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ASSESSING THE VALUE OF SMART CONTRACTS IN DIGITAL BRIDGE MAINTENANCE SYSTEMS

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The digital transformation of bridge management is enabling data-driven condition assessment and predictive maintenance through Structural Health Monitoring, Artificial Intelligence, and Digital Twins. However, beyond technical performance, the economic, social, and organizational benefits of automating maintenance processes through smart contracts remain largely unexplored. This paper assesses the potential economic, social, and inter-organizational value of adopting blockchain-based smart contracts in bridge maintenance workflows. A retrospective case study is conducted on an existing bridge that underwent condition-based maintenance interventions. The conventional management process is compared with an alternative scenario in which certified monitoring data, AI-assisted decision-making, maintenance execution, and payment mechanisms are governed through smart contracts. The comparative analysis examines operational indicators related to administrative effort, workflow efficiency, decision traceability, deadline control, and exposure to contractual disputes. Potential social and organizational benefits are also considered, including increased transparency, accountability, auditability, and coordination among infrastructure owners, operators, engineers, and service providers. The proposed approach supports scalable and replicable digital governance models while preserving human responsibility for engineering diagnosis and safety-critical decisions. The analysis indicates that integrating smart contracts into AI-driven bridge management frameworks can create value beyond monitoring performance by improving traceability, accountability, and inter-organizational coordination. Because historical administrative and contractual data were unavailable, the study does not claim realized percentage savings. Instead, it provides a transparent basis for identifying where workflow automation and verifiable governance can support more efficient and trustworthy infrastructure management.

Keywords: Blockchain, Structural health monitoring, Workflow automation, Infrastructure governance, Lifecycle resilience, Decision traceability.

1 INTRODUCTION

Bridge owners increasingly use Structural Health Monitoring (SHM), Artificial Intelligence (AI), and Digital Twins (DTs) for condition assessment and predictive maintenance. These technologies can identify structural changes under traffic and environmental variability (An *et al.* 2019, Malekloo *et al.* 2022, Zunino *et al.* 2025a, 2025b). Yet a monitoring result does not itself trigger a timely and accountable maintenance action.

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The transition from alert to intervention involves owners, operators, monitoring providers, engineers, authorities, inspectors, and contractors. Data, reports, approvals, work evidence, and payment documents often remain distributed across separate platforms. This fragmentation increases coordination effort. It also makes it difficult to verify which evidence supported a decision, whether deadlines were respected, and who approved each step.

Blockchain and smart contracts can provide tamper-evident records and deterministic workflow execution (Khan *et al.* 2021). Their use in construction has focused on document control, contractual coordination, and payment automation (Plevris *et al.* 2022, Zhang *et al.* 2023). In SHM, blockchain has been proposed to certify monitoring data, alerts, and reactions to detected damage (Xu *et al*. 2021, Mariniello *et al*. 2025). Recent work also highlights possible reductions in management cost and improved infrastructure resilience (Villa *et al.* 2025). Yet, the value created across a complete bridge maintenance workflow remains weakly quantified.

This paper presents a retrospective, scenario-based assessment of the Yonghe Cable-Stayed Bridge. Documented deterioration and rehabilitation events are mapped to a conventional workflow and a smart-contract-enabled counterfactual. The comparison addresses direct digital cost, coordination effort, deadline control, decision traceability, dispute exposure, public accountability, and inter-organizational coordination. Operational proxies are used because historical administrative and contractual records are unavailable, while engineering diagnosis and safety decisions remain under human responsibility.

2 ASSESSMENT METHOD

2.1 Case-Study Basis and Scope

The Yonghe Bridge is a long-span concrete cable-stayed bridge with an extensive monitoring and rehabilitation history. Long-term behavior was affected by concrete creep and shrinkage, cable relaxation, traffic growth, and environmental exposure. Progressive changes in deflection and cable forces were accompanied by localized damage. Major actions included replacement of a damaged closure segment, deck pavement refurbishment, complete stay-cable replacement, and multi-stage cable-force adjustment (Li *et al.* 2014, Li 2020, Zunino *et al.* 2025a).

