers establish the operational core of the framework. The Information Layer (L1) provides the approved technical reference against which all inspections are performed. Drawing on ISO 19650 principles [27], inspection activities are linked to project locations, disciplines, work packages, specifications, inspection and test plans (ITPs), work-breakdown structures and, where available, BIM objects and asset identifiers. This common information structure ensures that all quality records remain traceable and comparable across the project lifecycle.

The Execution Layer (L2) captures quality activities through mobile inspection platforms. Inspections are performed using standardised checklists tailored to specific work packages and generate structured records containing inspection outcomes, measurements, photographic evidence, responsible parties and closure requirements. Significant findings may remain at the field level, escalate to formal quality notifications or trigger enterprise-level processes depending on their severity and contractual significance.

Seven-Layer Closed-Loop Digital QA/QC Framework

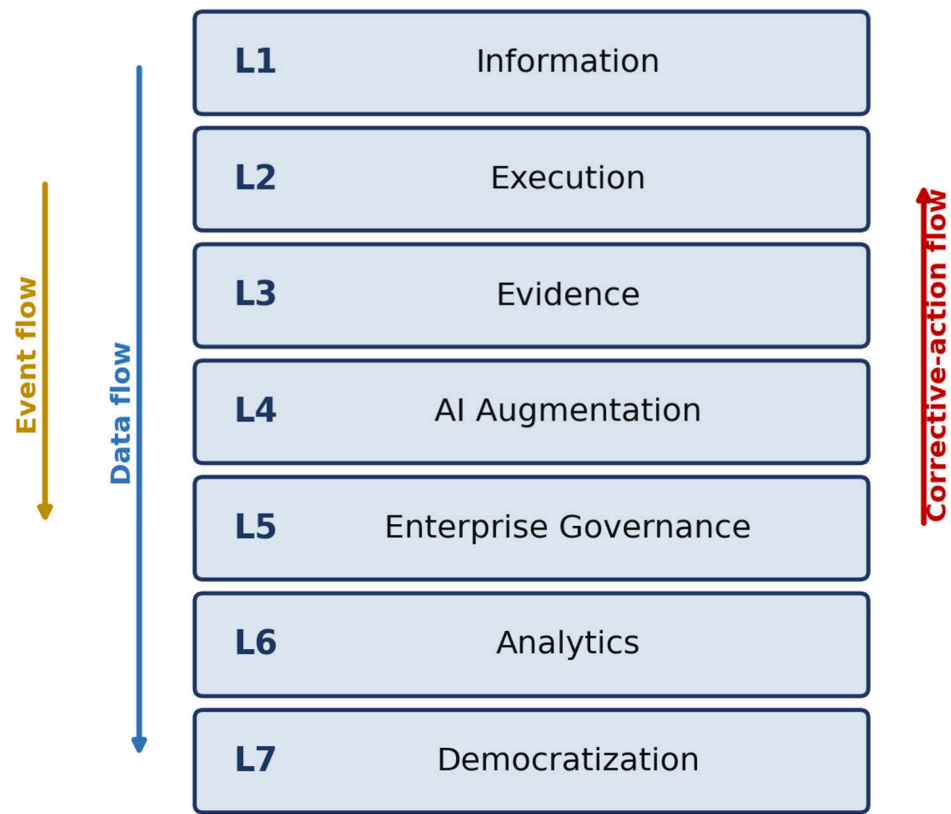


Figure 1. Seven-layer closed-loop digital QA/QC framework for mega construction projects. The figure is simplified in this revision to show only layer names, primary functions and the data-flow, event-flow and corrective-action-flow arrows described below; detailed sub-components are presented in Table 3.

Table 3. Seven-layer architecture of the closed-loop digital QA/QC framework.

Layer	Primary Tools (Examples)	Role in the Loop
L1—Information	Autodesk Construction Cloud; BIM 360 (Autodesk, Inc., San Francisco, CA, USA); CDE; specifications; ITPs	Defines the approved technical reference and master data for inspection.
L2—Execution	Autodesk Build; PlanGrid; Procore; Fieldwire	Captures inspections, checklists, defects, punch items and responsibilities.
L3—Evidence	OpenSpace; HoloBuilder; StructionSite; Matterport; laser scan	Provides time-stamped, location-linked visual records.
L4—Augmentation (AI)	Computer vision; LLM assistants; Scan-to-BIM engines	Flags candidate defects, classifies notes, suggests corrective actions.
L5—Enterprise (ERP)	SAP QM, MM, FI/CO, PS (or equivalent Oracle/IFS modules)	Records NCRs, allocates costs, scores suppliers, controls payments.
L6—Analytics	Power BI; Qlik Sense; SAP Analytics Cloud; Tableau	Aggregates and visualises time, quality and cost KPIs by role.
L7—Democratisation	Role-based access; mobile delivery; self-service; literacy programme	Translates integrated data into action by all stakeholders.
Output	SAP EAM; CxAlloy; asset register; digital twin platform	Transfers validated records into operations and digital twin.

The Evidence Layer (L3) complements inspection activities through systematic reality capture. Technologies such as 360-degree imagery, photogrammetry and laser scanning generate time-stamped and location-linked visual records that provide objective evidence of site conditions. The layer is particularly valuable for concealed works, commissioning activities and dispute resolution, where retrospective verification is often difficult or impossible.

The Augmentation Layer (L4) introduces artificial intelligence as a decision-support capability. Computer-vision applications identify candidate defects within visual records, Scan-to-BIM techniques highlight deviations between planned and actual conditions, and natural-language-processing tools classify inspection notes and quality observations into structured categories. Large language model (LLM) services additionally support the generation of role-specific summaries and analytical narratives. Consistent with quality-governance requirements, all AI outputs remain subject to human review and approval before influencing downstream decisions.

AI Augmentation Logic

Table 4 specifies the AI augmentation logic in greater detail, clarifying for each QA/QC task the candidate AI method, the required input data, the expected output and the principal validation risk that must be controlled through human review.

