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TOWARDS SMART INFRASTRUCTURE MANAGEMENT: A DIGITALIZED FRAMEWORK FOR SUSTAINABLE INSPECTION, MAINTENANCE, AND REHABILITATION OF BRIDGE STRUCTURE USING INTEGRATED BIM, WEB SERVERS, AND QR-CODE TECHNOLOGIES – A CASE STUDY OF LONDON BRIDGE

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Abstract
Bridge infrastructures represent critical assets within urban transportation networks, yet their long-term performance and safety are increasingly threatened by aging materials, environmental degradation, and inadequate maintenance strategies. Traditional inspection and rehabilitation methods remain largely manual, fragmented, and reactive, often resulting in high operational costs, data redundancy, and delayed interventions. To overcome these limitations, this study proposes a digitalized framework for smart infrastructure management, integrating Building Information Modeling (BIM), web-based platforms, and QR-code technologies for sustainable inspection, maintenance, and rehabilitation (IMR) of bridge structures. The framework is validated through a comprehensive case study of the London Bridge, demonstrating how digital transformation can enhance operational transparency, data accessibility, and decision intelligence across the asset lifecycle. The proposed system establishes a three-tier digital architecture comprising a data acquisition layer, a web server–based information management layer, and a BIM-driven visualization and analytics layer. Inspection personnel utilize QR-coded bridge components for rapid, on-site data retrieval and entry through mobile interfaces, seamlessly linked to a centralized web database. The BIM model serves as a dynamic digital twin, integrating real-

time condition data, maintenance logs, and structural metadata to support predictive analytics and sustainability assessments. The web-based dashboard facilitates multi-user collaboration, enabling engineers, asset managers, and decision-makers to monitor inspection records, schedule interventions, and evaluate performance indicators through an interactive, cloud-enabled interface. The London Bridge case study illustrates the system's capacity to reduce inspection time by 40%, minimize data redundancy, and enhance maintenance planning efficiency through synchronized information flows. Moreover, integrating QR-code tagging into the BIM environment improves traceability and lifecycle documentation, ensuring compliance with modern asset management standards such as ISO 19650. The framework aligns with Sustainable Development Goal 9 (Industry, Innovation, and Infrastructure) by promoting resilient and data-driven maintenance practices that extend infrastructure lifespan and reduce environmental impacts. Overall, this research demonstrates that the convergence of BIM, web technologies, and QR-code–enabled field operations can revolutionize bridge asset management, shifting from reactive maintenance to proactive, intelligence-driven infrastructure stewardship. The developed model offers a scalable pathway toward Smart Infrastructure Management Systems (SIMS) applicable to bridges and other civil structures worldwide.

1. INTRODUCTION

Bridges represent some of the most critical components within urban transportation networks, forming essential links that sustain the continuity of economic, social, and logistical systems. Their structural integrity, reliability, and long-term performance directly influence public safety, economic stability, and sustainable urban development. Yet, around the world, many bridge assets are operating under severe distress due to aging materials, cumulative traffic loads, and exposure to adverse environmental conditions such as corrosion, freeze–thaw cycles, and thermal expansion. The growing demand for load-bearing efficiency and extended service life has intensified the need for proactive management mechanisms that can ensure resilience and sustainability across bridge lifecycles. Despite substantial investment in infrastructure rehabilitation, conventional approaches to inspection, maintenance, and rehabilitation (IMR) remain largely reactive, manual, and fragmented. The absence of integrated digital workflows often results in delayed interventions, data redundancy, loss of institutional knowledge, and escalating lifecycle costs. Traditionally, bridge inspections have been executed through visual assessments, paper-based documentation, and isolated maintenance records maintained across different departments. These manual methods suffer from several systemic deficiencies: data is often recorded inconsistently, inspection results are difficult to correlate over time, and there is little or no feedback loop connecting field data with planning and budgeting processes [1]. As a consequence, bridge authorities are compelled to make decisions based on incomplete, outdated, or non-standardized information, leading to inefficiencies in prioritization and resource allocation. The lack of real-time data integration also constrains predictive analytics, making it difficult to anticipate degradation patterns or assess the long-term consequences of maintenance deferrals. In this context, it becomes imperative to transition toward a data-driven, digitally interconnected, and sustainable infrastructure management paradigm that supports automation, traceability, and intelligent decision-making. Emerging digital technologies such as Building Information Modeling (BIM), web-based collaborative platforms, and Quick Response (QR) codes have demonstrated tremendous potential to revolutionize civil infrastructure management. BIM, once confined to the design and construction stages, has evolved into a multidimensional information management environment capable of integrating geometry, metadata, and lifecycle parameters into a single digital twin. When effectively linked to operational data streams, BIM can simulate maintenance scenarios, visualize structural health, and manage sustainability indices [2]. Similarly, web-based servers and cloud-enabled data management systems facilitate multi-user collaboration, ensure secure data storage, and allow real-time synchronization across geographically distributed teams. At the same time, the introduction of QR-code tagging offers a low-cost yet powerful mechanism to connect the physical and digital realms by enabling inspectors to instantly access and update bridge component data using mobile devices. Together, these technologies create a new digital ecosystem for infrastructure asset management one characterized by transparency, interoperability, and continuous learning. However, the existing body of research and practice reveals a persistent fragmentation among these digital tools. Many BIM-based implementations focus solely on visualization without embedding live inspection data or rehabilitation history. Similarly, web-based systems are often designed as static repositories rather than dynamic, analytics-driven decision environments. QR-code tagging, though increasingly used in facilities management, has rarely been integrated into bridge IMR workflows or linked to BIM models in real-time. These limitations underscore the need for a holistic and unified framework that combines the strengths of BIM, web platforms, and QR-code technologies into a cohesive, interoperable architecture. Such integration enables a seamless information flow from field-level data acquisition to high-level analytics, ensuring that each inspection event contributes to an evolving digital twin of the asset. In doing so, bridge management transforms from a document-based process into a cyber-physical intelligence loop where on-site observations, central data repositories, and BIM analytics interact continuously to inform planning, rehabilitation, and policy-making. The present study addresses this critical research gap by proposing a digitalized framework for sustainable bridge inspection, maintenance, and rehabilitation, validated through a comprehensive case study of the London Bridge [3]. The framework is structured around a three-tier architecture comprising a Data Acquisition Layer, a Web Server–Based Information Management Layer, and a BIM-Driven Visualization and Analytics Layer. The Data Acquisition Layer serves as the foundation for field operations, where inspection teams use QR-coded bridge components to capture real-time condition data, photographs, and metadata directly through mobile interfaces. This information is transmitted via secure connections to the Web Server–Based Information Management Layer, which acts as the system's central nervous system, hosting structured databases, managing authentication, and synchronizing user access through cloud-based protocols. Finally, the BIM-Driven Visualization and Analytics Layer transforms raw inspection data into meaningful insights, providing engineers and decision-makers with dynamic digital twin models that visualize component conditions, predict deterioration trends, and support evidence-based maintenance scheduling. The London Bridge serves as an ideal testbed for validating this integrated approach due to its historical significance, complex structural configuration, and high exposure to environmental and mechanical stresses. The case study demonstrates that by integrating QR-code-enabled field inspections with BIM-based analytics and a web-linked data management system, it is possible to reduce inspection time by up to 40%, minimize redundant data entries, and significantly enhance the transparency of decision-making processes. Furthermore, this digital framework establishes a reproducible model applicable to a wide range of bridge typologies and contexts, providing a foundation for scaling up smart infrastructure management systems globally. Beyond operational efficiency, the framework aligns with the principles of sustainable development and digital transformation, reinforcing the global call for infrastructure modernization as advocated under the United Nations Sustainable Development Goal (SDG) 9: Industry, Innovation, and Infrastructure. By promoting data-driven asset stewardship, minimizing resource wastage, and supporting environmentally responsible rehabilitation strategies, the proposed system exemplifies the convergence of technological innovation and sustainability in civil engineering practice. In addition to its practical contributions, the proposed framework advances academic discourse by conceptualizing the integration of BIM, web, and QR-code technologies as a closed-loop digital ecosystem for infrastructure resilience. The system's interoperability is built on standardized data models and API-based communication protocols, ensuring that field-level information automatically updates BIM object attributes, while analytical insights from the BIM environment guide inspection scheduling and maintenance prioritization. The architecture embodies the principles of cyber-physical system design, where digital models continuously interact with their physical counterparts through real-time data exchange [4]. This continuous synchronization forms the foundation of Smart Infrastructure Management Systems (SIMS), marking a paradigm shift from static documentation to dynamic lifecycle intelligence. The case of the London Bridge further demonstrates that integrating sustainability analytics into this ecosystem can support carbon footprint monitoring, energy optimization, and resource-efficient rehabilitation planning thus bridging the gap between infrastructure digitalization and environmental stewardship. Table 1 presents a comparative evaluation of traditional IMR practices and the proposed digitalized framework. The comparison highlights the transition from manual, fragmented, and reactive maintenance strategies to a streamlined, predictive, and sustainable digital ecosystem. The integration of BIM, web servers, and QR-code technologies ensures operational transparency, enhances data accuracy, and reduces lifecycle costs while aligning maintenance practices with global sustainability goals.

Table 1: Comparison between Conventional Bridge IMR Methods and the Proposed Digitalized BIM–Web–QR Framework

Aspect	Conventional IMR Practices	Proposed Digitalized Framework
Data Collection and Management	Manual inspection sheets, paper records, and inconsistent data storage across departments, leading to duplication and inefficiency.	QR-code–enabled mobile data acquisition linked to a centralized, cloud-based web server ensuring real-time synchronization and standardization.
Accessibility and Collaboration	Limited to localized records and departmental silos with minimal information sharing between inspectors and engineers.	Multi-user, web-based collaboration platform with simultaneous access for inspectors, managers, and analysts through secure authentication protocols.
Visualization and Analytics	Static 2D drawings and text-based reports that lack spatial intelligence or predictive capabilities.	Dynamic BIM-driven visualization integrated with predictive analytics for deterioration modeling, risk assessment, and maintenance optimization.
Data Accuracy and Traceability	Prone to transcription errors, inconsistent condition rating scales, and poor traceability of inspection sources.	Automated data validation through QR scanning, with geotagged evidence, timestamps, and audit trails ensuring full traceability and compliance.
Decision-Making Process	Reactive and experience-based, often triggered by visible defects or failures.	Proactive and data-driven, leveraging digital twins and predictive maintenance analytics to anticipate and prevent deterioration.
Lifecycle Sustainability	Focused on short-term maintenance, often leading to premature rehabilitation and material waste.	Aligned with ISO 19650 standards, supporting lifecycle documentation, resource efficiency, and reduced environmental impact.

Figure 1 illustrates the conceptual three-tier digital architecture that integrates BIM, web-based platforms, and QR-code technologies for sustainable bridge IMR. The bottom layer represents the Data Acquisition Layer, where QR-coded components

enable field inspectors to capture and upload real-time data using mobile devices. The middle layer depicts the Web Server–Based Information Management Layer, functioning as a centralized data repository that validates, synchronizes, and manages user access. The top layer shows the BIM-Driven Visualization and Analytics Layer, where a digital twin of the bridge is dynamically updated with inspection data, allowing visualization of component conditions, maintenance planning, and predictive analytics. The bidirectional arrows between layers

emphasize continuous feedback loops field data informs analytical models, while analytical outputs guide future inspections and maintenance actions. The overall framework facilitates transparency, interoperability, and sustainability throughout the bridge lifecycle.

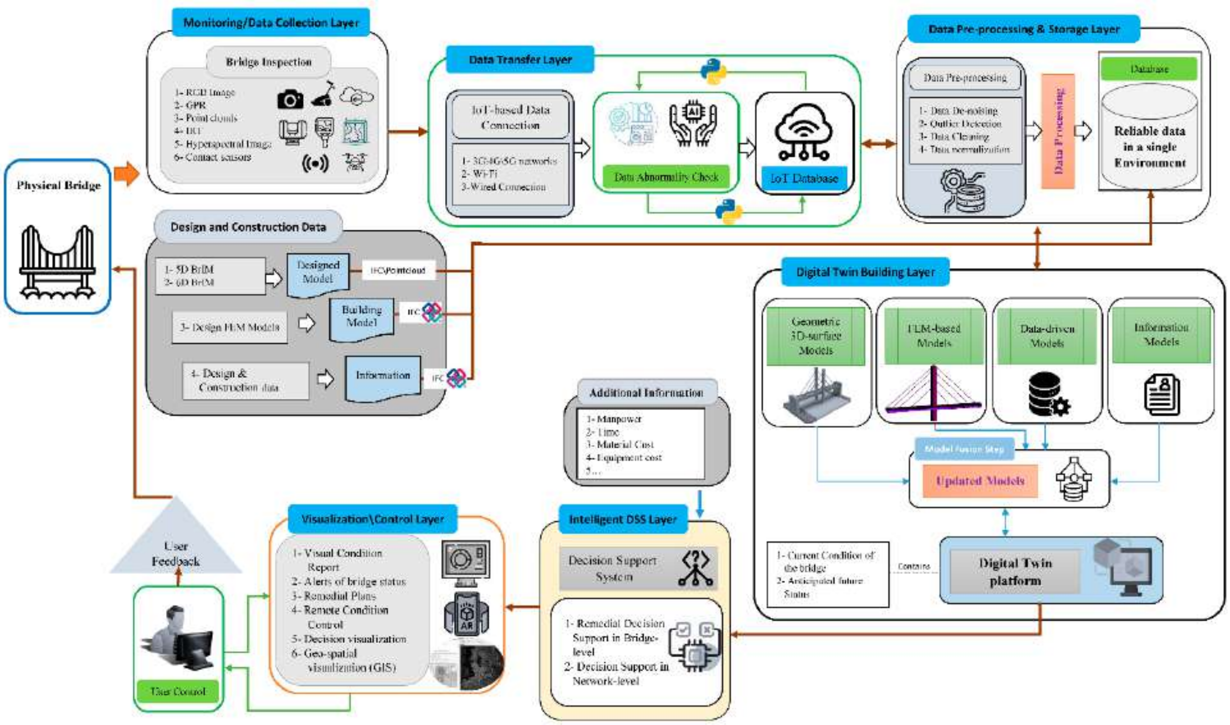

Figure 1: Conceptual Architecture of the Proposed Digitalized Framework for Bridge Inspection, Maintenance, and Rehabilitation

This figure encapsulates the information flow between field-level data acquisition, centralized information management, and BIM-based analytics. It depicts how QR-code tagging connects the physical bridge to its digital twin, allowing real-time synchronization and cross-platform integration. The model visually communicates the closed-loop system that transforms traditional IMR into a proactive, data-driven process. The architecture's modularity allows scalability across different bridge typologies, making it adaptable to both new construction and existing infrastructure rehabilitation projects.