Only these documented engineering events are treated as case evidence. Historical staff hours, procurement calendars, invoices, and dispute records were not available in the supplied studies. The conventional scenario is therefore a transparent reconstruction of the handoffs normally required around the documented events. The counterfactual preserves the same diagnosis, expert judgment, and intervention outcome. It changes only the governance and information flow.

2.2 Compared Scenarios and Indicators

In the conventional scenario, monitoring or inspection evidence is transferred to the asset owner through ordinary communication channels. Engineers are appointed, assessments are scheduled, reports are reviewed, and approvals are issued. The contractor submits progress evidence and requests acceptance and payment. Each organization controls its own document versions, deadlines, and archives.

The alternative scenario follows an integrated monitoring-to-action architecture in which blockchain acts as a governance layer (Mariniello *et al.* 2025, Marengo *et al.* 2026). Raw data, reports, images, and calculations remain off chain. Hashes and content identifiers certify provenance. Diagnostic outputs activate predefined response playbooks. Smart contracts issue notifications, enforce deadlines and escalation rules, record multi-signature approvals, and link

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accepted milestones to payment. Technical assessment and final safety decisions remain off chain.

Each workflow stage is examined for five features: automatic initiation, deadline or escalation control, persistent evidence, explicit human authorization, and conditional payment. The indicators are reported separately because they represent different forms of value. A benefit is considered supported when the alternative removes a manual initiation, creates an enforceable deadline, anchors evidence, identifies an approver, or links payment to verified acceptance. Direct technology cost is taken from the prototype implementation reported by Marengo *et al.* (2026).

2.3 Case-Based Workflow Mapping

The mapping is directly relevant to the Yonghe events. Severe cracking and reinforcement fracture at the midspan closure segment eventually required replacement. A smart contract could not select that technical solution. It could enforce immediate notification, preserve the operational state, require the responsible engineer and authority to sign the decision package, and record the transition to intervention. The multi-stage cable adjustment provides a second example. Measurement files, model outputs, acceptance signatures, and contractor milestones could be linked before the next stage or payment was enabled.

3 RESULTS

3.1 Economic and Process Value

All six stages in Table 1 can produce machine-verifiable records. Four transitions can be automated or made conditional: case creation, response activation, milestone progression, and payment release. Three human approval gates remain central: engineering validation, intervention authorization, and final acceptance or reopening. Automation is therefore concentrated on repeatable administrative actions rather than on structural judgment.

A common case identifier links the alert, reports, approvals, work evidence, and payment. Automated reminders and escalation reduce dependence on personal follow-up. Versioned evidence reduces repeated checks. Conditional payment narrows the gap between technical acceptance and invoice authorization. These mechanisms cannot remove all disputes, but they reduce disagreement about document timing, approval status, and the evidence used at each stage.

The prototype described by Marengo *et al.* (2026) had a reported smart-contract deployment cost of $0.11, a threshold-evaluation cost of $0.04, and an estimated annual execution cost of $25.33 under weekly execution with temporary cloud use. These figures refer only to prototype execution and exclude integration with legacy platforms, cybersecurity, legal configuration, training, and long-term system maintenance. They nevertheless indicate that ledger execution is unlikely to dominate the cost of inspection or rehabilitation.

Table 1. Stage-level comparison of the two workflow scenarios.

Stage	Conventional coordination	Smart-contract-enabled governance
Evidence and alert	Data and reports are exchanged and checked in separate systems.	Hashes certify provenance; a valid alert opens a case.
Response activation	Roles, notices, and deadlines are assigned manually.	A playbook notifies roles, assigns deadlines, and escalates delays.

