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From sensing to action: A digital framework for bridge management

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ABSTRACT: The continuous digitalization of bridge management is transforming how infrastructures are monitored, assessed, and maintained. Despite the availability of sensor data and AI-driven diagnostics, ensuring reliability, transparency, and traceability across the decision-making process remains challenging. This work presents a vision for an integrated, verifiable, and automated bridge management framework that links sensing, assessment, and intervention through emerging digital technologies. Advances in Artificial Intelligence and Machine Learning enable data-driven Structural Health Monitoring for damage detection and quantification under varying conditions. When combined within a Digital Management Environment (DME) compliant with a Digital Twin (DT) framework, these tools support real-time condition assessment and predictive maintenance through interaction between physical and virtual assets. To ensure trust and accountability, blockchain is introduced as a tamper-proof layer for certifying data provenance and AI-based decisions. Smart contracts can automate maintenance workflows while preserving human oversight in safety-critical operations.

Keywords: Bridge Management, SHM, Blockchain, Smart Contracts

1 INTRODUCTION

The digital transformation of civil infrastructures is redefining how bridges are monitored, assessed, and managed throughout their service life. Modern Structural Health Monitoring (SHM) systems, supported by artificial intelligence, enable continuous and data-driven evaluation of structural performance, allowing early damage detection under real operational and environmental conditions. Significant progress has been achieved in extracting damage-sensitive features and identifying anomalies even in the presence of traffic and environmental variability (An et al. 2019, Malekloo et al. 2022, Zunino et al. 2025).

By combining advanced signal processing and multivariate analysis techniques, various approaches can demonstrate the ability to localize structural anomalies under real operating conditions. While these results confirmed the potential of data-driven SHM for structural diagnostics, they also highlighted a critical limitation: monitoring outputs alone do not directly translate into engineering decisions or maintenance intervention.

As SHM systems mature, infrastructure assets continuously generate large and heterogeneous datasets from sensors, inspections, and maintenance activities. These data must be stored, shared, and interpreted by multiple stakeholders, including owners, operators,

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engineers, and authorities. Conventional centralized data management solutions, still not fully digitized, struggle to guarantee long-term integrity, traceability, and accountability, particularly when decisions and interventions must be justified years after their execution.

Thanks to the progressive introduction of a Digital Management Environment (DME) in asset management, increasing attention has been devoted to blockchain technologies and smart contracts as enablers of tamper-proof data governance and process automation. Comprehensive reviews such as Khan et al. (2021) and Liu et al. (2024) highlight core blockchain properties including immutability, transparency, and decentralized trust, as well as open challenges related to scalability and integration. Within the Architecture, Engineering, and Construction domain, blockchain applications have been explored across design, construction, and maintenance phases (Turk & Klinc 2017, Plevris et al. 2022, Christodoulou & Kalergis 2024), with particular emphasis on contract management, documentation, and payment automation (Zhang et al. 2022, Adel et al. 2023, Zhang et al. 2023). Despite their conceptual maturity, most implementations remain limited to prototypes or small-scale demonstrations.

In the SHM field, several studies have investigated blockchain-based architectures for monitoring data certification and alert management. Xu et al. (2021) proposed a blockchain-enabled SHM framework in which encrypted sensor data and alerts are registered on a private blockchain to ensure integrity and traceability. More recently, Mariniello et al. (2025) introduced the SHERPA framework, combining SHM, blockchain and smart contracts to provide auditable monitoring workflows and automated reactions to detected damage. These approaches demonstrate the potential of blockchain to enhance trust and transparency in SHM systems.

However, a critical gap remains between AI-based structural diagnostics and practical infrastructure management. Existing SHM systems are effective at detecting anomalies, but they rarely provide structured mechanisms to ensure that detected damage leads to timely, verifiable, and traceable interventions. Conversely, blockchain-driven platforms emphasize data integrity and automation, but often lack integration with real-time structural information and physics-informed indicators capable of supporting engineering decision-making.