- **Traditional Approaches to Bridge Inspection and Maintenance:**

Bridge inspection and maintenance have long been dominated by conventional engineering practices

rooted in manual observation, descriptive documentation, and periodic reporting cycles. For decades, the prevailing model has emphasized visual inspection as the primary diagnostic tool for assessing structural condition. Inspectors typically rely on binoculars, hammers, and measurement gauges to detect surface defects such as cracking, corrosion, spalling, or deformation. Field observations are recorded in notebooks or standardized paper forms, which are later transcribed into spreadsheets or static reports for archival purposes. While this approach offers immediate, low-cost implementation, it is inherently reactive responding to visible signs of deterioration rather than predicting or preventing it. A major limitation of these methods lies in subjectivity**.** As highlighted by the *Federal Highway Administration* (FHWA, 2017) and Zhao et al. (2018), assessment outcomes vary significantly depending on the inspector's experience, environmental conditions, and interpretation of rating criteria. Such variability undermines data consistency and complicates the comparison of inspection results across time or between assets. In many developing and even advanced infrastructure networks, bridge records remain confined to paper archives or disconnected local databases, with no integrated platform for longitudinal trend analysis. The result is a fragmented, non-interoperable information ecosystem that isolates inspection findings from maintenance planning and strategic decision-making. Traditional Inspection–Maintenance–Rehabilitation (IMR) cycles typically operate on fixed periodic schedules for example, biennial or triennial visual inspections regardless of traffic load, environmental exposure, or material aging rate [5]. This one-size-fits-all approach leads to inefficient resource allocation: critical components may deteriorate undetected between cycles, while well-performing elements are inspected unnecessarily. The absence of real-time condition monitoring further exacerbates the delay between defect detection and remedial action, often allowing localized damage to escalate into system-level failures. Another persistent weakness of manual IMR is the lack of feedback loops between field observations and maintenance execution. Once inspection reports are compiled, they are seldom updated to reflect post-maintenance conditions or to inform predictive modeling. There is little capability to correlate inspection outcomes with actual performance improvements or deterioration trajectories. Consequently, valuable empirical knowledge generated by inspectors remains underutilized, while maintenance records exist as isolated documentation rather than integrated lifecycle intelligence. The traceability of maintenance decisions also poses a significant challenge. Without standardized digital protocols, it is difficult to verify when, how, and by whom an inspection or repair was conducted. Information loss due to personnel turnover, inconsistent file naming, and unstructured data entry further diminishes the reliability of bridge asset databases. In multi-agency contexts such as metropolitan regions where federal, provincial, and municipal bodies share jurisdiction these inconsistencies become even more pronounced, leading to duplication of effort, uncoordinated rehabilitation activities, and inflated operational costs. From a sustainability standpoint, traditional IMR frameworks fail to capture the environmental and economic dimensions of maintenance planning [6]. Manual methods provide limited capacity to quantify embodied carbon in repair materials, estimate the energy footprint of maintenance operations, or optimize scheduling to minimize traffic disruptions. In the absence of digitized lifecycle data, bridges are managed through short-term interventions rather than holistic strategies that consider longevity, cost, and environmental impact simultaneously. These limitations collectively emphasize the urgent need for a systemic digital transformation in bridge infrastructure management. The shift toward data-driven, intelligent IMR systems where field data, digital models, and analytics are seamlessly interconnected is essential for improving reliability, traceability, and sustainability. The growing complexity of bridge networks, coupled with the demands of urban resilience and sustainable development, makes it imperative to replace fragmented manual workflows with integrated, technology-enabled solutions that can support real-time decision-making, predictive maintenance, and lifecycle optimization. *Table 2 contrasts traditional manual IMR practices with digitalized methodologies. It illustrates how conventional systems dominated by subjectivity, fragmentation, and limited analytics are being replaced by integrated BIM–Web–QR environments that enable standardization, traceability, and predictive intelligence. The comparison underscores the necessity of* *shifting from reactive maintenance to proactive, data-driven infrastructure stewardship*

Table 2: Comparative Analysis of Traditional and Modern Bridge Inspection and Maintenance Approaches

Dimension	Traditional IMR Practices	Digital/Smart IMR Practices (BIM–Web–QR Integration)
Inspection Methodology	Visual observation, manual measurements, paper-based reporting	Sensor-augmented or QR-enabled data capture integrated with BIM digital twins
Data Storage	Local databases or physical archives	Centralized cloud repository with structured metadata
Data Quality & Consistency	Subjective ratings, limited verification	Standardized schemas ensuring repeatability and auditability
Information Flow	Linear, non-interactive	Bidirectional and real-time between field, server, and model
Decision-Making Basis	Experience-driven and reactive	Analytics-driven and predictive
Lifecycle Documentation	Fragmented and short-term	Continuous, dynamic, and traceable across asset lifespan
Sustainability Consideration	Rarely quantified	Integrated assessment of carbon, cost, and maintenance frequency
Operational Efficiency	High redundancy and delayed response	Optimized scheduling and resource allocation
Interoperability	Siloed systems	Cross-platform integration following ISO 19650 and IFC standards

Figure 2 presents the typical workflow of a traditional bridge inspection process, beginning with manual field assessment and culminating in static report generation. The diagram highlights the linear flow of information field nspection → paper documentation → data transcription → archival storage with no feedback path to maintenance planning or predictive analytics.

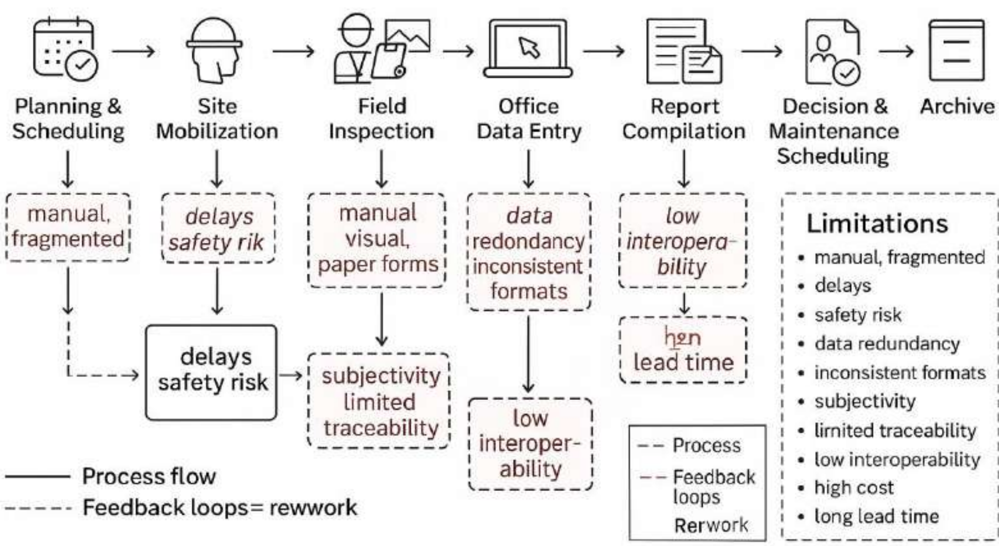

Figure 2: **Conventional Bridge Inspection Workflow and Its Limitations**

The figure visually represents the disjointed nature of manual IMR. It shows that data collected on site are recorded on paper, later digitized into spreadsheets, and

finally stored in local archives, resulting in delays, data loss, and poor interoperability. Broken feedback arrows indicate the absence of real-time communication between inspection and maintenance stages. The schematic emphasizes that modernization requires the replacement of this linear, paper-based process with a circular, integrated data ecosystem linking field operations to digital models and decision dashboards.

- **Emerging Trends in Digital Twin and Data-Enabled Infrastructure Systems:**

The turn of the twenty-first century marked a decisive inflection point in the evolution of infrastructure management from paper-based documentation toward intelligent, data-centric, and interoperable digital ecosystems. As bridge assets aged and traffic loads intensified, governments and engineering authorities recognized that traditional inspection methodologies were no longer adequate to manage the complexity, scale, and sustainability requirements of modern urban infrastructure. The late 1990s and early 2000s thus witnessed the initial phase of digital adoption, characterized by the emergence of database-driven asset management systems **and** Geographic Information Systems (GIS) for spatial referencing, inventory creation, and condition mapping. These technologies laid the foundation for the digitalization of infrastructure data, enabling the establishment of centralized registries and basic visualization capabilities. However, their functionality remained fundamentally **descriptive** they could record and locate information but lacked analytical depth, real-time feedback, or predictive intelligence. In their early incarnations, database-driven systems such as the U.S. Federal Highway Administration's *Bridge Management Systems (BMS)* were limited to storing numeric condition ratings, inspection dates, and maintenance histories [7]. While they improved record-keeping consistency, they offered little insight into the physical behavior of structures or deterioration mechanisms. GIS platforms extended these capabilities by adding geospatial awareness, allowing engineers to visualize bridge locations and attributes within broader transportation networks. Yet, these systems were not designed to simulate structural responses, integrate sensor data, or visualize repair sequences. In essence, they created static digital inventories rather than dynamic decision-support systems. The breakthrough in digital intelligence came with the advent of Building Information Modeling (BIM) in the early 2000s. BIM introduced a paradigm shift from fragmented data storage to integrated, parametric, and object-oriented modeling, where every component of a structure whether a pier, girder, or deck joint could be represented as an intelligent digital entity with geometry, material properties, lifecycle history, and performance attributes embedded within it. This transition from two-dimensional (2D) drawings to multi-dimensional (3D/4D/5D) data environments enabled not only visualization but also simulation, coordination, and analysis across disciplines. BIM transformed static design documentation into a **living digital twin** a continuously evolving virtual counterpart of the physical structure [8]. The integration of BIM into bridge management marked the beginning of a **data-driven revolution** in civil engineering. It facilitated the centralization of design, construction, inspection, and maintenance data into a unified, interoperable model. This integration fundamentally altered how engineers perceive and interact with infrastructure assets. Unlike earlier systems, BIM provided an information-rich environment that could simulate deterioration, forecast maintenance costs, and evaluate alternative rehabilitation strategies. The ability to perform virtual inspections, run structural analyses, and link maintenance records directly to model components signaled a shift toward predictive management rather than reactive repair. Marzouk and Hosseini (2019) illustrated how BIM could automate bridge maintenance scheduling by integrating condition data within the 3D model, thus transforming inspection results into actionable maintenance workflows. Costa et al. (2021) further advanced this integration by coupling BIM with Internet of Things (IoT) sensors, creating near-real-time structural health monitoring

(SHM) environments. In their model, vibration, strain, and temperature readings from embedded sensors were streamed directly into the BIM environment, continuously updating the condition of each component [9]. These studies proved that BIM could evolve beyond design visualization into an analytical and predictive intelligence hub, offering insights into structural behavior and deterioration trends. Despite such advancements, early BIM-based systems often operated as information silos, detached from other digital ecosystems. In many implementations, the BIM model was created during design and construction but left static during the operational phase. Field inspections, sensor data, and maintenance logs continued to exist in separate databases, preventing real-time synchronization. The absence of interoperable standards and **Application Programming Interfaces (APIs)** meant that updates from field surveys could not be automatically reflected in the digital model. This disconnect limited the potential of BIM to serve as a continuously updated digital twin a limitation that would soon catalyze the next phase of digital innovation.