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Table 1 (contd)

Stage	Conventional coordination	Smart-contract-enabled governance
Technical assessment	Experts review evidence; reports and versions follow ordinary approval channels.	Analysis remains off chain; report hashes, versions, and signatures are logged.
Authorization	The owner and authority approve actions and transmit work instructions.	Multi-signature approval unlocks the authorized work package.
Execution and acceptance	Each party checks and archives progress and acceptance documents.	Milestone evidence and acceptance signatures control progression.
Payment and archive	Invoices are reconciled with fragmented progress and acceptance records.	Verified acceptance can release payment; one audit package preserves the history.

3.2 Social and Inter-Organizational Value

An immutable and tamper-evident event history can show when an alert was issued, which evidence was reviewed, who approved a restriction or intervention, and when the action was completed. This supports internal control, regulatory review, and retrospective investigation. It can also support public accountability by making the safety-management process auditable. Sensitive monitoring data and proprietary models can remain off-chain under role-based access, while identifiers, approvals, and proofs are shared.

At ecosystem level, owners, operators, engineers, authorities, contractors, and technology providers interact through defined roles and reusable playbooks. A consortium ledger can provide shared control and privacy among identified organizations. Contractors can prove milestone completion. Owners can demonstrate that approvals and payments followed predefined conditions. Monitoring providers can identify the dataset and output that supported an alert. The shared record reduces information asymmetry and provides a common factual basis when contractual or technical disagreements arise.

3.3 Synthesis of Assessed Value

Table 2 distinguishes evidence measured in the prototype from effects inferred through the case-based workflow mapping. This separation prevents direct transaction costs from being confused with wider organizational benefits.

Table 2. Summary of operational indicators and supporting evidence.

Operational indicator	Result	Evidence basis
Workflow stages linked to persistent evidence	6 of 6	Case-based workflow mapping
Automated or conditional transitions	4 of 6	Case-based workflow mapping
Explicit human approval gates	3	Governance architecture
Smart-contract deployment cost	$0.11	Prototype implementation
Threshold-evaluation cost	$0.04	Prototype implementation
Estimated annual execution cost	$25.33	Prototype assumptions: weekly execution with temporary cloud use

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4 DISCUSSIONS

The strongest value appears in standardized activities: alert registration, inspection requests, deadlines, evidence submission, milestone acceptance, and payment authorization. Value is weaker when the task is dominated by case-specific structural reasoning. Smart contracts should therefore act as governance and orchestration tools, not as autonomous engineering decision-makers.

A blockchain record is only as reliable as the information submitted to it. Sensor faults, poor data quality, incorrect thresholds, and opaque algorithms can still produce unreliable alerts. Data-quality contracts and certified computation through Trusted Execution Environments or cryptographic proofs can reduce these gaps, but they do not remove the need for validation and professional oversight. Smart-contract code also creates risks related to software defects, upgrades, access rights, privacy, and legal enforceability. Human override must remain available for safety-critical operations.

The assessment is scenario-based. It identifies potential process value and reports low prototype execution costs, but it does not report realized savings from the historical rehabilitation. Administrative timing, staff hours, dispute records, and payment data were unavailable. The supported finding is narrower: the architecture identifies where manual coordination can be replaced, where evidence becomes verifiable, and where accountability is strengthened without changing the engineering decision.

5 CONCLUSIONS

This paper assessed the potential economic, social, and inter-organizational value of smart contracts in bridge maintenance through a retrospective scenario analysis of the Yonghe Bridge. The workflow mapping showed that six stages can be connected to persistent evidence, four transitions can be automated or made conditional, and three safety-critical gates remain subject to explicit human authorization. Smart contracts can therefore formalize notifications, deadlines, escalation, milestone progression, acceptance, and payment without replacing engineering diagnosis or intervention design.

The main benefit is the formalization of the pathway from evidence to action. Human approval remains essential for diagnosis, safety measures, intervention design, and reopening. Around these decisions, a shared and tamper-evident workflow can reduce administrative friction, clarify responsibilities, mitigate document-based disputes, and improve coordination among infrastructure stakeholders. Smart contracts add value when they are implemented as a controlled governance layer within an AI- and DT-supported management system.

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