Table 4. AI augmentation logic: methods, data, outputs and validation risk.

QA/QC Task	AI Method	Input Data	Output	Validation Risk/Control
Visual defect detection	Computer vision (CNN/Vision Transformer)	Site photographs, 360° images	Candidate defect flag	False positive/false negative; human verification
Scan-to-BIM deviation detection	Point-cloud/image matching	Laser scan, BIM model	Geometric deviation flag	Tolerance-threshold error
NCR/inspection-note classification	Transformer-based NLP (e.g., BERT/RoBERTa)	Free-text inspection notes, NCR descriptions	Structured defect category	Ambiguous or non-standard language
Similar-case retrieval	Embeddings/retrieval-augmented generation	NCR archive, specifications	Similar historical cases	Retrieval error; source verification required
Role-specific summary generation	Large language model (LLM)	NCR records, inspection logs	Role-specific summary	Hallucination risk; non-authoritative output

Consistent with this logic, AI functions strictly as a decision-support capability rather than an autonomous decision-maker: no NCR closure, payment-gate transition or backcharge is triggered without human approval. False positives and false negatives identified in visual detection and NLP classification are subject to periodic manual audit, and model drift is monitored through recurring performance review against newly labelled data. Outputs generated by large language models are explicitly classified as non-authoritative, role-specific summaries rather than as formal quality records. This is consistent with recent evidence that, although GPT-based large language models can support a range of construction-management tasks, their outputs require use-case-specific validation and human oversight, given risks such as hallucination and non-deterministic generation [28].

Natural-language processing is particularly relevant for transforming unstructured inspection notes, NCR descriptions and punch-list comments into structured QA/QC categories. Recent work demonstrates the feasibility of this approach in a closely related domain: Wang [29] evaluated five transformer-based text-classification methods (BERT, RoBERTa, ALBERT, DistilBERT and XLNet) for automated fire-door defect classification from inspection text, while Wang [30] further compared graph neural network-based text classifiers (TextGCN, TextING, TensorGCN and BERT-GCN) for the same defect-classification task. Both studies report strong classification performance from inspection-record text and illustrate how the AI augmentation layer proposed here could be operationalised and empirically validated in future work.

Three information flows connect these layers. Data flows downward through the architecture as inspection records, evidence and KPI information accumulate. Event flows propagate quality notifications, escalations and payment-related triggers toward enterprise systems. Corrective-action flows return decisions, assignments and closure requirements to field execution, thereby completing the feedback loop. Through this structure, the framework transforms isolated quality observations into enterprise-wide information assets capable of supporting operational, contractual and financial decision-making.

4.2. Enterprise Integration Layer

The Enterprise Integration Layer (L5) represents the principal contribution of the proposed framework. While previous studies have generally linked construction quality management to ERP-based quality-notification processes, the present framework extends integration beyond quality management and explicitly incorporates procurement, financial control and project-management functions. The objective is to ensure that quality events remain connected to the organisational processes through which their contractual, operational and financial consequences are ultimately realised.

The architecture treats ERP not as a repository for quality records but as the governance environment in which quality outcomes acquire organisational significance. As summarised in Table 5, quality events originating in the execution layer propagate across multiple enterprise functions. A non-conformance report (NCR) raised during inspection generates a formal quality notification, while supplier-related failures initiate procurement controls and quality-related costs are allocated to dedicated financial structures. The same event may therefore influence corrective actions, supplier performance, payment certification, project forecasting and management reporting simultaneously. Although the illustrative data flows in Table 5 are described using SAP module terminology (QM, MM, FI/CO) for concreteness, the architecture itself is not SAP-specific: equivalent functionality—quality notifications, procurement holds, cost-of-poor-quality postings and payment blocking—can, in principle, be implemented within Oracle ERP, Microsoft Dynamics 365, IFS or Infor environments that support comparable quality-management, procurement and finance/controlling modules.

Quality-management processes constitute the first component of the enterprise layer. Escalated field issues are transformed into structured quality notifications containing location references, evidence links, severity classifications, responsible parties and corrective-action requirements. The resulting CAPA workflow provides formal governance for investigation, containment, correction, verification and closure. Closure requires both documentary approval and verification against the evidence layer, ensuring that quality records remain auditable throughout their lifecycle.

Table 5. Cross-module ERP data flow triggered by quality events. Each row shows how a quality event propagates across SAP modules in the proposed framework.

Triggering Event	Source Module	Target Module	Result
NCR raised from field inspection	L2 Execution	SAP QM	Quality notification opened; CAPA assigned.
NCR closed—subcontractor fault	SAP QM	SAP FI/CO	Backcharge document auto-drafted; COPQ cost element posted.
Material delivery to site	SAP MM	SAP QM	Goods-receipt inspection lot created; invoice held pending result.
Inspection lot failed	SAP QM	SAP MM	Material blocked; supplier scorecard updated; invoice withheld.
Subcontractor submits payment certificate	SAP FI/CO	L6 Analytics	Five-gate check triggered; gate states surfaced to both parties.
NCR closed; rework cost booked	SAP QM/FI/CO	SAP PS	WBS activity updated; float impact computed; milestone forecast revised.