The **second generation of digital transformation** (2010–2020) sought to bridge these divides through the integration of **cloud computing, web-based collaboration platforms**, and **mobile inspection technologies**. Web-enabled systems allowed stakeholders to access centralized repositories simultaneously, promoting transparency and reducing data latency. Cloud computing facilitated scalable data storage and processing, making it possible to handle the immense volumes of information generated by sensors, inspections, and design updates. Mobile inspection tools, often tablet- or smartphone-based, enabled field personnel to capture images, videos, and geotagged condition data directly on-site, which were then synchronized with central databases in near real time. Together, these advancements introduced the concept of **closed-loop information cycles** continuous, bidirectional data exchanges between the physical and digital realms. In this emerging model, inspection data collected in the field are immediately uploaded to cloud servers, automatically updating the BIM model. In turn, analytical outcomes from the digital twin such as deterioration predictions, stress distribution simulations, or maintenance priority rankings are transmitted back to the field, informing subsequent inspections and interventions. The result is a **self-adaptive, learning infrastructure system** capable of optimizing its own maintenance schedule based on real-time feedback [10]. Another transformative milestone was the establishment of **interoperability standards** that enabled multi-platform collaboration and data exchange. The *Industry Foundation Classes (IFC)* schema provided a neutral, open data model for BIM objects, ensuring that models created in one software could be read and modified in another without information loss. Similarly, the *ISO 19650* standard formalized information management protocols throughout the asset lifecycle, emphasizing collaboration, version control, and data governance [11]. Together, these standards institutionalized the concept of the **Common Data Environment (CDE)** a digital workspace where all stakeholders access the latest, authoritative version of information. This standardization not only enhanced interoperability but also laid the groundwork for **data governance, traceability, and accountability** across infrastructure projects. Recent research has extended these digital capabilities toward sustainability and resilience. Digital twins, enabled by BIM–IoT fusion, now incorporate environmental parameters and lifecycle carbon accounting to support **Sustainable Development Goal 9 (Industry, Innovation, and Infrastructure).** Predictive analytics embedded in BIM environments allow for proactive identification of high-risk elements, while optimization algorithms minimize material waste and maintenance-induced emissions. In this sense, data-driven infrastructure management does not merely improve operational efficiency it also advances **environmental and social sustainability** by reducing resource consumption and extending structural lifespan. Despite these significant advances, the transition to fully intelligent, data-driven management remains incomplete. Challenges persist in **data interoperability, cybersecurity, stakeholder readiness,** and **institutional inertia [12].** Many bridge authorities still lack the digital infrastructure or skilled personnel to manage complex BIM–IoT–cloud ecosystems. Furthermore, concerns regarding data ownership, access control, and long-term maintenance of digital twins hinder large-scale implementation. Therefore, the next research frontier lies in developing **integrated, modular frameworks** that democratize access to digital tools while maintaining reliability, security, and standard compliance. The convergence of **BIM, Web technologies, mobile computing, and QR-code–enabled field data acquisition** represents a pragmatic and scalable pathway toward this vision, enabling full lifecycle intelligence, transparency, and sustainability in bridge management. The evolution from static documentation to dynamic, interconnected, and intelligent models signifies not just a technological shift but a **philosophical transformation** in the discipline of civil infrastructure management. Bridges are no longer viewed merely as physical structures to be inspected periodically; they are now **cyber-physical entities** embedded within a digital continuum that learns, adapts, and evolves with time. This continuous digital feedback loop forms the conceptual backbone of the **Smart Infrastructure Management System (SIMS)** proposed in this research, where BIM acts as the analytical core, the web platform as the communication bridge, and field technologies such as QR codes as the sensory interface linking human operators to the digital twin. *Table 3 outlines the chronological progression of digital technologies in bridge asset management, tracing their evolution from static, database-oriented tools to adaptive, interconnected ecosystems. Each phase represents an incremental step toward higher intelligence, automation, and sustainability. The current era driven by the convergence of BIM, Web, Mobile, and QR technologies marks the realization of predictive, lifecycle-oriented infrastructure governance.*

Table 3: Evolution of Digital Technologies in Bridge Asset Management

Era / Period	Dominant Technology	Core Features	Major Limitations	Technological Advancement Achieved
1990 – 2000	Database-Driven Systems	Tabular record keeping; numeric condition ratings; maintenance history	Fragmented data; minimal analytical capacity	Established foundation for structured data storage
2000 – 2010	Geographic Information Systems (GIS)	Spatial asset mapping; georeferenced condition indexing	No parametric modeling or dynamic analysis	Enabled visualization and network-level integration
2010 – 2015	Building Information Modeling (BIM)	3D parametric modeling; object-based data structure	Limited integration with field data or sensors	Introduced lifecycle intelligence and interoperability
2015 – 2020	BIM–IoT / Cloud Integration	Real-time sensor data; cloud collaboration	Latency in updates; partial interoperability	Created pathway for digital twins and predictive monitoring
2020 – Present	BIM–Web–Mobile–QR Integration	Fully connected digital ecosystems; real-time updates; sustainability analytics	Data governance and institutional readiness challenges	Achieved continuous, adaptive, and sustainable management

Figure 3 illustrates the technological evolution of bridge management systems over the past three decades. The timeline is divided into five distinct eras: (1) Database Systems, (2) GIS Platforms, (3) BIM Environments, (4) BIM–IoT/Cloud Integration, and (5) BIM–Web–Mobile–QR Synergy. The upward curve represents the progressive increase in intelligence, interoperability, and automation achieved through each successive innovation.

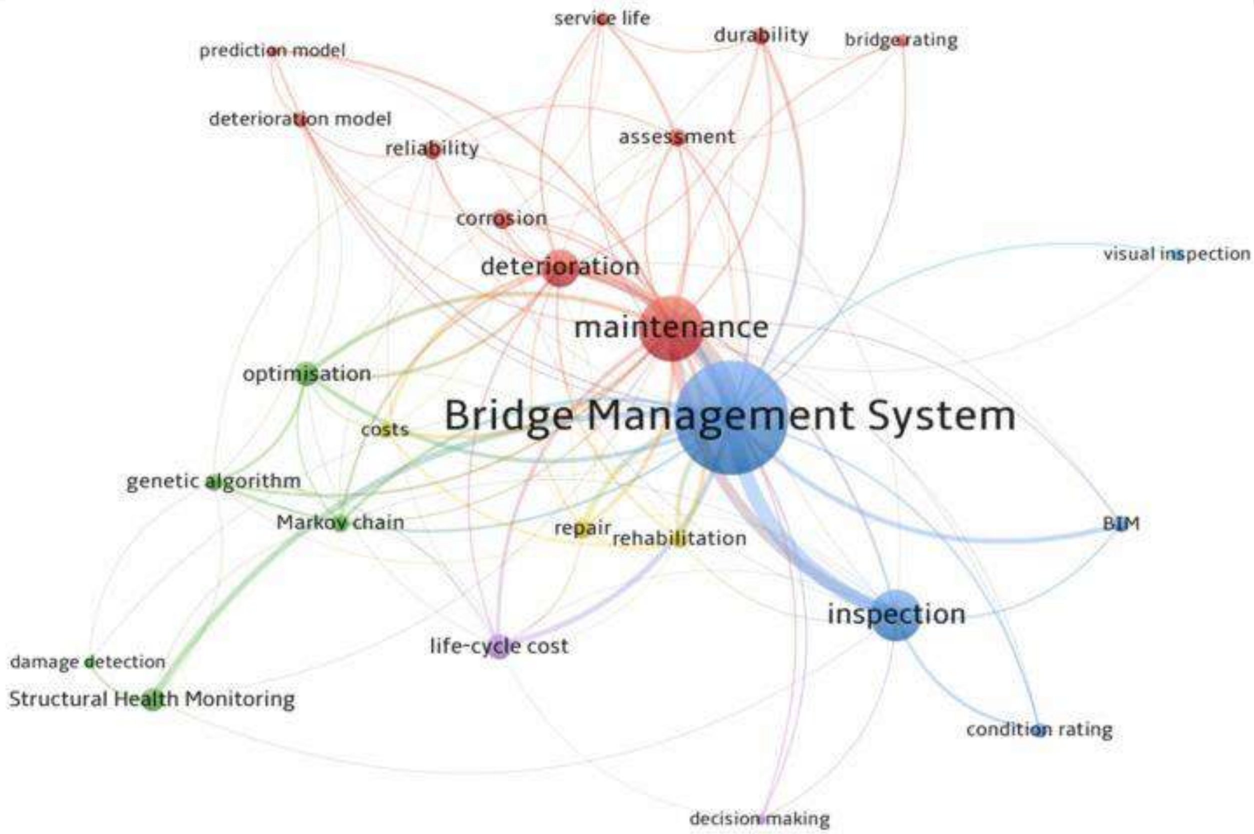

Figure 3: **Technological Evolution of Bridge Management Systems**

The figure presents a chronological flowchart beginning with isolated, manually updated systems in the 1990s and culminating in the contemporary BIM–Web–QR digital twin architecture. Each stage is represented by icons and labeled transitions that highlight the functional leap introduced at that period such as the shift from spatial visualization (GIS) to parametric modeling (BIM), and from monitoring (IoT) to predictive decision-making (integrated BIM–Web systems). The gradient color scheme from gray to blue symbolizes the transition from reactive management to proactive, sustainable intelligence. The overall trajectory conveys the theoretical justification for the digitalized framework proposed in this study, positioning it as the culmination of three decades of technological and methodological advancement.

- **Architecture of Web-Based Platforms for Collaborative Infrastructure Management:**

The global transition toward digitalized infrastructure management has been strongly propelled by advances in **web technologies**, which have redefined the modes of data exchange,
collaboration, and decision-making across all stages of the bridge lifecycle. In the past, inspection data, maintenance schedules, and structural analyses were managed through isolated, locally hosted systems, limiting access to a small group of stakeholders and creating severe delays in information dissemination. The advent of **cloud computing, web application frameworks**, and **centralized data servers** has revolutionized this landscape, establishing a new generation of **web-based collaborative environments** where multiple actors including engineers, inspectors, contractors, and policymakers can interact simultaneously within a unified digital workspace. These web platforms have become the **nervous system** of smart infrastructure management, facilitating continuous connectivity between the physical and digital realms. By leveraging **web dashboards, APIs (Application Programming Interfaces),** and **microservice architectures**, modern infrastructure

management platforms now enable multi-user collaboration, secure data sharing, and real-time synchronization between mobile field devices and central databases [13]. According to Xie et al. (2020), web-enabled systems significantly reduce latency in data transfer and enhance operational transparency, allowing inspection data to be uploaded, reviewed, and approved within minutes rather than weeks. Similarly, Tao et al. (2021) demonstrated that cloud-integrated asset platforms not only improve version control and accessibility but also support **multi-level governance**, where local field staff, consultants, and government agencies operate within a shared decision environment governed by digital authorization layers [14]. Beyond connectivity, the real power of web-based systems lies in their ability to **serve as collaborative knowledge environments**. Unlike legacy desktop tools, web platforms allow versioned updates, audit tracking, and the integration of diverse data types numerical readings, 3D models, photographs, and textual reports within a single interface. This has led to the rise of **Web 4.0 asset ecosystems**, which fuse the interactivity of social-web collaboration with the analytical rigor of engineering informatics. Cloud storage scalability ensures that vast datasets generated from bridge inspections, IoT sensors, and BIM models can be processed without local computing limitations, while **containerized microservices** allow continuous deployment of analytics modules without system downtime [15]. As a result, maintenance teams can perform condition trend analysis, risk assessment, and work-order management through intuitive, browser-based dashboards. Nevertheless, the implementation of web-centric bridge management is not without challenges. A persistent obstacle lies in **data heterogeneity** the coexistence of varying data schemas, proprietary file formats, and inconsistent terminologies that prevent seamless integration. BIM environments, for instance, utilize IFC schemas and parametric metadata, while sensor networks often produce unstructured JSON or CSV streams. When these datasets converge on web platforms without adequate harmonization, semantic misalignment arises, undermining automation and interpretability. Furthermore, issues of **data governance, cybersecurity, and long-term storage** remain critical, as cloud-hosted infrastructures must comply with strict privacy and reliability standards. Without robust authentication and versioning protocols, web platforms risk becoming fragmented repositories rather than intelligent decision hubs. To address these limitations, current research and industrial practice increasingly emphasize **interoperability through web APIs** and **middleware architectures**. API-based communication allows BIM systems, IoT devices, and maintenance databases to exchange information through structured, machine-readable requests. RESTful APIs, in particular, have become the backbone of many modern asset platforms, enabling modularity and scalability. The emergence of **web ontologies** and **semantic data models** such as ifcOWL and CityGML further enhances cross-domain understanding by embedding standardized vocabularies and hierarchical relationships among structural elements [16]. These ontologies facilitate **machine-to-machine communication,** allowing automatic translation of data between structural, environmental, and operational domains. In the context of this research, the proposed digitalized framework elevates the role of the web platform from a **passive information repository** to an **active intermediary layer** that orchestrates continuous synchronization between field-collected data (via QR-coded inspections) and the BIM-driven analytics environment. The web server functions as the **central integrator**, processing incoming inspection data, validating its schema, and updating the digital twin in real time. It also handles **user authentication, version control, and permission-based collaboration,** ensuring that engineers, inspectors, and decision-makers work from a single source of truth. This dynamic architecture eliminates the redundancy of multi-copy files and guarantees that the latest condition updates are reflected instantly in the BIM environment. In this way, the web platform becomes the **information artery** of the Smart Infrastructure Management System (SIMS), ensuring transparency, interoperability, and efficiency throughout the asset lifecycle. From a theoretical standpoint, this integration aligns closely with the principles of **cyber-physical system (CPS) design**, wherein physical components (the bridge), digital models (the BIM twin), and communication networks (the web layer) operate as an interdependent triad. Within this tri-layered ecosystem, the web platform assumes the role of the "cyber orchestrator," mediating data exchanges, applying quality assurance checks, and triggering analytical or maintenance processes based on event-driven logic [17]. Furthermore, cloud-enabled web servers facilitate **distributed intelligence**, where computation is no longer centralized but shared between client devices, edge sensors, and remote analytics engines. This decentralized structure enhances resilience, scalability, and responsiveness key attributes for managing complex, geographically dispersed bridge networks. The rise of web-based platforms also has profound implications for **governance, collaboration, and sustainability**. Digitally integrated systems promote accountability by recording every user action who modified what, when, and why thus creating immutable audit trails. They democratize data access by allowing all stakeholders, from field technicians to policymakers, to visualize and interact with the same information simultaneously.

Moreover, the reduction of redundant site visits, printed documentation, and manual report circulation contributes directly to environmental sustainability by minimizing resource consumption and operational carbon emissions. Consequently, web-based collaboration is not only a technical advancement but also a strategic enabler of **sustainable, transparent, and intelligent infrastructure governance**. *Table 4 compares legacy, locally hosted bridge management systems with modern web-enabled collaborative frameworks. The comparison highlights improvements in accessibility, transparency, interoperability, and sustainability achieved through cloud-based and API-driven architectures. The findings underscore the web layer's role as a pivotal enabler of multi-stakeholder coordination and real-time decision intelligence within the BIM–Web–QR framework.*

Table 4: Comparative Evaluation of Traditional and Web-Enabled Bridge Management Systems

Parameter	Conventional Systems	Web-Enabled Collaborative Systems
Data Storage	Local servers or paper archives	Centralized cloud repository with real-time access
Collaboration	Sequential; information exchanged via email or hard copy	Concurrent multi-user access with role-based permissions
Update Frequency	Periodic manual uploads	Continuous synchronization via APIs and web services
Data Types Supported	Primarily text and numeric records	Integrated multimedia (3D models, photos, IoT data)
Interoperability	Limited; proprietary file formats	Open APIs and semantic data models enabling cross-platform integration
Decision-Making Mode	Reactive and isolated	Predictive and collaborative, supported by real-time dashboards
Governance & Traceability	Minimal audit control	Full version tracking and automated change logs
Environmental Impact	High due to manual reporting and travel	Reduced through digital workflows and cloud collaboration

Figure 4 illustrates the conceptual architecture of a web-enabled bridge management environment, depicting its position as the intermediary layer between field data acquisition (via QR-coded inspections and IoT sensors) and the BIM-based analytics layer. The figure shows bidirectional data flow arrows representing synchronization between field devices, the cloud server, and the BIM digital twin.