This paper addresses this gap by proposing BLOCK-MIND (BLOCKchain-enabled Monitoring, INterpretation and Decision-making), an integrated framework that links SHM, DME, and blockchain technologies within a closed-loop decision process for bridge management. Building upon the SHM experience gained on the Yonghe Bridge (Zunino et al. 2025), BLOCK-MIND formalizes the transition from sensing to action by introducing explicit decision logic, risk-aware intervention classes, and verifiable governance mechanisms. Blockchain and smart contracts are employed to certify alerts, decisions, and interventions, while preserving human supervision for safety-critical operations.

The remainder of the paper is organised as follows. Section 2 presents the BLOCK-MIND methodology, detailing the integration of SHM, DME and blockchain within a closed-loop decision framework. Section 3 introduces an application scenario based on the Yonghe Cable-Stayed Bridge, illustrating how the proposed approach can be deployed on a real asset with an extensive monitoring history. Finally, Section 4 discusses the main implications of the framework and outlines directions for future developments.

2 METHODOLOGY

BLOCK-MIND implements a closed-loop workflow that links SHM evidence to verifiable maintenance actions by integrating AI-based diagnostics, a Digital Management Environment (DME), and blockchain smart contracts. Two orthogonal distinctions are used throughout the framework: *offline* elements (prepared once and periodically updated, e.g., DT what-if analyses and response policies) versus *online* elements (executed upon incoming monitoring data); and *on-chain* records (immutable proofs, hashes, approvals, logs) versus *off-chain* artefacts (raw SHM streams, physics-informed decision-support environment, inspection files). Figure 1 provides a conceptual overview of the BLOCK-MIND architecture, highlighting the separation between offline and online processes, as well as between off-chain computation and on-chain governance.

In the following, the methodology is presented as a single end-to-end path from data acquisition to intervention.

2.1 *SHM data management and provenance certification*

Continuous SHM data are collected from the bridge sensor network and stored off-chain using a distributed content-addressed storage (IPFS). This includes raw sensor streams, high-frequency signals, Digital models, and inspection artefacts. IPFS enables scalable storage of large and heterogeneous datasets while ensuring integrity through content-based hashing.

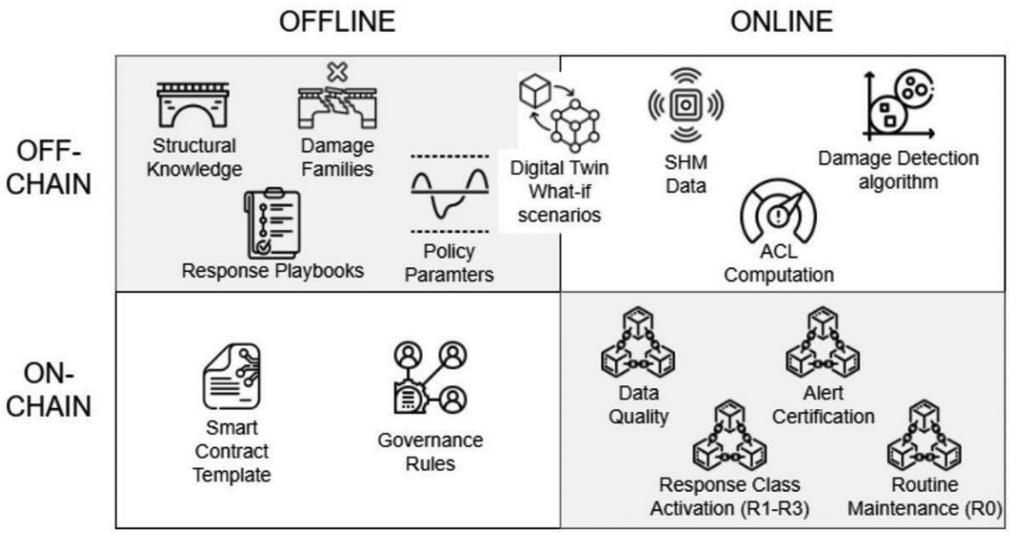

Figure 1. Conceptual overview of BLOCK-MIND showing the separation between offline vs. online processes and off-chain vs. on-chain components.