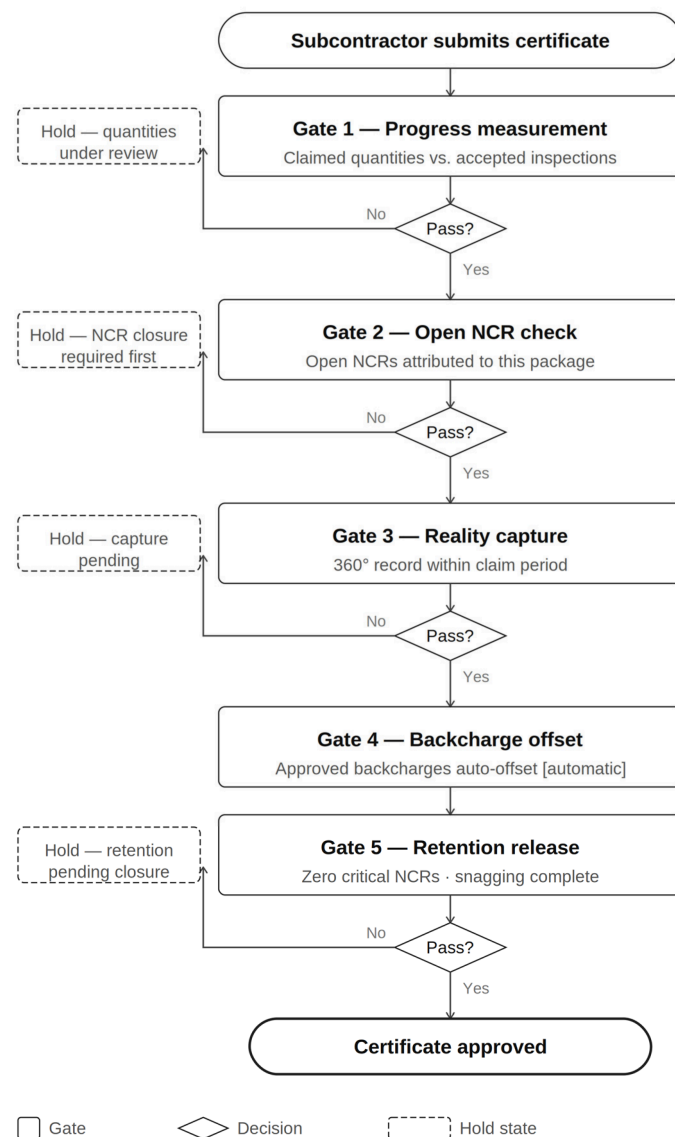
The second component extends integration into procurement and supplier-quality management. Vendor qualification status, goods-receipt inspections and supplier-performance indicators are continuously updated through quality outcomes generated during project execution. Deliveries associated with failed inspections may be blocked from use, supplier-performance scores adjusted and invoice processing restricted until corrective actions have been completed. In this manner, quality performance becomes directly connected to procurement decision-making rather than remaining isolated within QA/QC functions.

The third component links quality management to financial control. Cost-of-poor-quality (COPQ) accounting structures capture prevention, appraisal, internal-failure and external-failure costs as distinct categories. Rework activities are allocated to specific work packages, trades and project zones, enabling visibility of the true financial impact of quality deficiencies. Where contractual responsibility is established, backcharge documentation can be generated using the same evidence base that supported quality closure, thereby reducing administrative effort and dispute potential.

The fourth component integrates quality events with project structures and schedule management. Inspection records, NCRs and rework activities are linked to work-breakdown structures and project-control systems, allowing quality-related delays to be measured through consumed float, affected activities, milestone impacts and revised completion forecasts. Quality performance, therefore, becomes visible not only as a compliance metric but also as a project-delivery metric.

A particularly important extension of the enterprise layer concerns subcontractor payment governance. The proposed framework introduces a five-gate payment-control mechanism illustrated in Figure 2. Progress claims are evaluated against accepted inspections, open NCR status, reality-capture verification, approved backcharges and retention-release requirements. Rather than introducing new contractual obligations, the mechanism formalises quality-performance requirements that already exist implicitly within construction contracts and translates them into transparent, evidence-based decision rules. By making gate status visible to both contractor and subcontractor, the framework seeks to reduce

ambiguity, strengthen accountability and align commercial outcomes with demonstrated quality performance.



All gate states visible to contractor and subcontractor in real time.
Gate 4 (backcharge offset) is automatic — no approval decision required.

Figure 2. Five-gate payment governance mechanism linking quality performance and payment certification.

Through these mechanisms, the Enterprise Integration Layer transforms quality management from an isolated inspection function into a cross-functional governance process linking field execution, procurement, financial control and project delivery within a single auditable information environment.

Gate states are visible to both contractor and subcontractor in real time. Gate 4 (backcharge offset) is automatic—no approval decision is required.

4.2.1. Verification and Dispute Resolution Procedures

Table 6 specifies, for each of the five payment gates, the verification evidence required, the party responsible for approval, the principal dispute risk and the corresponding resolution mechanism.

Table 6. Payment-gate verification and dispute resolution.

Gate	Verification Evidence	Approver	Dispute Risk	Resolution Mechanism
Gate 1	Accepted inspection quantity	QA/QC and commercial teams	Measured-quantity disagreement	Joint re-measurement
Gate 2	Open NCR list	QA/QC manager	NCR attribution dispute	NCR review board
Gate 3	Reality-capture record	BIM/reality-capture lead	Evidence-timing dispute	Timestamp audit
Gate 4	Approved backcharge	Commercial manager	Liability dispute	Contractual clause review
Gate 5	Snagging/retention status	Client and contractor	Defect-closure dispute	Joint close-out inspection

4.2.2. Adaptation to Contract Type

The relative weight and configuration of the five gates is not fixed but is expected to vary with contract type, jurisdiction and subcontractor agreement, as summarised in Table 7.

Table 7. Payment-gate adaptation across contract types.

Contract Type	Gate Adaptation
Lump-sum	Gate 1 operates primarily through milestone-based payment certificates
Unit-price/remasurement	Gate 1 operates through measured-quantity verification
Engineering–Procurement–Construction (EPC)	Gate 5 is strengthened through commissioning and performance-acceptance criteria
Design–Build	Design responsibility and NCR attribution are assessed jointly across Gates 2 and 4
Management contracting	Gate approval authority is distributed to the relevant package manager

These adaptations are illustrative rather than exhaustive; the specific contractual clauses required to operationalise each gate should be defined jointly with legal counsel during project-specific implementation.