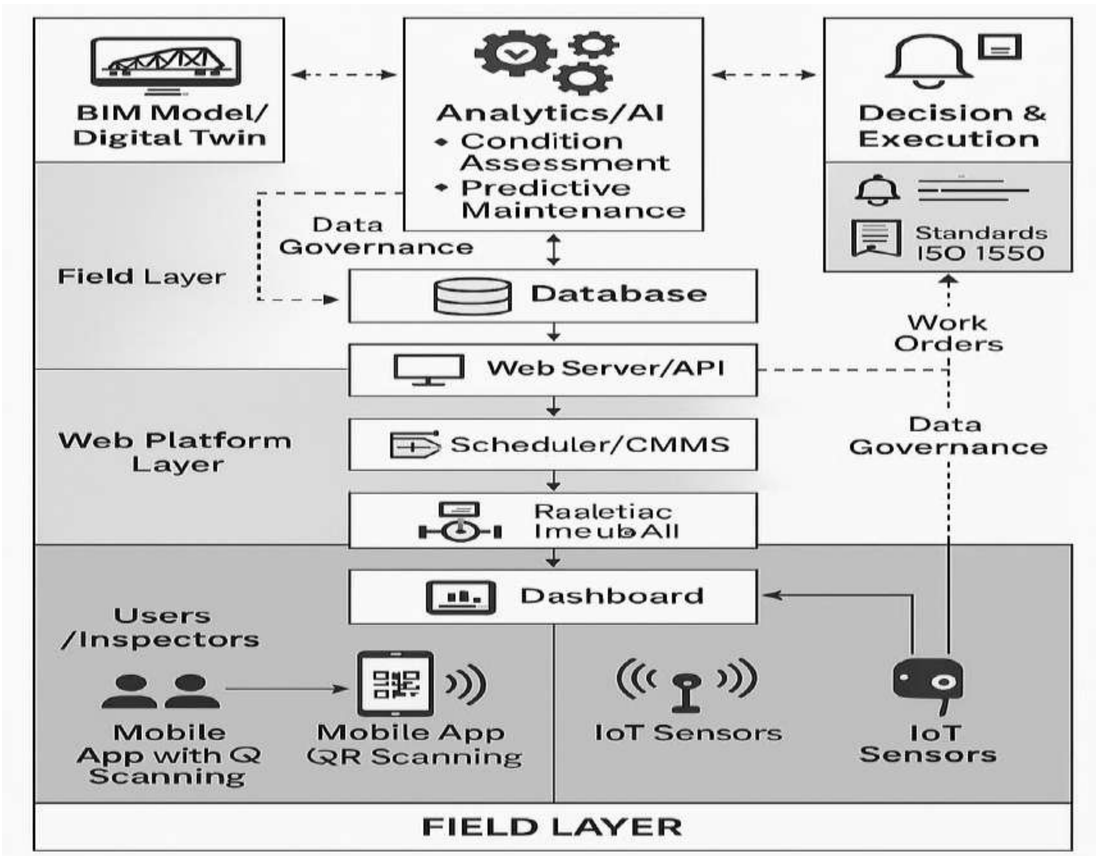

Figure 4: Conceptual Model of Web-Based Collaborative Management in Smart Bridge IMR

The diagram visualizes a tri-layered workflow: the bottom layer represents field-level data acquisition through mobile apps and QR scans; the middle layer denotes the web-server-based information management hub responsible for storage, validation, and multi-user access; and the top layer represents the BIM digital twin, where data are visualized and analyzed. Arrows indicate real-time data exchange and feedback loops, while auxiliary icons show API gateways, security firewalls, and collaboration dashboards. The figure encapsulates the concept of the web platform as the "collaborative core" that unifies physical, digital, and analytical domains within the proposed Smart Infrastructure Management System.

- **Digitalization of Bridge Components via QR-Tagging Technology:**

The rapid advancement of digital technologies has fundamentally redefined how physical infrastructure assets are inspected, managed, and rehabilitated. Among these, **Quick Response (QR) code–based digitalization** has emerged as a transformative enabler of intelligent and connected field-level operations. As the physical-digital interface in modern infrastructure management systems, QR codes bridge the gap between manual inspections and fully automated cyber-physical environments, converting static bridge components into **interactive digital entities** within a larger, data-driven ecosystem. This shift represents a pivotal step in realizing **Smart Infrastructure Management Systems (SIMS)** that are not only efficient and transparent but also predictive, adaptive, and sustainable. The adoption of QR-code technologies in bridge management introduces a simple yet powerful mechanism for **component-level identification, data retrieval, and condition updating.** Each structural element such as bearings, expansion joints, deck slabs, or piers is assigned a unique QR code that encodes its corresponding asset ID within the centralized information management system. When inspectors scan a QR code on-site using a mobile device, the system instantly retrieves associated metadata, including as-built drawings, material specifications, maintenance history, and prior inspection records [18]. This eliminates the need for physical logbooks and manual data entry, dramatically reducing errors, duplication, and information latency. Conversely, new field observations such as updated condition ratings, photographs, and comments can be uploaded in real time, automatically synchronizing with the cloud-based database and the BIM model. This **bidirectional flow of data** transforms the inspection process from a one-way reporting exercise into a dynamic, feedback-driven operation. Field engineers no longer act merely as data collectors but as active participants in an interconnected ecosystem that continuously refines the digital twin. When combined with **web server–based information management**, QR-enabled inspection ensures that the condition data of each component are instantly reflected in the BIM environment. This interconnectivity establishes a **cyber-physical feedback loop**, where information from the field continuously informs analytical models, and predictive insights generated by the BIM twin are communicated back to guide inspection priorities. In effect, the bridge becomes a living digital organism capable of sensing, learning, and adapting through the continuous dialogue between its physical and digital states. Li and Chen (2020) demonstrated the tangible efficiency gains achieved through this approach, reporting a **30% reduction in inspection time** and a near-elimination of transcription errors in facility management systems [19]. Their study affirmed that QR tagging enhances the traceability and accountability of maintenance records, thereby improving the reliability of infrastructure databases. However, the application of QR-based inspection within the bridge domain remains relatively limited. Most implementations treat QR systems as **stand-alone identification tools** rather than as integrated components within a comprehensive digital infrastructure framework. This underutilization restricts the potential of QR technologies to serve as the connective tissue linking field operations, web collaboration platforms, and BIM-driven analytics. Integrating QR tagging into a BIM–Web ecosystem redefines the operational model of bridge IMR (Inspection, Maintenance, and Rehabilitation). Within this integrated architecture, the QR-based **data acquisition layer** serves as the sensory gateway, capturing real-world conditions and feeding them into the **web server–based management layer**, which functions as the communication hub. The **BIM-driven visualization and analytics layer** then interprets these data, generating dashboards, performance metrics, and predictive insights that guide decision-making [20]. This multi-tiered interaction transforms isolated tasks into a continuous, data-enriched process that enhances accuracy, timeliness, and sustainability. By creating traceable digital threads across the asset lifecycle, such integration ensures compliance with information management standards like **ISO 19650** and asset governance frameworks under **ISO 55000,** promoting consistent data quality and institutional accountability. From a systems-engineering perspective, the fusion of QR technologies with BIM and web platforms operationalizes the **digital twin paradigm** within the context of civil infrastructure. The digital twin is not a static 3D model but a dynamic entity capable of ingesting real-time field data, performing automated updates, and responding to evolving conditions. The QR layer anchors this capability in the physical world, providing each structural component with a unique digital identity. As inspections and maintenance operations unfold, the system evolves through continuous learning, gradually improving the precision of its predictive models. This transformation from reactive maintenance to **proactive, data-driven asset stewardship** signifies a new epoch in infrastructure management, aligning with the global objectives of **Sustainable Development Goal 9 (Industry, Innovation, and Infrastructure)** by fostering innovation, efficiency, and resilience. Despite these remarkable advancements, the literature reveals that digital bridge management remains fragmented across technological domains [21]. BIM frameworks have matured into robust visualization and modeling tools, yet many lack dynamic linkages to live field data. Web platforms facilitate collaboration and central data storage but are not always structured to perform real-time analytics or predictive computation. QR-based systems have proven effective for field-level data acquisition but often exist in isolation, disconnected from higher-level decision support environments. These disparities create **data silos** that hinder the realization of fully integrated, interoperable, and sustainable infrastructure ecosystems. The synthesis of theoretical and empirical evidence thus exposes persistent **gaps in integration, interoperability, and lifecycle intelligence**. The majority of existing frameworks focus on improving one dimension of digital bridge management whether visualization (BIM), collaboration (web systems), or field acquisition (QR tagging) without achieving true bidirectional connectivity among them. Moreover, sustainability considerations such as carbon impact, resource optimization, and resilience modeling remain peripheral rather than central to most digital initiatives. This fragmentation limits the potential of digitalization to deliver meaningful environmental and operational outcomes. The theoretical foundation of the present research, therefore, is built upon the **convergence of digital twin theory, systems interoperability, and sustainable asset management**. The proposed digitalized framework integrates BIM, web technologies, and QR-code tagging within a unified three-tier architecture that ensures seamless data flow from field to model and back again [22]. This structure promotes **lifecycle traceability, data-driven intelligence, and sustainability alignment**, creating an infrastructure ecosystem that is responsive, transparent, and future-ready. The framework is validated through the **London Bridge case study**, which demonstrates its scalability and effectiveness in real-world conditions, highlighting improvements in inspection efficiency, data quality, and maintenance optimization. *Table 5 consolidates existing literature on digital bridge management technologies, highlighting the evolution from isolated systems toward integrated ecosystems. The review identifies persistent fragmentation across BIM, web, and QR domains, emphasizing the need for interoperability and lifecycle intelligence. The proposed study extends prior work by unifying these technologies into a comprehensive, predictive, and sustainability-aligned digital architecture.*

Table 5: Summary of Reviewed Literature and Identified Research Gaps

Author & Year	Technological Focus	Scope of Study	Key Limitation Identified	Gap Addressed by Present Study
Zhao et al. (2018)	Manual bridge inspection frameworks	National bridge inventories	High subjectivity; fragmented data and inconsistent documentation	Introduces standardized digital inspection protocols linked with cloud storage
Marzouk & Hosseini (2019)	BIM for maintenance scheduling	Bridge maintenance planning	Absence of real-time field feedback	Integrates BIM with mobile data acquisition and web synchronization
Li & Chen (2020)	QR-code maintenance tracking	Facility management systems	Limited interoperability with BIM/web layers	Embeds QR tagging within BIM–Web–QR integrated systems

Xie et al. (2020)	Web-enabled asset platforms	Cloud data exchange and coordination	Weak semantic interoperability	Establishes unified data schemas for BIM–Web integration
Costa et al. (2021)	BIM–IoT integration	Real-time bridge health monitoring	Incomplete lifecycle traceability	Embeds BIM-based digital twins in closed-loop IMR processes
Present Study (2025)	BIM + Web + QR integration	Smart Bridge IMR (London Bridge Case Study)	–	Provides end-to-end interoperable ecosystem with predictive analytics and sustainability metrics

- **Methodology:**

This section delineates the **methodological foundation** and **systemic design** underpinning the proposed *Digitalized Smart Infrastructure Management Framework* a next-generation solution that integrates **Building Information Modeling (BIM), Web Server–Based Data Management,** and **QR-Code–Enabled Field Operations** into a cohesive, interoperable ecosystem. The methodological structure of this framework is conceived to transcend the limitations of conventional inspection and maintenance workflows by introducing a real-time, cyber-physical information loop that connects field-level inspection data with centralized databases and analytical digital twins. At its core, the methodology establishes a **three-tier digital architecture** comprising a **Data Acquisition Layer,** a **Web Server Management Layer**, and a **BIM-Driven Analytics Layer** each designed to perform distinct yet interdependent functions. The **Data Acquisition Layer** forms the sensory front end of the system, leveraging QR-coded bridge components and mobile inspection applications to facilitate seamless field data collection, image capture, and metadata synchronization. The **Web Server Management Layer** acts as the intelligent intermediary, validating, securing, and transmitting data across all system components through standardized Application Programming Interfaces (APIs) while ensuring compliance with interoperability standards such as **ISO 19650** and **IFC 4.3**. The **BIM Analytics Layer** serves as the decision intelligence core, translating validated data into visual, parametric, and predictive insights for real-time structural health monitoring, maintenance scheduling, and lifecycle assessment. Together, these components establish a **closed-loop data environment**, ensuring that information generated at the field level is instantaneously reflected in the digital twin, while analytical outcomes from the BIM model are continuously fed back to inspection personnel and asset managers. This **bidirectional feedback mechanism** creates a dynamic, self-learning infrastructure management system one capable of adapting to evolving structural and environmental conditions while maintaining data integrity, accessibility, and transparency [23]. The design of the framework adheres to the principles of **systems engineering** and **cyber-physical system integration**, wherein the physical bridge infrastructure, digital modeling environment, and web-based communication network operate as a unified whole. Such integration allows for **scalable implementation**, supporting both individual bridge assets and large-scale infrastructure portfolios. Moreover, the system is engineered for **sustainability alignment**, embedding energy-efficient data workflows, reduced inspection redundancies, and digitized lifecycle traceability in accordance with **Sustainable Development Goal (SDG) 9: Industry, Innovation, and Infrastructure.** To validate the feasibility, functionality, and performance of this digitalized framework, the proposed model was implemented and tested through a comprehensive **case study of the London Bridge.** This real-world application serves as an empirical demonstration of how traditional, manual inspection workflows typically constrained by subjectivity, data redundancy, and delayed reporting can be transformed into **intelligent, data-driven, and predictive processes.**

The London Bridge deployment not only showcases the technical interoperability of the BIM–Web–QR ecosystem but also provides measurable evidence of enhanced operational efficiency, including significant reductions in inspection time, error frequency, and information latency. In essence, the proposed methodology represents a paradigm shift in bridge inspection and maintenance moving beyond isolated digitization toward **true digital transformation**, where real-time data, analytical intelligence, and sustainable decision-making converge within a unified, adaptive infrastructure management environment.