Before diagnostics are trusted, sensor batches are validated and certified through a *Data Quality and Provenance Contract*, which stores timestamps, data hashes, metadata identifiers, and oracle attestations (e.g., from the SHM provider). This step establishes traceability and prevents undetected tampering or retroactive alteration of monitoring evidence. Additional trust guarantees can be provided by validating the diagnostic algorithm through cryptographic attestations (e.g., zeroknowledge proofs) and by executing it within secure environments such as Trusted Execution Environments (TEE).

2.2 *From AI-based diagnostics to structural criticality assessment*

Validated SHM data feed the AI-based anomaly detection pipeline, including feature extraction and data-driven models. Each detected anomaly generates a standardised alert $A = \{t, c, DF, x, e\}$, where t is the timestamp, c is the hypothesised affected component (if identifiable), DF is the inferred damage family, x is the feature vector, and e summarises environmental and operational conditions. When localisation is uncertain, the alert is associated to a candidate component set $\mathcal{C}_{DF}$, defined through structural knowledge and used to ensure conservative interpretation. The diagnostic output and its integrity proofs can be certified on-chain via a *Diagnostic Contract*.

To cope with the intrinsic ambiguity of SHM-based localisation, BLOCK-MIND introduces *damage families* as an intermediate abstraction between anomaly patterns and structural components. Each damage family DF is mapped offline to a set of plausible components $\mathcal{C}_{DF} \subseteq \mathcal{C}$, informed by engineering judgement and numerical model-consistent degradation scenarios. During online operation, this mapping enables robust alert interpretation even when the affected component cannot be uniquely identified.

Structural relevance is quantified through a *Structural Impact Index* (*SII*), assigned offline to each component $c \in \mathcal{C}$ by means of physics-based model with *static what-if* analyses. The *SII* measures the potential for a local component degradation to induce disproportionate effects at the global structural level, drawing inspiration from robustness and progressive collapse concepts. In

this sense, *SII* captures both component criticality and system robustness, providing a ranking of how local damage may propagate into global performance deterioration.

The information provided by AI-based diagnostics, damage-family mappings, and the Structural Impact Index is combined to determine the *Alert Criticality Level* (ACL). The ACL is defined as a function of the structural impact associated with the affected or candidate components, together with contextual factors reflecting extraordinary environmental or operational conditions not explicitly represented in the physics-based model. This formulation ensures that alerts associated with structurally critical elements or exceptional conditions are conservatively assigned higher criticality, thereby triggering appropriate levels of engineering assessment and response.

2.3 *Decision logic: From criticality to response playbooks*

The Alert Criticality Level (ACL) is translated into a discrete response class, which defines the intent and urgency of the intervention independently of its detailed technical solution. The mapping policy adopted in the framework is summarised in Table 1.

Table 1. Mapping between Alert Criticality Level (ACL) and response classes.

ACL level	Response class	Intervention intent
-	R0: Scheduled	Routine activities (time-driven)*
Low ($ACL < 0.3$)	R1: Enhanced Monitoring	Monitoring and inspection escalation
Medium ($0.3 \leq ACL < 0.6$)	R2: Rapid Assessment	Time-bound engineering assessment
High ($ACL 0.6$)	R3: Emergency Safeguards	Immediate risk mitigation

* Independent of ACL

Once the response class is assigned, the corresponding *Response Playbook Contract* is activated. The playbook does not encode engineering solutions; it automates the *governance of the response* by orchestrating predefined conservative actions, enforcing deadlines and escalation rules, and managing multi-signature approvals for safety-critical decisions. Detailed technical assessments and intervention designs remain off-chain until validated.

Table 2 summarises example class-level response playbooks for R0-R3, highlighting the separation between automatic actions, approval-gated actions, stakeholder involvement, and time constraints.

Table 2. Representative example of smart-contract playbooks for the four response classes (R0-R3).