4.3. Analytics and Data Democratisation

The Analytics and Data Democratisation Layer (L6–L7) converts integrated quality information into actionable decision support for stakeholders operating at different organisational levels. While the preceding layers focus on generating, validating and governing quality information, the purpose of this layer is to ensure that such information can be effectively interpreted and used to influence project outcomes.

The analytics component aggregates data originating from inspections, quality notifications, reality-capture systems and ERP processes into a unified semantic model. Time, quality and cost indicators are calculated from a common data structure and presented through role-specific dashboards. Strategic dashboards support executive sponsors, clients and programme leadership through high-level performance indicators and trend analysis. Tactical dashboards support project managers, QA/QC managers and commercial managers through workflow, compliance and performance-monitoring views. Opera-

tional dashboards provide site engineers, foremen and subcontractor supervisors with near real-time visibility of inspections, assigned actions and unresolved quality issues.

To maintain consistency and trust, all dashboard views are governed by four design principles. First, indicator definitions are standardised and maintained centrally so that the same metric produces identical results regardless of user role. Second, progressive disclosure allows users to move from summary indicators to underlying records without leaving the analytical environment. Third, actionability is preserved by linking every indicator to the operational processes capable of influencing it. Finally, transparency is maintained by ensuring that unfavourable indicators remain visible rather than being selectively filtered or hidden.

The effectiveness of analytical systems depends not only on visualisation quality but also on organisational access to information. For this reason, the framework treats data democratisation as a deliberate architectural objective rather than as a secondary consequence of dashboard deployment. Data democratisation is defined here as the controlled distribution of information, analytical capability and decision-support tools across organisational levels while maintaining appropriate governance, accountability and confidentiality mechanisms.

Implementation is supported through five complementary mechanisms: role-based access management, self-service analytical capability, mobile-first information delivery, closed feedback loops linking insights to corrective actions and transparent visibility of quality-related payment and retention status. Together, these mechanisms reduce dependence on manual reporting and enable stakeholders to engage directly with quality information relevant to their responsibilities.

However, technology alone is insufficient to achieve meaningful democratisation. Sustainable adoption additionally requires supporting organisational conditions, including data literacy development, governance of KPI definitions, clearly defined access rights and visible leadership commitment to evidence-based decision-making. These conditions ensure that information is not only available but also interpreted consistently across project participants. Accordingly, data democratisation as proposed here does not imply unrestricted data access; it is implemented through governed, role-based and auditable access consistent with information-management principles established in ISO 19650 [27] and with the FAIR principles of findable, accessible, interoperable and reusable data [31].

The organisational significance of democratisation extends beyond efficiency gains. Aben et al. [24] argue that digital transformation in complex contractual environments requires mechanisms capable of reducing both information asymmetry and interpretive ambiguity. The present framework operationalises this principle by providing shared access to quality-performance information while preserving role-specific responsibilities. Project managers, commercial managers, QA/QC personnel and subcontractors therefore operate from a common information base, reducing disputes regarding performance status, contractual obligations and payment conditions.

By extending analytical capability beyond specialist QA/QC teams, the framework redistributes quality awareness to the point of production where corrective action can be taken most effectively. In this sense, data democratisation functions not merely as a reporting capability but as a governance mechanism that transforms isolated quality records into organisation-wide learning and decision-making assets.

4.4. Handover and Digital Twin Readiness

The final output of the framework is not a collection of completed inspections or closed non-conformance reports, but a validated and traceable information asset capable of supporting facility operation, maintenance and future digital-twin applications. By preserving

the relationships between inspections, visual evidence, corrective actions, supplier records, financial transactions and project structures, the framework enables quality information generated during construction to remain useful beyond project delivery.

At handover, the framework produces a structured information set consisting of verified asset records, commissioning evidence, inspection histories, defect-resolution records, warranty information and supplier-performance data. Because these records are generated and maintained within an integrated information environment rather than assembled retrospectively, the burden traditionally associated with handover documentation is substantially reduced.

This continuity is particularly important for digital-twin readiness. Previous studies have demonstrated that BIM-enabled information management can significantly improve information quality at project closeout and reduce data-acquisition effort during facility operation [32]. Similarly, digital-twin research emphasises the importance of maintaining traceable relationships between physical assets, information objects and operational records throughout the asset lifecycle [33], consistent with the digital-twin reference architecture defined in ISO 23247 [34]. The proposed framework contributes to this objective by ensuring that quality-related information remains connected to its originating asset, location, supplier, inspection history and contractual context.

From a lifecycle perspective, the framework therefore extends the role of QA/QC beyond defect detection and compliance verification. Quality information becomes a persistent organisational resource that supports operational decision-making, maintenance planning, warranty management and future digital-twin development. In this sense, handover is not treated as the end of the quality-management process, but as the transition point through which validated construction knowledge is transferred into the operational phase of the asset lifecycle.

5. Implementation and Evaluation Framework

5.1. Implementation Logic

The proposed framework is intended to be implemented at the work-package level and follows a structured sequence linking quality planning, inspection execution, evidence generation, enterprise integration and organisational learning. Rather than representing isolated activities, these stages operate as an interconnected cycle through which quality information is continuously created, verified, governed and reused.

Implementation begins with the definition of inspection requirements. Inspection and Test Plans (ITPs), acceptance criteria, hold points and work-package-specific checklists are established within the project information environment and linked to locations, disciplines, work packages and BIM objects where applicable. Changes in approved design information automatically trigger review of the associated inspection scope to maintain alignment between design intent and field verification activities.

Field inspections are subsequently performed through mobile inspection platforms using structured digital records containing inspection outcomes, measurements, photographic evidence and responsibility assignments. To strengthen traceability and auditability, inspection activities are complemented by systematic reality capture, including 360-degree imagery, photogrammetry or laser scanning at predefined intervals and critical hold points.