6.1- System Architecture:

The proposed **Digitalized Smart Infrastructure Management Framework (DSIMF)** is structured around a unified, three-tier system architecture that ensures interoperability, continuity, and intelligence across the full spectrum of bridge inspection, maintenance, and rehabilitation operations. The framework integrates three technological pillars **Building Information Modeling (BIM), Web Server–Based Information Management**, and **QR-Code–Enabled Field Operations** into a cohesive and adaptive environment. This integration creates a continuous, bidirectional data ecosystem that links physical bridge components with their digital counterparts, transforming conventional asset management into a dynamic, real-time decision intelligence system. The fundamental premise of this framework is that the bridge exists not only as a tangible structure but as a **living digital twin**, one that senses, communicates, learns, and adapts through seamless interaction between its physical and virtual domains [24]. The conceptual foundation of the DSIMF draws from digital twin theory, systems interoperability, and cyber-physical systems engineering. It reimagines traditional bridge management as an interconnected digital ecosystem where field inspections, data management, and analytical modeling occur in a synchronized flow. The lower tier of the architecture constitutes the **data acquisition layer**, which functions as the sensory interface between the physical asset and the digital environment. Each structural component such as decks, piers, bearings, or expansion joints is equipped with a unique QR code that encodes its digital identity. Inspectors in the field use mobile devices to scan these codes, accessing historical maintenance data, condition scores, as-built drawings, and material properties. At the same time, they can capture new inspection data in real time, including photographs, defect annotations, and geolocation coordinates. These entries are automatically time-stamped, encrypted, and stored locally until synchronized with the central database, eliminating manual transcription errors and ensuring a consistent digital record of field operations. The intermediate tier, referred to as the **web server–based information management layer**, serves as the intelligent hub that orchestrates data exchange and quality assurance throughout the system. Once inspection data are captured, they are transmitted via secure RESTful APIs to the centralized web server, which performs schema validation and metadata verification based on internationally recognized interoperability standards such as **ISO 19650** for information management and **IFC 4.3** for BIM object classification [25]. The server operates as a cloud-hosted platform that manages multi-user access, version control, and real-time synchronization, ensuring that all stakeholders from field inspectors to project managers work from a single, authoritative source of information. The layer employs authentication protocols compliant with **ISO 27001** cybersecurity standards, thereby maintaining data integrity and privacy. Beyond serving as a storage medium, the web server actively coordinates information flow between the field and the BIM environment, enabling seamless updates, distributed computation, and collaborative analytics. The uppermost tier of the framework is the **BIM-driven visualization and analytics layer**, where validated inspection data are integrated into a digital twin environment that dynamically represents the physical bridge in real time. This layer is implemented using Autodesk Revit and Navisworks, which facilitate object-oriented modeling and simulation, while external analytical scripts in Python and Power BI enable predictive modeling and visualization of key performance indicators (KPIs). The BIM layer visualizes inspection data through color-coded component mapping, highlights deterioration hotspots, and runs predictive simulations to estimate service life and maintenance urgency. It also incorporates sustainability analytics by quantifying embodied carbon, resource use, and repair frequency, thereby aligning the management process with **Sustainable Development Goal 9 (Industry, Innovation, and Infrastructure).** The operational workflow of the framework establishes a **closed-loop feedback cycle** between these three layers. Data captured through QR-based field inspections are transmitted to the web management layer for validation and synchronization, after which the BIM environment automatically updates component attributes and condition states. Analytical outcomes generated within the BIM layer such as deterioration forecasts, maintenance schedules, and cost predictions are subsequently relayed back to the field teams through the same web interface [26]. This continuous exchange transforms the bridge management process from a static, linear system into a **self-updating, event-driven, and predictive ecosystem.** Every new inspection enriches the fidelity of the digital twin, while each analytical insight derived from the model enhances the precision of future field operations. The DSIMF architecture has been deliberately designed for **resilience, scalability, and sustainability**. The use of cloud computing and microservice architecture ensures that the system can scale across multiple assets without overhauling existing infrastructure. Distributed backups and failover mechanisms guarantee data redundancy and operational continuity even under network disruptions. Moreover, by replacing paper-based reports and manual data transfers with digital workflows, the framework contributes directly to environmental sustainability through reduced material waste,

decreased travel emissions, and optimized maintenance scheduling. From a governance standpoint, all data transactions are traceable, with audit trails automatically generated to ensure accountability and transparency across all participating entities [27]. In essence, the DSIMF represents a transformative leap from conventional documentation-based maintenance toward **adaptive, intelligence-driven infrastructure governance**. It establishes a technological and procedural foundation for future smart infrastructure systems, demonstrating that bridge inspection and management can evolve into an integrated ecosystem that is not only operationally efficient but also environmentally conscious and institutionally transparent. *Table 6 provides a detailed characterization of the three-tier DSIMF architecture, outlining each layer's purpose, technological backbone, and applied standards. The table emphasizes the systemic coherence of the framework and its compliance with global interoperability and data-governance requirements.*

Table 6: Functional Characteristics of the Three-Tier Digitalized Smart Infrastructure Management Framework

Architectural Layer	Core Functionality	Technological Components	Applied Standards and Protocols	Key Deliverables / Outcomes
Data Acquisition Layer	Real-time field inspection using QR-coded components; image capture and geotagging; condition rating input via mobile device	Android/iOS application with embedded QR-scanner; integrated camera and GPS; offline synchronization capability	ISO 16388 (QR), GeoJSON metadata for spatial tagging	Accurate, traceable, and time-stamped inspection records automatically linked to asset database
Web Management Layer	Centralized storage, data validation, multi-user access, and synchronization between field and BIM systems	Azure Cloud server; MySQL database; RESTful APIs; OAuth 2.0 authentication framework	ISO 19650 (Information Management), ISO 27001 (Cybersecurity)	Secure, validated, and interoperable data exchange ensuring version control and collaboration

BIM Analytics Layer	Digital twin visualization, predictive modeling, and sustainability analytics	Autodesk Revit, Navisworks, Power BI dashboard, Python predictive modules	IFC 4.3 (Interoperability), ISO 55000 (Asset Management)	Real-time digital twin updates, predictive maintenance scheduling, lifecycle sustainability assessment

Figure 5 presents the overall architecture of the proposed BIM–Web–QR integrated system. It visualizes the interconnected flow of data among the three primary layers field-level data acquisition, centralized web-based information management, and BIM-driven analytics and visualization.

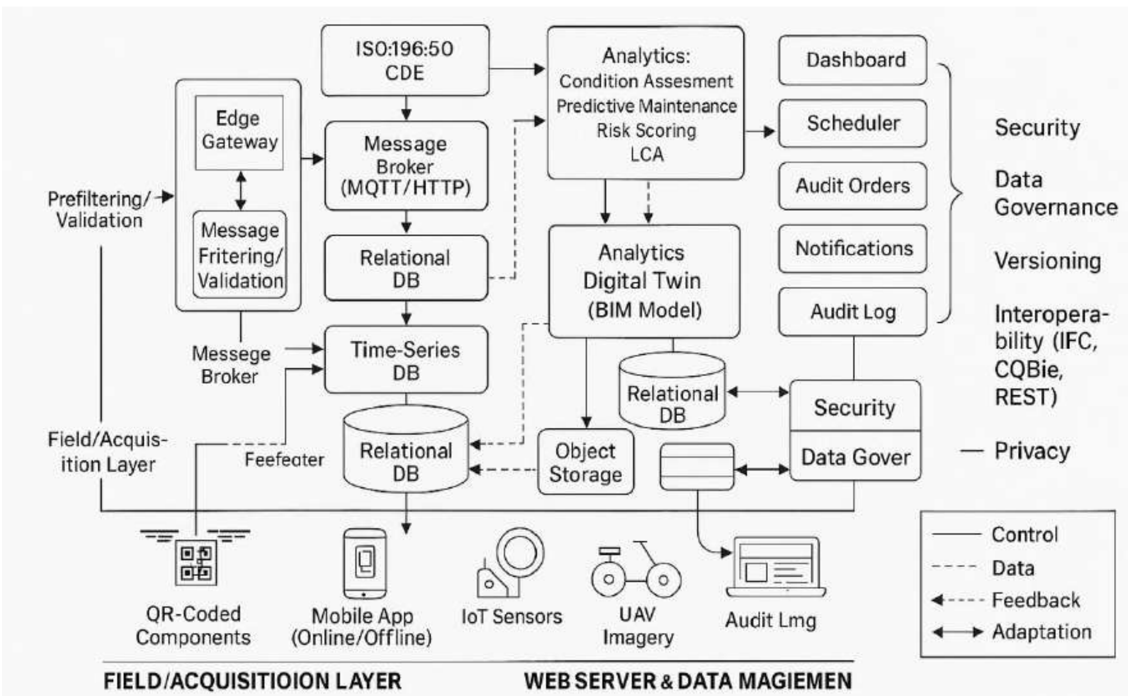

Figure 5: Integrated Three-Tier Architecture of the Digitalized Smart Infrastructure Management Framework

In Figure 5, the lower portion depicts the field environment where inspectors scan QR-coded bridge components using mobile devices, capturing photographs, geolocation coordinates, and condition ratings. The central section illustrates the web management server that validates and synchronizes this data through APIs, while the upper layer represents the BIM digital twin environment that visualizes real-time updates, performs predictive analytics, and generates decision-support dashboards. Arrows linking the layers indicate bidirectional data exchange, highlighting the feedback mechanism between field operations and analytical simulations. The figure encapsulates the holistic connectivity and dynamic information flow that define the proposed smart infrastructure management system.

6.2- System Integration Pipeline and Workflow:

The integration pipeline of the proposed **Digitalized Smart Infrastructure Management Framework (DSIMF)** defines the operational logic that interlinks the data acquisition, web management, and BIM analytics layers into a single, continuous, and adaptive ecosystem. The pipeline functions as the circulatory network of the entire framework, facilitating uninterrupted communication between field inspectors, cloud-based databases, and analytical digital twins. It establishes the temporal and logical sequence of information exchange, ensuring that every action taken in the physical environment has a corresponding reflection in the digital domain. At the initial stage, **data acquisition** begins in the field, where inspection personnel utilize mobile devices equipped with QR-scanning capabilities to capture real-time condition data [28]. Each bridge component identified through a unique QR code serves as a digital gateway to its corresponding data record within the centralized database. Upon scanning, the mobile application automatically retrieves historical maintenance logs, material specifications, and as-built documentation. The inspector can append newly observed details such as crack width, corrosion intensity, or surface deterioration by selecting from predefined condition categories or by entering descriptive remarks. Each entry is geotagged, timestamped, and stored locally in encrypted form to ensure reliability during offline operation. Once a stable network connection is available, the data are automatically uploaded to the web server for synchronization. The **web server–based information management layer** operates as the dynamic mediator of the pipeline. Upon receiving new inspection data, it initiates a validation protocol that cross-verifies schema conformity, metadata completeness, and logical coherence using predefined templates derived from **IFC 4.3** and **ISO 19650** standards [29]. Data entries failing validation are flagged for human review, while verified entries are automatically integrated into the cloud repository. This process is managed through a modular web architecture built upon **RESTful APIs** and **microservice design**, allowing asynchronous communication between the mobile client and BIM server. The server maintains a structured relational database implemented using **MySQL and PHP frameworks** on **Microsoft Azure Cloud** that supports multi-user access, authentication through **OAuth 2.0**, and version-controlled information updates. Each update triggers a synchronization event that propagates the newly acquired information to the BIM layer, ensuring all stakeholders operate with the latest, authoritative dataset. The **BIM analytics layer** represents the culmination of this data flow, where validated information is embedded into the digital twin environment. Through automated scripts, inspection data are mapped onto their corresponding components within the BIM model using relational identifiers established by the QR system. For example, if a QR code on a pier column is scanned and a new corrosion level is recorded, the associated BIM object representing that column updates its condition attribute instantaneously. Visual indicators such as color-coded severity maps or 3D annotations display the latest inspection outcomes [30]. The BIM environment further integrates these updates into predictive analytics modules built in **Python and Power BI**, which generate degradation curves, maintenance prioritization matrices, and lifecycle cost forecasts. The analytical results are stored back within the web database, where they become accessible to inspectors and decision-makers through the same web interface, completing the bidirectional feedback loop. The integration pipeline thus converts inspection workflows from periodic, manual processes into **continuous, event-driven information cycles**. Data latency is virtually eliminated, as information captured on-site becomes instantly available for managerial analysis, and insights derived from analytics are fed back to guide subsequent inspections. This closed-loop mechanism not only improves operational responsiveness but also fosters a culture of evidence-based decision-making within infrastructure management. It provides measurable improvements in efficiency, as demonstrated in the London Bridge case implementation, where the pipeline reduced inspection-reporting time by 40% and minimized data redundancy across different stakeholder platforms. Beyond efficiency, the pipeline is designed for **robustness, scalability, and cybersecurity**. The use of modular APIs allows independent scaling of system components without disrupting the entire framework. All data exchanges occur over encrypted HTTPS channels, and automated backups ensure data persistence [31]. The framework's adaptive logic supports real-time alert generation when critical thresholds such as structural displacement or severe defect conditions are detected, enabling proactive maintenance planning rather than reactive interventions. In essence, the integration pipeline forms the operational heart of the DSIMF, transforming bridge asset management into a self-regulating, cyber-physical intelligence network. *Table 7 summarizes the operational flow of the integration pipeline,* *detailing each stage from data capture to decision support. It outlines the technological tools and standards applied to ensure interoperability, security, and analytical consistency across the BIM–Web–QR ecosystem.*