Response class	Smart-contract playbook
R0 Scheduled	**Automatic actions:** notify contractor/inspector; request evidence hash; record completion on-chain; optional milestone payment. **Approval-gated actions:** schedule override; contractor reassignment; non-routine safety actions. **Stakeholders:** Contractor, Inspector, Owner. **Deadlines:** predefined execution window; escalation on missed deadlines.
R1 Enhanced Monitoring	**Automatic actions:** increase monitoring; trigger surveys; schedule visual inspection. **Approval-gated actions:** traffic measures; escalation to R2. **Stakeholders:** Operator, SHM provider, Inspector. **Deadlines:** short-term inspection and reporting windows.
R2 Rapid Assessment	**Automatic actions:** open assessment case; request targeted inspection; notify responsible engineer. **Approval-gated actions:** traffic restrictions; case closure or escalation to R3. **Stakeholders:** Engineer, Operator, Inspector, Authority. **Deadlines:** time-bound assessment and validation.
R3 Emergency Safeguards	**Automatic actions**: emergency notification; activate safeguards; immediate inspection. **Approval-gated actions**: reopening; major intervention decisions. **Stakeholders**: Authority, Owner, Operator, Engineer. **Deadlines**: immediate response; controlled de-escalation.

2.4 *Intervention execution and audit trail*

Execution artefacts (inspection reports, images, scans, calculation files) are stored off-chain, while their content hashes, approvals, and completion proofs are recorded on-chain to preserve full auditability without compromising scalability.

Playbook completion (or escalation) produces a verifiable decision package that links: the original alert evidence, the computed ACL, the activated response class, and signed approvals and completion proofs. This package supports accountability across stakeholders and long-term traceability of actions taken on the asset.

The complete data-flow and contract interactions of the framework are summarised in Figure 2. While the following section illustrates how this framework can be applied on a real bridge asset.

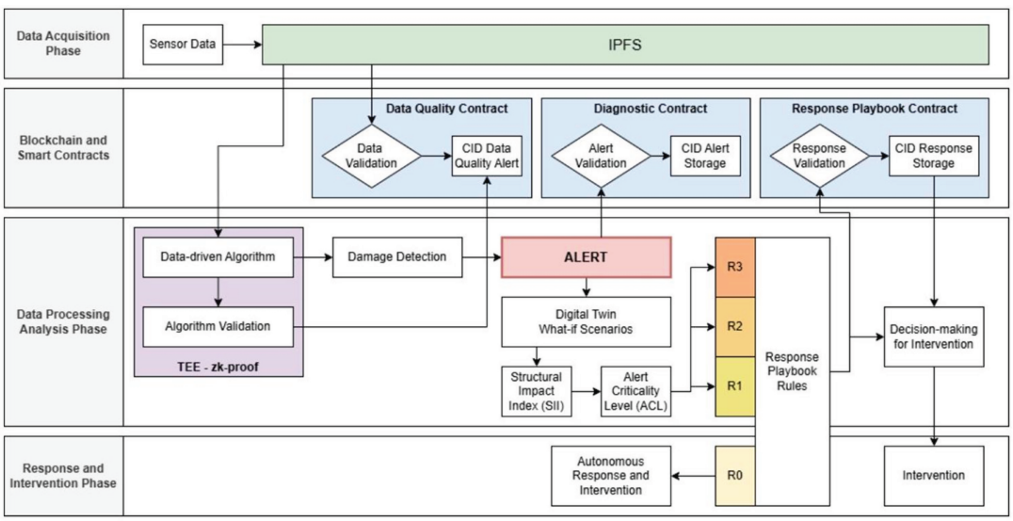

Figure 2. Data-flow of the BLOCK-MIND framework: from SHM to intervention.

3 APPLICATION SCENARIO: THE YONGHE BRIDGE

3.1 *The Yonghe Bridge as a managed asset*

The Yonghe Cable-Stayed Bridge is adopted as an illustrative application to demonstrate how the BLOCK-MIND framework can be applied to a real bridge characterized by structural complexity, long-term deterioration processes, and a well-documented monitoring history. The bridge, depicted in Figure 3, is a representative example of a long-span concrete cable-stayed structure that has experienced progressive deviation from its original configuration, localized damage, and major rehabilitation interventions during its service life (Li et al. 2014, Li 2020, Zunino et al. 2025).