Artificial intelligence functions as an augmentation layer rather than an autonomous decision-maker. Computer-vision applications identify candidate defects, natural-language-processing tools classify inspection observations and analytical services support the generation of corrective-action recommendations. Consistent with the governance principles of the framework, all AI-generated outputs remain subject to human verification prior to influencing downstream processes.

Quality events are then evaluated according to their significance and routed through the appropriate governance pathway. Minor issues may be resolved within field workflows, whereas more significant events generate formal quality notifications and initiate enterprise-level integration with procurement, financial-control and project-management systems. Corrective actions are assigned together with responsibility, due dates, evidence requirements and closure criteria.

Following closure, quality events are reconciled against schedule, cost and payment-control processes. Rework activities, quality-related delays and associated financial impacts are linked to project-control structures, enabling quality performance to be assessed alongside project-delivery performance. The resulting information is subsequently aggregated within the analytics layer, distributed through role-based dashboards and incorporated into organisational learning mechanisms, thereby completing the closed-loop logic of the framework.

5.2. Implementation Maturity and Phasing

Because the full seven-layer architecture presented in Section 4 is ambitious relative to the digital maturity of many construction organisations, implementation is expected to proceed through four cumulative maturity levels rather than as a single deployment. Level 1, digitised inspection, comprises mobile inspection forms, photographic documentation and basic NCR logging. Level 2, evidence-linked QA/QC, adds systematic linkage between BIM/Common Data Environment records and reality-capture evidence. Level 3, enterprise-integrated QA/QC, connects quality processes to ERP quality-management, procurement and finance/controlling modules. Level 4, closed-loop governance, introduces payment-gate governance, role-based analytics dashboards, AI augmentation and the feedback mechanisms described in Sections 4 and 5. Organisations are expected to progress through these levels according to their existing digital capability, and the framework does not presuppose that Level 4 is achievable without prior investment in Levels 1–3.

5.3. KPI Measurement Framework

Evaluation of the proposed framework is based on a multidimensional KPI structure covering time, quality and cost performance. The KPI model constitutes an integral design component of the framework because it specifies not only what should be measured, but also how quality-management outcomes can be translated into operational, managerial and financial performance indicators.

The framework assumes that all indicators are derived automatically from inspection records, quality notifications, reality-capture systems and ERP transaction logs. This approach reduces dependence on manual reporting while improving consistency and auditability. The KPI set is intended to provide a standardised evaluation template for future empirical implementations and for the controlled case-study protocol proposed in Section 8.

Table 8 presents the proposed KPI measurement model across the three evaluation dimensions.

The time dimension evaluates process efficiency through indicators such as inspection execution time, reporting cycle time, issue-assignment time, issue-closure time, hold-point waiting time and quality-related delay days. Together, these measures assess how rapidly quality information is processed and translated into corrective action.

The quality dimension evaluates effectiveness through indicators including NCR rate, first-time-right ratio, reopened-issue ratio, visual-evidence coverage and supplier-quality performance. These measures focus on defect prevention, closure effectiveness and evidence completeness.

Table 8. KPI measurement model across time, quality and cost dimensions.

Dimension	KPI	Definition/Measurement
Time	Inspection execution time	Average elapsed time per checklist between start and completion.
Time	Reporting cycle time	Average elapsed time between inspection completion and report distribution.
Time	Issue assignment time	Timestamp (assignment)/timestamp (issue creation).
Time	Issue closure time	Timestamp (accepted closure)/timestamp (issue creation), by severity.
Time	Hold-point waiting time	Elapsed time between inspection request and approval.
Time	Quality-related delay days	Network-activity float consumed attributable to open quality events.
Quality	NCR rate	Number of NCRs ÷ number of inspections (or per 1000 m ²).
Quality	First-time-right ratio	Inspections accepted at first check ÷ total inspections.
Quality	Reopened issue ratio	Reopened issues ÷ closed issues.
Quality	Visual evidence ratio	Records with linked 360°/photographic evidence ÷ total QA/QC records.
Quality	Supplier quality index	Moving-window composite of defect rate, NCR rate and closure timeliness.
Cost	Rework cost	Labour, material and equipment cost booked to rework cost elements.
Cost	QA/QC labour saving	(Baseline QA/QC hours – digital hours) × average hourly cost.
Cost	Delay overhead cost	Reduced quality-related delay days × daily site overhead cost.
Cost	Backcharge realisation	Approved backcharges ÷ identified backcharge opportunities.
Cost	COPQ % of contract value	Total COPQ (prevention + appraisal + internal + external failure) ÷ contract value.

The cost dimension evaluates economic outcomes through rework cost, QA/QC labour savings, delay-related overhead reductions, backcharge realisation and cost-of-poor-quality (COPQ) performance. These indicators quantify the financial consequences of quality management and provide the basis for assessing business value.

5.4. KPI Selection and Measurement Validity

KPI selection in Table 8 follows four criteria: measurability directly from system logs (inspection platforms, quality notifications and ERP transaction records) without reliance on manual data collection; relevance to QA/QC governance rather than to general project performance; traceability to a specific operational action that the indicator is intended to inform; and non-redundant representation of the time, quality and cost dimensions. Several time-dimension indicators—inspection execution time, reporting cycle time, issue-assignment time and issue-closure time—are expected to be statistically correlated in practice, since they represent sequential stages of the same workflow; nevertheless, each measures a conceptually distinct process stage (inspection speed, communication speed,

responsibility allocation and corrective-action completion, respectively) and is retained for diagnostic purposes rather than as an independent composite score.

Universal KPI weights are deliberately not imposed in this framework, because relative priorities are expected to differ across clients, contract strategies and project types. Weighting is instead treated as a project-specific implementation choice, which may be informed by client priorities, contract-specific risk allocation or structured methods such as the Analytic Hierarchy Process in future empirical applications of the framework.