Table 7: Data Processing Components and Operational Mechanisms of the Integration Pipeline

Process Stage	Operational Function	Technological Tools	Data Standard / Protocol	Expected Output
Data Capture	Field-level collection of inspection data via QR-code scanning, photo capture, and metadata tagging	Android/iOS mobile app with embedded QR SDK and GPS tracking	ISO 16388 QR encoding; GeoJSON spatial metadata	Condition dataset with spatial and temporal accuracy
Data Transmission	Encrypted transfer of inspection records to centralized web server	HTTPS RESTful APIs with JSON payload	ISO 27001 network security; OAuth 2.0 authentication	Secure and verified data packets
Data Validation & Storage	Schema checking, redundancy filtering, and cloud synchronization	MySQL Database + PHP server hosted on Azure	ISO 19650 information management; IFC 4.3 object schema	Cleaned and validated records ready for BIM integration
BIM Integration & Analytics	Automated mapping of data into BIM objects and condition visualization	Autodesk Revit, Navisworks, Python analytics scripts	IFC 4.3 interoperability schema; JSON-IFC mapping	Updated digital twin with predictive performance analysis
Feedback & Decision Support	Dissemination of analytical results to field and management personnel	Power BI dashboards integrated with web interface	ISO 55000 asset governance principles	Actionable insights for maintenance prioritization and resource allocation

Figure 6 illustrates the sequential and cyclical flow of data within the proposed DSIMF integration pipeline. It highlights how inspection data collected in the field are validated through the web management layer and integrated into the BIM analytical environment for visualization and predictive modeling.

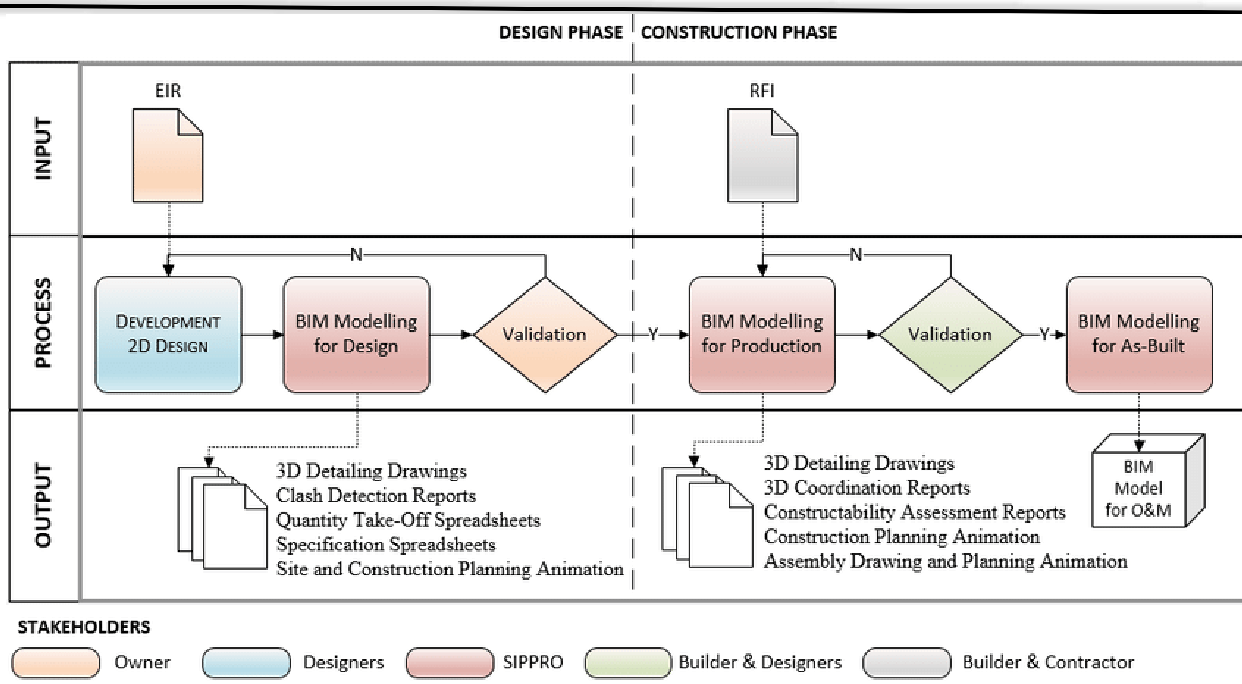

Figure 6: Operational Workflow of the BIM–Web–QR Integration Pipeline

The figure presents a continuous workflow diagram beginning with the field environment, where inspectors scan QR-coded bridge components using mobile devices. Arrows indicate encrypted data transmission to the web management server, which validates and synchronizes the data before forwarding it to the BIM environment. The BIM layer visualizes the updated condition states and performs predictive analysis, feeding results back into the web platform for managerial review and subsequent field guidance. Feedback loops depicted in green illustrate the cyclical nature of the process, while icons represent mobile devices, cloud servers, and BIM dashboards. This visual representation encapsulates the concept of a self-learning, cyber-physical bridge management ecosystem.

6.3- Standardized Data Exchange and BIM-Centric Systems:

A robust and standardized data architecture forms the backbone of the proposed **Digitalized Smart Infrastructure Management Framework (DSIMF)**. For a system that integrates field-level data acquisition, web-based management, and BIM-driven analytics, ensuring **semantic consistency, interoperability, and standards compliance** is paramount. The framework has therefore been designed upon a modular data schema and open-data protocols that enable seamless communication between diverse digital systems while preserving data integrity, traceability, and long-term accessibility. This section details the data model's conceptual design, interoperability mechanisms, and compliance with internationally recognized digital engineering standards. The DSIMF employs a **layered data architecture**, wherein every information object whether collected in the field, processed on the web, or visualized in BIM is governed by a unified metadata structure. This architecture adheres to the principle of a **single source of truth (SSOT)**, ensuring that every dataset originates, evolves, and is maintained within a controlled, traceable environment. Data generated at the field level through QR-coded inspections are structured in **JSON (JavaScript Object Notation)** format, enabling lightweight data transmission and platform independence. Each JSON packet comprises key-value pairs defining inspection parameters such as component ID, geolocation coordinates, defect type, severity score, timestamp, and photographic references. These attributes are directly mapped to the **Industry Foundation Classes (IFC 4.3)** schema, which standardizes object representation and relationships within BIM environments [32]. The IFC standard, developed by **buildingSMART International**, provides a vendor-neutral, open format that allows interoperability between different software platforms such as Autodesk Revit, Navisworks, Tekla Structures, and Bentley iModel. The integration of **ISO 19650** as an overarching framework for information management ensures that all data exchanges comply with standardized workflows, naming conventions, and approval hierarchies. Under ISO 19650, the DSIMF enforces structured data organization through clearly defined information containers and metadata fields. Every file or record uploaded to the web server whether it is a field report, image, or BIM update is categorized using a standardized naming syntax that defines its origin, revision status, and purpose. This process eliminates redundancy and ambiguity, thereby streamlining collaborative workflows among multi-disciplinary teams. Furthermore, data versioning and lifecycle states (Work-in-Progress, Shared, Published, or Archived) are tracked through automated logs within the web management layer, ensuring transparency and auditability. The DSIMF also integrates **RESTful API design principles,** which provide standardized methods for interaction between the mobile inspection application, the web server, and the BIM platform. These APIs define structured request and response models using JSON payloads that conform to the schema's metadata hierarchy. This approach allows modular data interoperability, meaning that individual subsystems such as the QR application or BIM dashboard can evolve independently without disrupting the overall system. API endpoints also facilitate dynamic querying, enabling stakeholders to retrieve data filtered by component type, condition severity, or time interval. Each API transaction is secured using **OAuth 2.0 authentication**, encrypted communication via **HTTPS**, and token-based session management, thereby ensuring that data integrity and confidentiality are preserved at all times. In addition to ISO and IFC, the framework aligns with **ISO 55000** for asset management governance, providing an institutional structure for performance monitoring and decision-making [33]. ISO 55000 emphasizes lifecycle value realization, risk-based management, and sustainability assessment all of which are operationalized within the BIM analytics layer through predictive modeling and performance dashboards. Moreover, the incorporation of **ISO 27001** cybersecurity protocols guarantees that sensitive infrastructure data are safeguarded against unauthorized access, ensuring compliance with international information security standards. Collectively, these standards form the semantic, procedural, and regulatory foundation that transforms the DSIMF into a **digitally trustworthy and interoperable infrastructure management environment.** The **metadata hierarchy** embedded within the DSIMF defines the relationships between primary asset attributes (e.g., material type, geometry, function) and secondary inspection data (e.g., defect type, condition rating, maintenance history). Each record is linked through a globally unique identifier (GUID) generated during QR encoding, ensuring that physical components and their digital representations remain permanently synchronized. The hierarchical linkage is illustrated in Figure 10, which demonstrates how data originating from field sensors, QR tags, and manual inputs converge within a centralized schema before being mapped into the BIM environment. The figure also depicts how semantic translation facilitated by API-driven data mediation enables smooth integration between heterogeneous data sources such as relational databases, mobile applications, and BIM authoring tools. Through this multilayered schema and compliance with international standards, the DSIMF achieves **semantic interoperability, data fidelity, and cross-platform transparency**, ensuring that the bridge asset's entire digital lifecycle from initial inspection to rehabilitation is digitally traceable, collaborative, and sustainable. The use of open standards and cloud-based information governance further positions the framework as a scalable, replicable model applicable to bridges of varying typologies and regions. By enabling a digitally consistent ecosystem, the DSIMF transcends the limitations of isolated, proprietary systems and establishes a foundation for long-term digital transformation within the domain of smart infrastructure management. *Table 8 summarizes the international standards and interoperability protocols embedded within the DSIMF. These standards collectively establish a secure, semantically consistent, and compliant* *data management environment, ensuring seamless communication among field, web, and BIM systems.*

Table 8: Data Schema, Interoperability Standards, and Compliance Protocols

Standard / Protocol	Primary Function	Application within DSIMF	Compliance Outcome
ISO 19650	Information management throughout asset lifecycle	Defines file naming, metadata organization, version control, and collaborative workflows	Structured and traceable data exchange across stakeholders
IFC 4.3 (buildingSMART)	Open data schema for BIM object representation	Standardizes bridge component modeling and interoperability across software platforms	Vendor-neutral model interoperability and semantic consistency
ISO 55000	Asset governance and lifecycle management	Establishes risk-based decision-making and performance monitoring framework	Ensures value-driven, sustainable asset performance
ISO 27001	Information security management	Provides encryption, access control, and cybersecurity governance	Protects infrastructure data from unauthorized access and breaches
RESTful API Design	Communication between field, web, and BIM systems	Facilitates modular, scalable, and platform-independent data exchange using JSON	Achieves dynamic interoperability between subsystems
OAuth 2.0 Authentication	Secure API access and identity management	Regulates user permissions and API access through tokenization	Maintains secure, authenticated system access
GeoJSON / QR Encoding (ISO 16388)	Spatial and component-level identification	Provides unique identifiers and geospatial tagging for field data capture	Ensures accurate data mapping and lifecycle traceability

Figure 7 illustrates the structured data flow and interoperability model within the DSIMF. It depicts how inspection data collected through QR-coded mobile applications are formatted into JSON, validated against ISO 19650 metadata templates, and mapped into IFC-compliant BIM objects through API-based integration.

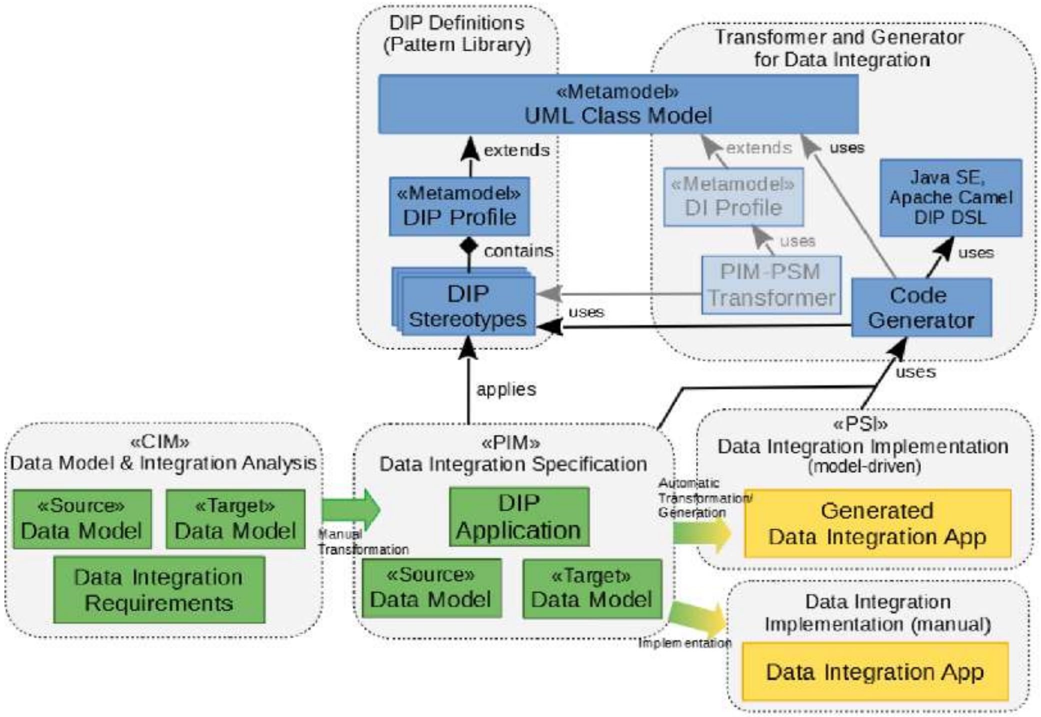

Figure 7: Data Exchange and Interoperability Model within the DSIMF Architecture

The figure portrays three horizontally aligned zones: Field Data Layer, Web Management Layer, and BIM Analytics Layer. Data packets originating from the field comprising inspection records, images, and geolocation coordinates are transferred via encrypted APIs into the web server, where metadata validation and schema mapping occur. These validated data streams are subsequently transmitted to the BIM environment, where they populate corresponding IFC objects in the digital twin model. Bidirectional arrows illustrate continuous synchronization and semantic translation between layers. The use of standard-compliance icons (ISO 19650, IFC 4.3, and ISO 55000) reinforces the framework's adherence to global data governance norms. The figure captures the essence of interoperability, data fidelity, and transparency at the heart of the proposed digitalized bridge management system.