5.5. Cost–Benefit Evaluation Logic

The proposed evaluation framework assesses value creation through six categories of benefit: rework reduction, QA/QC labour savings, delay-cost reduction, documentation-efficiency gains, dispute and claim avoidance, and realised backcharges. Together, these categories capture both direct and indirect effects of improved quality information management.

Net benefit is defined as total gross benefit minus digital implementation cost, while return on investment (ROI) is calculated as net benefit divided by implementation cost. Detailed formulations, variable definitions and computational assumptions are provided in Table S2 of the Supplementary Materials.

The purpose of this formulation is not to estimate universal savings applicable to all projects. Rather, it provides a transparent analytical structure through which future implementations can evaluate the operational and financial implications of the proposed framework using project-specific data and assumptions.

6. Framework Demonstration and Sensitivity Analysis

The objective of this section is to demonstrate how the proposed framework can be operationalised and evaluated within a realistic project environment. Consistent with the Design Science Research approach adopted in this study, the demonstration is intended to illustrate framework functionality rather than provide empirical validation. The numerical values presented below are therefore hypothetical and are derived from transparent assumptions informed by publicly reported industry benchmarks related to rework, labour utilisation and project overhead costs. Their purpose is to demonstrate the application of the KPI structure and cost–benefit logic developed in Sections 4 and 5.

6.1. Demonstration Scenario

To illustrate framework operation, a hypothetical mixed-use mega project (Project X) is considered. The project comprises approximately 180,000 m² of gross floor area, a contract value of USD 220 million and a planned duration of 30 months. Quality-management activities are demonstrated across six representative work packages: MEP first-fix installation, fire stopping, waterproofing, ceiling closure, common-area finishes and tenant handover.

The demonstration compares two conceptual operating states. The first represents a conventional fragmented quality-management environment characterised by disconnected inspection, reporting and documentation processes. The second represents the integrated digital environment enabled by the proposed framework. To ensure comparability, both states are evaluated over an equivalent 12-week observation period. Key assumptions concerning labour cost, project overhead and implementation expenditure are summarised in Table S3 of the Supplementary Materials.

The purpose of the illustrative scenario is not to estimate achievable project performance or to provide empirical evidence of framework effectiveness. Rather, it serves to demonstrate how the proposed framework operationalises the KPI structure and estab-

lishes traceable links between quality events, operational processes and financial outcomes within a closed-loop digital environment.

6.2. Demonstration of KPI Evaluation

The proposed KPI framework is applied to the demonstration scenario to illustrate how operational performance can be measured across time, quality and cost dimensions. The resulting indicators are presented in Table 9.

Table 9. Illustrative time and quality KPI results for the demonstration scenario.

KPI	Baseline (Hyp.)	Digital (Hyp.)	Change	% Change
Inspection execution time (min/checklist)	42	24	−18	−43%
Reporting cycle time (hours/week)	26	8	−18	−69%
Issue assignment time (hours)	16	2	−14	−88%
Issue closure time, critical (days)	11.4	5.2	−6.2	−54%
Hold-point waiting time (hours)	18	6	−12	−67%
Quality-related delay days (window)	9	3	−6	−67%
First-time-right ratio	0.74	0.88	+0.14	+19%
Visual evidence ratio	0.34	0.96	+0.62	+182%
NCR rate (per 1000 inspections)	72	44	−28	−39%

The illustrative results indicate substantial improvements in process efficiency following implementation of the integrated framework. Inspection execution time, reporting cycle time, issue-assignment time and hold-point waiting time all decrease, reflecting improved information availability and workflow coordination. Similarly, quality-related indicators such as first-time-right performance, NCR frequency and visual-evidence coverage demonstrate the ability of the framework to improve traceability and accelerate issue resolution.

The purpose of these values is not to estimate expected performance improvements for future projects. Rather, they demonstrate how the KPI structure can be used to evaluate quality-management performance within a unified digital environment and how operational outcomes can be translated into measurable indicators.

6.3. Demonstration of Cost–Benefit Logic

The KPI outputs generated in the previous section are subsequently translated into economic impacts through the cost–benefit framework proposed in Section 5. Six categories of benefit are considered: rework reduction, QA/QC labour savings, delay-related overhead reduction, documentation-efficiency gains, realised backcharges and dispute-avoidance value.

Under the assumptions adopted for the demonstration scenario, these categories produce a hypothetical gross benefit of USD 1.582 million. After deducting the assumed implementation expenditure of USD 420,000, the resulting illustrative net benefit is approximately USD 1.162 million, corresponding to an indicative ROI of 277%. A detailed breakdown of all categories is provided in Table S4 of the Supplementary Materials. This indicative ROI figure is reported solely as an illustration of the evaluation logic under the

stated assumptions; it is not an expected or predictive project outcome and should not be generalised beyond the demonstration scenario described here.

These values should be interpreted solely as an illustration of the framework's evaluation logic. They are not empirical findings and should not be regarded as predictive estimates of project performance.

6.4. Sensitivity Analysis

Because the demonstration scenario is assumption-driven, sensitivity analysis is used to evaluate the robustness of the cost–benefit formulation. Figure 3 presents the distribution of net benefit obtained from a Monte Carlo simulation comprising 10,000 iterations. Uniform probability distributions bounded by $\pm 30\%$ around the central estimates of the six benefit categories were assumed, while implementation cost remained fixed.

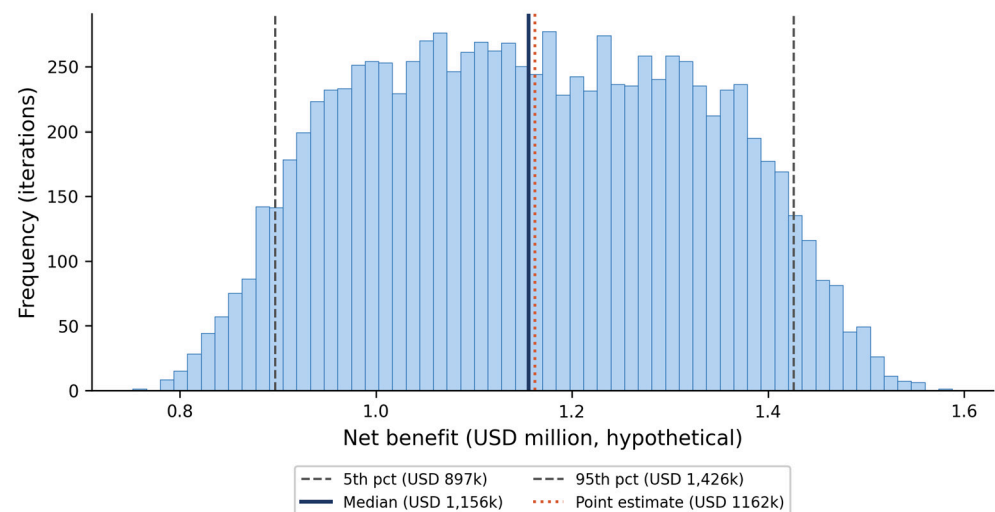


Figure 3. Output distribution of illustrative net benefit from Monte Carlo simulation. Note: (10,000 iterations, $\pm 30\%$ uniform bounds on all six saving categories, implementation cost fixed at USD 420,000). Dashed lines show 5th and 95th percentiles; solid dark line shows median; dotted line shows point estimate. All values hypothetical.

The simulation results indicate that the median net benefit closely approximates the central deterministic estimate, suggesting that the analytical structure is not materially dependent on a single assumption set. Across the tested range, the framework continues to generate positive net-benefit outcomes, with the 5th and 95th percentile values remaining above the implementation-cost threshold. The high proportion of positive net-benefit outcomes observed across the simulated range reflects the structural dominance of the rework-saving category within the tested $\pm 30\%$ assumption bounds, and should not be interpreted as evidence of robustness independent of these bounded assumptions; full distributional detail is reported in Table S6 of the Supplementary Materials.

The objective of this analysis is not to predict future project outcomes but to demonstrate that the proposed evaluation framework remains internally consistent under plausible variations in the assumptions used to calculate benefits. Detailed deterministic and probabilistic sensitivity results are reported in Tables S5 and S6 of the Supplementary Materials.

7. Discussion

7.1. Integration as the Primary Source of Value

The principal contribution of the proposed framework does not arise from any individual technology. BIM, mobile inspection systems, reality capture, artificial intelligence and

ERP platforms have each been studied extensively and are increasingly deployed across the construction sector. The persistent challenge identified throughout the literature is not the absence of digital tools, but the fragmentation of information across organisational, contractual and technological boundaries.

Previous studies demonstrated the benefits of BIM-enabled quality management [3], reality-capture technologies [4,6] and AI-assisted inspection processes [16]. However, these technologies typically operate within separate information domains. Quality observations often remain disconnected from procurement decisions, financial accountability and contractual governance mechanisms. As a result, organisations continue to rely on manual reconciliation processes to establish relationships between quality events, responsible parties, project impacts and financial consequences.

The proposed framework addresses this limitation by establishing a closed-loop information architecture in which quality events remain traceable across operational, contractual and financial domains. In this architecture, inspection records, visual evidence, corrective actions, supplier performance indicators and financial transactions become components of a common information chain rather than isolated datasets. From this perspective, the framework's value derives less from the introduction of new technologies than from the elimination of information discontinuities that prevent organisations from transforming quality data into actionable knowledge.

7.2. Enterprise Integration and Behavioural Governance

The most significant architectural extension of the framework concerns ERP integration beyond conventional quality-management functions. Existing construction QA/QC implementations frequently terminate at quality-notification workflows, leaving procurement and financial-control processes disconnected from quality outcomes. Consistent with the observations of Tatari et al. [18] and Galagali et al. [19], the present framework treats integration depth as a critical determinant of organisational value.

The procurement extension enables quality performance to influence supplier qualification, goods-receipt inspection, vendor evaluation and future procurement decisions. Quality, therefore, becomes a preventive mechanism operating upstream of construction activities rather than a corrective process applied after defects occur. Similarly, the extension into financial-control functions transforms quality from a descriptive reporting activity into a measurable economic variable through cost-of-poor-quality accounting, rework attribution and evidence-supported backcharge processes.

A particularly important consequence concerns subcontractor payment governance. The five-gate payment mechanism aligns commercial outcomes with demonstrated quality performance while maintaining transparency for all parties. Rather than introducing new contractual obligations, the framework formalises quality expectations that already exist implicitly within construction contracts and translates them into auditable decision rules. By establishing a transparent relationship between quality performance and payment certification, the framework has the potential to reduce closure-cycle times, improve accountability and decrease disputes associated with commercial settlement processes.

7.3. Data Democratisation, AI and Decision Support

The framework further contributes to the literature by treating data democratisation as an architectural requirement rather than a reporting feature. Many digital construction initiatives focus on data collection and dashboard development, but devote comparatively little attention to how information is distributed, interpreted and used across organisational levels. In contrast, the proposed framework assumes that quality information creates value only when it reaches decision-makers in a form capable of influencing behaviour.

This perspective also extends to the role of artificial intelligence. AI is positioned throughout the framework as an augmentation capability rather than an autonomous decision-making mechanism. Computer vision, natural-language processing and large language model services assist with detection, classification, prioritisation and communication, but responsibility for quality-critical decisions remains with human actors. This design choice reflects both the current maturity of construction-specific AI applications and the contractual and safety implications of QA/QC decisions. The combination of democratised information access and AI-assisted decision support has the potential to reduce information asymmetry, accelerate issue resolution and improve organisational learning, provided that governance structures and stakeholder trust remain sufficiently robust.