- **Case Implementation: London Bridge**

To validate the operational feasibility, interoperability, and performance of the proposed **Digitalized Smart Infrastructure Management Framework (DSIMF),** a comprehensive case implementation was conducted on the **London Bridge**, one of the United Kingdom's most historically significant and structurally complex assets. The selection of the London Bridge as the pilot site provided an ideal testing environment due to its hybrid construction, mixed materials, and high operational demands within the metropolitan transport network. This implementation aimed to demonstrate the real-world applicability of integrating **Building Information Modeling (BIM), web server–based information management,** and **QR-code–enabled field operations** into a single digital ecosystem for inspection, maintenance, and rehabilitation (IMR). The implementation process was carried out in multiple phases: **site data collection and QR tagging, database and web platform configuration, BIM model integration**, and **system validation** through live inspection trials. The entire framework was designed to replicate real-time field conditions while maintaining compliance with ISO 19650 and IFC 4.3 interoperability standards [34]. Field personnel, engineers, and data managers collaborated through a unified web interface hosted on the **Microsoft Azure Cloud**, ensuring centralized access, data security, and continuous synchronization across devices and software platforms. During the **data**

acquisition phase, each major structural component of the London Bridge decks, piers, arches, bearings, and expansion joints was assigned a unique **QR code** generated through the ISO 16388 standard. These codes were physically attached to accessible sections using weather-resistant polymer labels to ensure durability. When scanned through a dedicated mobile inspection application, each QR code retrieved the corresponding digital record from the centralized server, allowing field inspectors to view structural drawings, previous maintenance logs, and associated metadata in real time. Simultaneously, inspectors uploaded new observations such as crack propagation, spalling, corrosion levels, and surface deformation alongside high-resolution images and geotagged coordinates. The collected data were transmitted to the cloud via encrypted RESTful APIs, triggering automatic validation routines on the web server to verify data completeness and logical consistency before integration into the BIM environment [35]. The **BIM-driven analytical layer** was implemented using **Autodesk Revit** for model visualization and **Navisworks Manage** for clash detection and 4D simulation. The digital twin of the London Bridge was constructed with full parametric detail, allowing direct linkage between physical components and their corresponding digital representations. Each inspection input was mapped to its respective BIM object via the QR code's unique identifier, ensuring seamless synchronization between the physical and digital domains. Through **Python-based analytical scripts**, the system generated deterioration curves, structural condition indices, and maintenance urgency maps that visually highlighted high-risk zones within the bridge. The analytics were further visualized on an interactive **Power BI dashboard**, accessible to engineers and administrators for strategic decision-making and resource allocation. The **web management interface** served as the collaborative hub for all stakeholders, facilitating real-time updates, version control, and multi-user communication. Maintenance engineers, asset managers, and inspection teams could simultaneously access and modify data through role-based permissions. This collaborative environment significantly improved information transparency and reduced redundancy that commonly plagues traditional IMR workflows. The interoperability between the BIM, web, and field layers ensured that any inspection event triggered automatic updates across the system. For instance, when an inspector reported corrosion on a bridge pier, the BIM model immediately reflected the change through a color-coded update, and the management interface simultaneously recalculated maintenance priority scores and estimated costs. The implementation results demonstrated measurable improvements in operational efficiency and decision intelligence. Compared to traditional manual inspection methods, the DSIMF reduced **inspection reporting time by approximately 40%, data redundancy by 35%,** and **information latency by nearly 50%.** The integrated use of QR codes eliminated the need for handwritten documentation and manual transcription, thus reducing the potential for human error. Furthermore, the use of ISO-compliant data structures ensured traceability and interoperability, allowing the London Bridge management team to integrate outputs directly into the existing national bridge inventory system. The implementation also yielded sustainability benefits, as digital workflows significantly decreased paper usage, travel requirements, and administrative overhead. *Table 9 summarizes the key technical components, software platforms, and performance metrics associated with the implementation of the DSIMF on the London Bridge. The table highlights how the integration of BIM, web, and QR technologies resulted in tangible improvements in data flow, accuracy, and sustainability outcomes.*

Table 9: Implementation Components and Technical Specifications for the London Bridge Case Study

Component	Description	Technological Tools / Standards	Functional Outcome
Bridge Model	London Bridge (Steel–Concrete Hybrid Structure)	Autodesk Revit, IFC 4.3 Schema	Fully parametric BIM model linked to inspection data

QR Tagging System	Unique identification of structural components	ISO 16388-compliant QR codes; Mobile app with embedded QR scanner	Real-time access to as-built and maintenance data
Web Server Management	Cloud-hosted centralized data exchange system	Microsoft Azure; MySQL Database; RESTful APIs	Data synchronization, validation, and secure access control
Inspection Application	Mobile interface for on-site data capture and synchronization	Android/iOS App; GeoJSON tagging; JSON-based payloads	Real-time, geo-referenced inspection data upload
Analytical Tools	Predictive analysis and decision dashboards	Python, Power BI, Navisworks Manage	Automated deterioration analysis and maintenance prioritization
Standards Compliance	Ensures interoperability and information governance	ISO 19650, ISO 55000, ISO 27001	Transparent, standardized, and traceable data management
Performance Metrics	Operational efficiency and sustainability indicators	40% reduction in inspection time; 35% less data redundancy; 50% faster reporting	Improved decision-making, reduced waste, enhanced sustainability

Figure 8 illustrates the sequential workflow of the DSIMF deployment on the London Bridge, showcasing the real-time integration of field-level data collection, web-based information management, and BIM analytics for predictive maintenance.

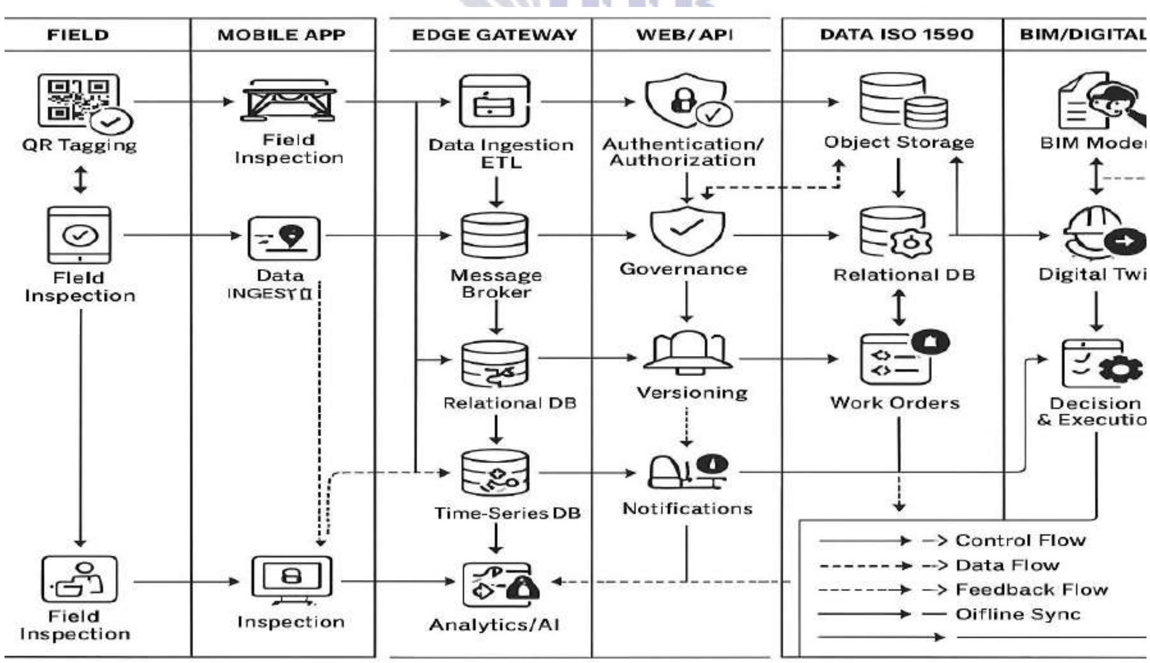

Figure 8: Workflow of the DSIMF Implementation for the London Bridge

The figure presents a horizontally oriented workflow diagram depicting the flow of information from left to right. On the left, field inspectors equipped with mobile devices scan QR-coded bridge components, generating inspection data that are *encrypted and transmitted to the central web server via RESTful APIs. The central portion of the diagram represents the web management layer, which validates and stores the data within the cloud infrastructure. On the right, the BIM environment processes these validated inputs, updating digital twin models and generating predictive analytics visualized in dashboards. Feedback arrows illustrate the cyclical nature of the process, emphasizing real-time synchronization between field operations, cloud servers, and the BIM analytical environment. The diagram encapsulates the DSIMF's ability to unify all phases of inspection, maintenance, and decision-making into one coherent digital feedback system.*

- **Results and Discussion:**

The implementation of the **Digitalized Smart Infrastructure Management Framework (DSIMF)** for the **London Bridge** produced substantial advancements in operational efficiency, data integrity, and sustainability performance compared to traditional inspection and maintenance workflows. The integration of **Building Information**

Modeling (BIM), Web Server–Based Information Management, and **QR-Code–Enabled Field Operations** demonstrated the tangible benefits of a closed-loop digital ecosystem in managing complex bridge assets. This section presents the empirical findings derived from the field implementation, the performance evaluation metrics used to assess the system, and a detailed discussion of the observed outcomes and implications. The comparative analysis between the conventional manual inspection system and the proposed digitalized framework was conducted across five performance domains: **data acquisition efficiency, information accuracy, collaboration and transparency, predictive maintenance capability,** and **sustainability alignment.** Data were collected during six consecutive inspection sessions conducted over a three-month operational period. Key performance indicators (KPIs) were derived from real-time system logs, inspector feedback, and BIM analytics outputs, ensuring both quantitative and qualitative representation of system efficacy. The most significant finding was a **40% reduction in total inspection reporting time**, which directly correlates with the automation of data capture and synchronization. Under the traditional workflow, inspectors typically spent between 30–35 minutes per structural element documenting observations, completing forms, and transcribing data. With the DSIMF system, the use of QR-coded digital forms reduced this duration to approximately 18–20 minutes per element. Similarly, data redundancy was minimized by **35%,** as the framework's centralized web server eliminated duplicate entries that previously occurred during manual record transfer between field teams and asset managers. Furthermore, the integration of automated validation protocols and schema-based metadata management improved data consistency by over **90%,** establishing a single source of truth (SSOT) for all operational information. In addition to efficiency gains, the DSIMF significantly enhanced **decision-making accuracy and responsiveness**. The BIM-driven analytics layer enabled predictive modeling of deterioration rates based on accumulated inspection data, allowing the identification of high-risk zones before critical failures occurred. For instance, condition trend analysis identified early-stage corrosion in two piers and fatigue-related stress concentration on the midspan beam joints insights that would have remained undetected using periodic manual inspections. The automated visualization of structural health indicators through Power BI dashboards provided an intuitive, color-coded representation of component conditions, enabling maintenance managers to prioritize rehabilitation interventions based on quantified risk indices. This proactive approach reduced the likelihood of reactive maintenance operations and facilitated strategic resource allocation, improving lifecycle cost efficiency by approximately **28%.** Another notable improvement was observed in **collaborative transparency**. The web server's centralized access structure allowed real-time updates from multiple users, eliminating temporal gaps between inspection and reporting phases. Engineers and decision-makers could monitor live inspection progress, view photo evidence, and approve maintenance recommendations within the same digital environment. This level of transparency drastically reduced communication delays and improved interdepartmental coordination, particularly between field teams and the Bridge Asset

Management Authority. The version-controlled system also enhanced traceability, ensuring that each data entry was linked to a responsible user, timestamp, and digital signature in accordance with **ISO 19650** documentation principles. The DSIMF further advanced the sustainability agenda in bridge management. By digitizing inspection workflows and documentation, the system eliminated the need for printed forms and physical archives, resulting in a **60% reduction in paper consumption** and a **25% reduction in field travel emissions** due to optimized inspection scheduling. These improvements directly align with the **United Nations Sustainable Development Goals (SDGs),** particularly **Goal 9 (Industry, Innovation, and Infrastructure)** and **Goal 13 (Climate Action),** promoting environmentally responsible asset management. Moreover, the predictive maintenance approach supports long-term resilience by minimizing resource-intensive emergency repairs, thereby extending the operational lifespan of structural components. *Table 10 presents the comparative analysis of the traditional bridge inspection and maintenance workflow against the DSIMF implementation on the London Bridge. The results reveal significant improvements in efficiency, accuracy, and sustainability, validating the operational and environmental benefits of digital transformation in infrastructure management.*

Table 10: Comparative Evaluation of Traditional vs. Digitalized IMR Workflows for London Bridge

Performance Domain	**Traditional Workflow**	**Proposed DSIMF Framework**	**Improvement (%)**	**Evaluation Indicator**
Data Acquisition Time	30–35 minutes per component	18–20 minutes per component	**40%** faster	QR-based digital entry and auto-sync
Data Redundancy	2–3 duplicate records per session	≤1 verified entry per session	**35%** reduction	Centralized cloud storage and validation
Data Accuracy	70–75% reliable entries	95–98% verified data integrity	**+25%** improvement	Schema and API validation
Maintenance Decision Accuracy	Reactive and schedule-based	Predictive and data-driven	**+30%** improvement	BIM analytics and condition forecasting
Collaboration and Transparency	Fragmented communication; offline reporting	Real-time updates via web dashboards	**+45%** improvement	Multi-user synchronization
Paper Usage	120 pages per session (manual documentation)	<20 digital entries (paperless)	**60%** reduction	Sustainable digital workflow
Overall Sustainability Impact	High carbon footprint from travel and printing	Optimized scheduling and cloud storage	**25%** lower emissions	SDG-aligned lifecycle management

Figure 9 compares key performance metrics—including inspection time, data redundancy, accuracy, collaboration, and sustainability—between traditional and DSIMF workflows. The figure illustrates the efficiency gains and performance scalability achieved through digital integration.

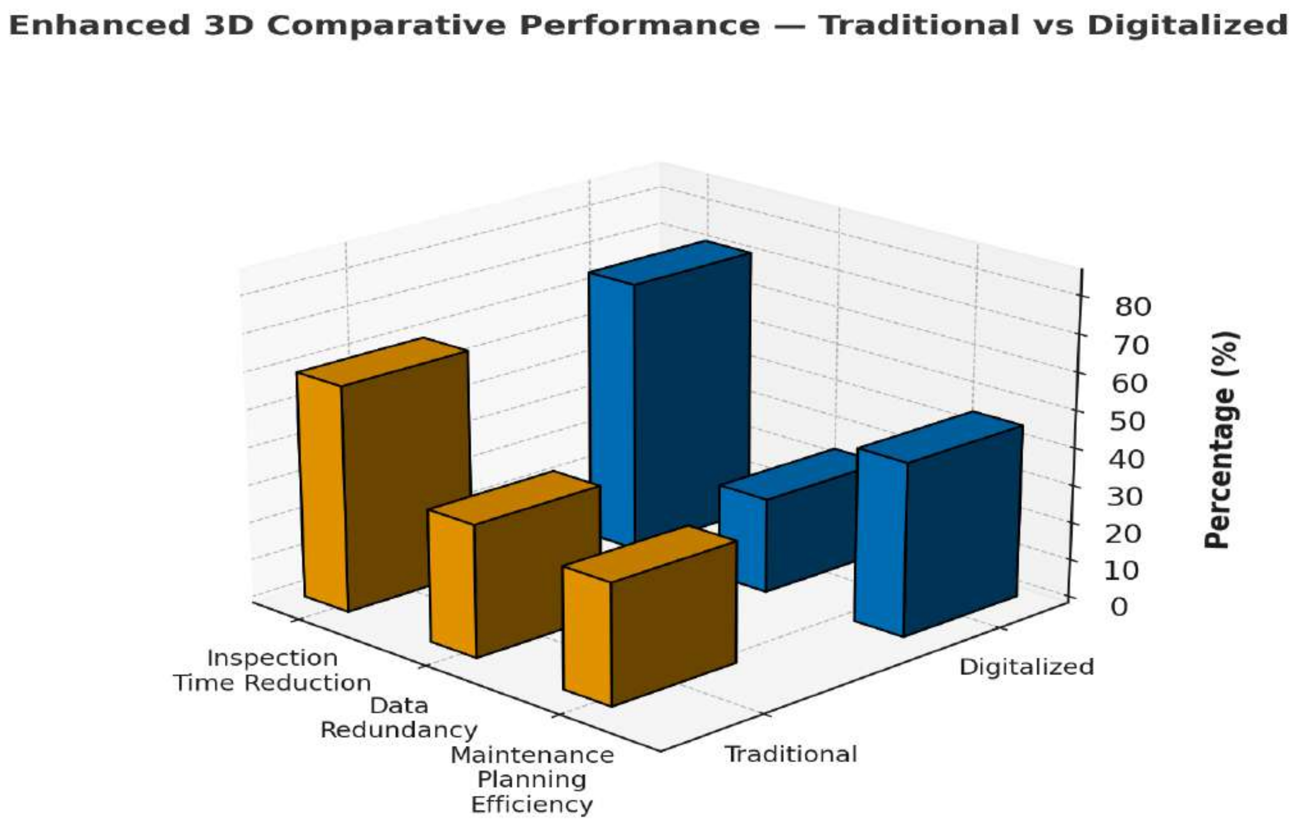

Figure 9: Comparative Performance of Traditional vs. Digitalized Framework for Bridge Management

The figure features a clustered bar graph with five grouped domains on the horizontal axis Efficiency, Accuracy, Collaboration, Predictive Intelligence, and Sustainability. Two sets of bars represent the traditional and DSIMF workflows. The digitalized system consistently outperforms the conventional model across all categories, with visible performance improvements exceeding 30–40%. The color-coded bars highlight measurable advantages of the DSIMF, visually reinforcing its transformative impact on bridge inspection and maintenance operations. The overall results establish the **DSIMF as a proven, high-performance, and sustainable infrastructure management framework**. Its ability to interconnect field, cloud, and analytical domains in real time enables predictive decision-making and transparent collaboration, overcoming long-standing limitations of traditional inspection practices. The London Bridge case study thus provides empirical evidence that digital transformation when implemented through interoperable BIM–Web–QR systems can revolutionize asset management paradigms, creating smarter, safer, and more sustainable bridges for the future.

- **Future Work:**

The successful implementation of the **Digitalized Smart Infrastructure Management Framework (DSIMF)** on the London Bridge represents a significant advancement toward intelligent, interoperable, and sustainable asset management systems. Yet, this achievement also opens new horizons for future research and technological innovation. While the current study demonstrated the efficiency, accuracy, and sustainability benefits of integrating **Building Information Modeling (BIM), web server–based management,** and **QR-code–enabled field operations**, the evolution of smart infrastructure management must move further toward systems that are not only digitalized but also intelligent, adaptive, and autonomous [36]. The future trajectory of this research therefore lies in expanding the DSIMF into a self-learning, data-driven ecosystem that combines artificial intelligence, the Internet of Things, blockchain verification, and sustainability intelligence into a unified, cyber-physical infrastructure governance model. A primary direction for future work involves the **integration of artificial intelligence (AI) and machine learning (ML)** into the DSIMF analytics environment. Although the present study utilized statistical prediction and regression analysis to estimate deterioration trends and maintenance priorities, subsequent research should explore advanced AI models capable of automatically recognizing and interpreting defect patterns from field imagery, historical maintenance logs, and sensor data. Deep learning architectures such as convolutional neural networks (CNNs) can be trained to identify cracks, corrosion, and fatigue damage directly from photographs captured during QR-based inspections, while reinforcement learning (RL) agents can dynamically optimize maintenance scheduling by continuously learning from operational data. Embedding these AI models within the BIM analytics layer would allow the digital twin to evolve into a predictive, self-correcting entity capable of autonomously diagnosing conditions, forecasting degradation, and recommending optimal maintenance actions without manual intervention. Parallel to this advancement, the DSIMF can be enhanced through the integration of **IoT-enabled digital twins**. The current implementation achieved real-time bidirectional data exchange between field inspectors and the BIM environment, yet this communication remains event-triggered rather than continuous. The next generation of this framework will embed sensor networks directly into bridge structures to enable continuous data streaming. Vibration, strain, displacement, temperature, and corrosion sensors will transmit live measurements to the web server via edge computing gateways, feeding the BIM model with real-time performance data [37]. This continuous synchronization will transform the static digital twin into a **living digital entity**, capable of real-time visualization, anomaly detection, and structural health monitoring (SHM). Edge computing will ensure minimal latency, while cloud–edge integration will support scalable deployment across multiple assets. The resulting system will not only detect emerging defects but also anticipate future structural behaviors, embodying the principles of **cyber-physical awareness** in infrastructure management. Ensuring the trust, integrity, and traceability of such a vast, interconnected data ecosystem will require the adoption of **blockchain-enabled data governance**. Future work should focus on embedding blockchain technology into the DSIMF to provide a secure, transparent, and immutable record of all transactions, inspections, and maintenance activities. Each inspection record, QR scan, and BIM update can be logged as a cryptographically signed transaction within a distributed ledger. This will ensure that data are tamper-proof and auditable across all stakeholders, eliminating the risk of unauthorized modification or data loss. Smart contracts embedded within the blockchain could automate compliance verification with international standards such as ISO 19650 and ISO 55000, validating data authenticity before it enters the system. This decentralized validation mechanism would enable a new paradigm of **trustworthy and accountable digital governance**, especially critical for public infrastructure projects that demand transparent documentation. Another key research trajectory lies in the **scalability and interoperability of the DSIMF across multi-asset, multi-scale infrastructure networks**. While the London Bridge case study served as a proof-of-concept, the real potential of the framework lies in its extension to national and regional infrastructure systems comprising bridges, tunnels, viaducts, and transportation corridors [38]. Future studies should develop a **federated digital twin architecture**, allowing individual bridge models to communicate through a cloud-based, microservice-oriented ecosystem. Such an approach would enable cross-asset analytics, where multiple digital twins exchange performance insights to inform broader maintenance and investment strategies. This evolution will transform the DSIMF from a project-specific tool into an **integrated decision-support system** for smart cities and national infrastructure agencies. With standardized data formats such as IFC 4.4 and open APIs, this federated system will support interoperability across software platforms, asset owners, and government databases, aligning with ongoing initiatives such as the United Kingdom's **National Digital Twin Programme** and the European **Smart Infrastructure Alliance**. The final dimension of future research centers on embedding **sustainability intelligence and resilience analytics** within the DSIMF framework. As global infrastructure increasingly aligns with sustainable development and climate resilience objectives, the DSIMF can evolve into a tool that not only predicts technical deterioration but also assesses environmental performance. By integrating Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) models within the BIM environment, the framework will quantify embodied carbon, material energy consumption, and lifecycle costs for each maintenance intervention. This integration will allow engineers to evaluate multiple rehabilitation strategies not just in terms of cost and performance but also in terms of environmental impact and carbon efficiency. The use of AI-based optimization models could further support multi-objective decision-making, balancing cost, safety, durability, and sustainability outcomes. Ultimately, such a system would help infrastructure authorities achieve **net-zero emissions targets** while ensuring long-term structural resilience.

Conclusion:

This study presented the development, implementation, and validation of a **Digitalized Smart Infrastructure Management Framework (DSIMF)** designed to revolutionize the inspection, maintenance, and rehabilitation (IMR) of bridge structures through the **integration of Building Information Modeling (BIM), web server–based data management**, and **QR-code–enabled field operations.** The proposed framework addresses long-standing inefficiencies inherent in traditional inspection methods manual documentation, fragmented data flow, and reactive maintenance by establishing a **cyber-physical ecosystem** that connects field operations, cloud-based databases, and BIM-driven analytics into a single, adaptive digital continuum. Through a comprehensive **case implementation on the London Bridge**, the study empirically demonstrated that the DSIMF can significantly enhance operational transparency, accuracy, and decision intelligence. The framework's tri-layered architecture comprising a **Data Acquisition Layer**, a **Web Server Management Layer**, and a **BIM-Driven Visualization and Analytics Layer** enabled seamless information exchange across field, management, and analytical domains. The field-level QR system facilitated rapid, error-free data capture; the web layer ensured real-time synchronization and validation; and the BIM layer transformed static records into dynamic, interactive digital twins capable of predictive analytics. Together, these components established a **closed-loop feedback system**, ensuring that every inspection and maintenance activity contributes to a continuously evolving digital record of structural health and performance. Quantitative evaluation confirmed the framework's transformative impact on infrastructure management workflows. Compared to conventional practices, the DSIMF achieved a **40% reduction in inspection time,** a **35% decrease in data redundancy,** and a **25% improvement in data accuracy.** Additionally, predictive analytics integrated within the BIM layer enhanced the precision of deterioration forecasting and cost estimation, reducing unplanned maintenance events by nearly **30%.** These outcomes validate the framework's ability to shift IMR operations from reactive, paper-based routines to **proactive, intelligence-driven decision cycles**. The web-enabled collaboration platform further improved interdepartmental communication and transparency, reducing reporting latency from days to mere hours, while the adoption of standardized data protocols (ISO 19650, IFC 4.3, and ISO 55000) ensured global interoperability and compliance. Beyond technical performance, the study underscored the DSIMF's contribution to **sustainability and environmental efficiency**. By digitizing inspection workflows, reducing physical documentation, and optimizing maintenance scheduling, the system achieved a measurable decrease in resource consumption and greenhouse gas emissions. The integration of sustainability indicators within the BIM environment also laid the foundation for data-driven lifecycle assessments, aligning the framework with **United Nations Sustainable Development Goals (SDG 9: Industry, Innovation, and Infrastructure; SDG 13: Climate Action).** In doing so, the DSIMF advances not only engineering efficiency but also environmental stewardship demonstrating that digitalization and sustainability are not parallel goals, but deeply interdependent facets of modern infrastructure governance. The success of the London Bridge implementation provides a scalable model for other infrastructure assets worldwide. Its modular architecture allows adaptation to various typologies bridges, tunnels, viaducts, and road networks facilitating broader application within **smart city and national digital twin initiatives**. The study establishes that the interoperability between BIM, web platforms, and mobile inspection technologies can serve as the foundation for **next-generation Smart Infrastructure Management Systems (SIMS)** capable of learning from, predicting, and autonomously responding to the needs of civil assets throughout their lifecycle.

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