7.4. Transferability, Limitations and Implementation Risks

Although the framework is designed primarily for mega construction projects, its underlying logic is transferable to other project environments. The degree of implementation may vary according to project size, contractual structure and digital maturity, but the core principle of maintaining traceable connections between quality events, evidence, governance and financial consequences remains applicable across contexts.

Several implementation challenges should nevertheless be acknowledged. First, interoperability remains a persistent industry challenge. Construction projects commonly involve multiple software vendors, subcontractors and project stakeholders operating within different information environments. Achieving reliable data exchange between BIM platforms, field-inspection applications, reality-capture systems and enterprise platforms, therefore, requires consistent data structures, governance rules and ownership definitions throughout the project lifecycle.

Second, organisational adoption may represent a more significant challenge than technology deployment itself. Transparent quality governance can alter established reporting practices, commercial relationships and decision-making behaviours. Resistance may emerge when quality-performance indicators become directly linked to supplier evaluation, payment certification or financial accountability. Successful implementation, therefore, requires leadership commitment, stakeholder engagement and appropriate training programmes in addition to technical integration.

Third, AI-assisted processes remain vulnerable to false positives, inconsistent classifications and model drift. Although AI can improve efficiency and reduce administrative effort, the reliability of quality-related decisions remains dependent on human review and contextual judgement. Human accountability, therefore, remains an essential design principle of the proposed framework.

Finally, data governance, privacy and confidentiality considerations become increasingly important as quality information becomes integrated with commercial and contractual processes. These issues do not invalidate the framework but instead define important conditions for implementation and future empirical evaluation.

Boundary Conditions and Limitations

The following boundary conditions apply to the proposed framework and should be read alongside the discussion above. First, no empirical validation of the framework has yet been conducted; all numerical results reported in Sections 6 and 7 are hypothetical and assumption-driven. Second, the reported ROI and cost-benefit figures are illustrative and cannot be generalised to specific projects without project-specific data. Third, AI-component performance is dependent on the quality, volume and consistency of available inspection and reality-capture data, and has not been empirically benchmarked in this study. Fourth, enterprise integration across quality, procurement and financial-control

functions presupposes a level of organisational and digital maturity that many construction organisations do not yet possess, as discussed in the implementation-maturity model above. Fifth, the specific configuration of the payment-gate mechanism is expected to vary with contract type and jurisdiction, and the contractual clauses required to operationalise it have not been drafted or tested in this study. Sixth, the framework is designed primarily for mega construction projects; its full seven-layer configuration may be disproportionately complex for smaller projects with lower organisational capacity.

Taken together, these considerations suggest that the value of digital QA/QC depends not only on technology adoption but also on the successful alignment of information architecture, governance structures, organisational behaviour and contractual incentives. The controlled case-study protocol proposed in the following section is intended to assess these relationships and determine the extent to which the anticipated operational, behavioural and economic benefits can be realised in practice.

8. Conclusions

This study develops a closed-loop digital QA/QC framework for mega construction projects that integrates BIM, mobile field inspection, reality capture, AI-assisted analytics and enterprise resource planning within a unified governance architecture. The framework is founded on the premise that the principal challenge of contemporary digital construction quality management is no longer the availability of digital tools, but the absence of effective integration between them. Accordingly, quality management is conceptualised not as an isolated inspection function but as an enterprise-wide information architecture linking field evidence, contractual obligations, financial accountability and stakeholder decision-making within a single auditable environment.

The study contributes to the construction informatics and digital quality-management literature in several ways. First, it positions integration itself as the primary design objective and proposes a closed-loop architecture that maintains continuity between inspection activities, visual evidence, enterprise governance and organisational learning. Second, it extends the scope of ERP-enabled quality management beyond conventional quality-notification workflows by explicitly incorporating procurement, supplier-quality management and financial-control functions. Third, it treats data democratisation as a formal architectural component of digital QA/QC systems, recognising that quality outcomes depend not only on data collection but also on the accessibility, interpretability and operational use of information across organisational levels.

From a managerial perspective, the framework provides a structured mechanism through which quality information can influence operational, contractual and financial decision-making. The proposed payment-governance mechanism aligns quality performance with payment certification through transparent and auditable decision rules, while the integration of quality, procurement and financial-control processes improves visibility of supplier performance, rework attribution and cost-of-poor-quality (COPQ) performance. More broadly, the framework demonstrates how digital quality-management systems can transform isolated inspection records into reusable information assets that support project delivery, organisational learning and lifecycle information continuity.

The contribution of this study is conceptual and architectural in nature. The proposed framework, implementation logic and KPI structure are demonstrated through a Design Science Research approach rather than empirically validated. Consequently, the illustrative scenario presented in this paper should be interpreted as a demonstration of framework functionality rather than evidence of realised project performance. The framework further assumes the availability of key digital foundations, including BIM-enabled information management, mobile inspection capability, reality-capture technologies and

ERP infrastructure. Projects lacking these prerequisites may require additional investment and organisational preparation before implementation becomes feasible.

The immediate next stage of research is the controlled empirical case study outlined in Table S7 of the Supplementary Materials. This study will evaluate the proposed KPI structure using system-derived project data and assess the operational, behavioural and economic implications of the framework under real project conditions. Beyond this planned validation, future research may explore multi-project implementation across different asset classes, empirical benchmarking of AI-assisted quality-management functions and cross-country studies examining the influence of contractual, regulatory and cultural factors on digital quality-governance practices. This protocol is designed as a controlled before-and-after case study comprising a twelve-week baseline (fragmented) window and a twelve-week digital (framework-enabled) window on a single active project. It draws on system-derived inspection logs, SAP QM/MM/FI/CO transaction data, payment certificates and semi-structured interviews with QA/QC, commercial and site personnel to evaluate the KPI structure proposed in Section 5 under real operating conditions.

By maintaining a closed-loop integration logic while allowing implementation configurations to vary according to project context, the proposed framework provides a foundation for future research into enterprise-wide digital quality management and its contribution to lifecycle information continuity, facilities management and digital-twin readiness.

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