From a management perspective, the Yonghe Bridge can be interpreted as a continuously evolving asset rather than a static structure. Over time, the combined effects of creep and shrinkage of concrete, cable relaxation, increasing traffic loads, and environmental exposure led to both global structural changes and localized damage phenomena. These processes ultimately required significant interventions, including the replacement of closure segments, refurbishment of the deck pavement, and full replacement and adjustment of the stay-cable system.

A comprehensive Structural Health Monitoring system has been installed on the bridge, providing long-term measurements on the deck, pylons, and stay cables. The monitoring system enables the observation of both global response indicators (e.g., deflections, cable forces, modal properties) and local response features associated with specific structural

Figure 3. View of the Yonghe Bridge, Tientsin, China.

components. This rich dataset has previously been exploited for damage detection and localisation under varying environmental and operational conditions.

In the context of this work, the Yonghe Bridge is not treated as a benchmark for validating individual SHM algorithms. Instead, it is considered as a managed asset whose lifecycle events, monitoring evidence, and interventions can be interpreted through a structured, monitoring-driven decision framework. This perspective makes Yonghe particularly suitable for illustrating how BLOCK-MIND connects sensing, structural interpretation, and intervention governance within a unified DME.

3.2 *Prospective application of BLOCK-MIND*

This section illustrates the intended operational deployment of BLOCK-MIND on the Yonghe Bridge, explicitly grounding the framework in the real damage mechanisms and intervention decisions documented during the bridge service life; quantitative validation is deferred to future work.

Within the BLOCK-MIND framework, monitoring data collected on the Yonghe Bridge would be continuously processed to detect anomalies and generate structured alerts. Each alert is interpreted not only in terms of statistical deviation from a baseline state, but also through its structural context, using damage families and candidate component sets to conservatively address damage localisation uncertainty. This aspect is particularly relevant for the Yonghe bridge, where local damage phenomena, such as cracking at closure segments or degradation of auxiliary support systems, were accompanied by global response changes, including increasing midspan deflections and redistribution of cable forces.

The physics-based digital model of the bridge plays a central role in this interpretation process. Offline *what-if* analyses are performed on a model updated using long-term monitoring data, closely reflecting the actual structural state of the bridge. The *static what-if* scenarios are defined based on damage typologies observed in practice, including loss of continuity at closure segments, degradation of stay cables, and loss of vertical support due to pull-rod failure. For a cable-stayed bridge such as the Yonghe bridge, the analyzes focus on key response quantities such as bending moments at the tower bases and at midspan, horizontal tower displacements, support uplift, and axial forces in the stay cables. The outcomes are summarised through a Structural Impact Index, allowing component-level alerts to be ranked according to their potential impact on global structural performance, and interpreted through a robustness-oriented perspective accounting for both direct and indirect consequences (Baker et al. 2008).

Based on the inferred structural criticality and contextual information, alerts are translated into Alert Criticality Levels, which in turn activate predefined response classes. For example, early-stage anomalies related to progressive cable-force imbalance or corrosion-induced degradation of individual stay cables (as observed prior to the 2005-2007 rehabilitation) would typically activate Enhanced Monitoring (R1) workflows, including monitoring escalation and targeted inspections. These actions are well suited for automation through smart-contract playbooks, as they involve standardized procedures, predefined deadlines, and verifiable outcomes.

Conversely, anomalies affecting structurally critical and weakly redundant components, such as closure segments or auxiliary support systems, would rapidly lead to Rapid Assessment (R2) or Emergency Safeguards (R3) workflows. In the real case, severe cracking and reinforcement fracture at the midspan closure segment ultimately motivated the replacement of the damaged segment, while progressive deterioration of the stay-cable system led to full cable replacement and subsequent multi-stage force adjustment. Within BLOCK-MIND, these decisions would remain entirely engineering-driven and off-chain; however, their initiation, escalation, and governance would be formalized through smart contracts. Playbooks would automatically enforce inspection requests, notification of responsible engineers and authorities, time-bound assessments, and immutable logging of approvals and execution milestones, without encoding the technical solution itself (see the examples in Table 2).

A particularly illustrative example is the post-replacement cable adjustment campaign, which in practice required multiple stages guided by numerical modelling and measurement-based trial-and-error. In a digitalized BLOCK-MIND setting, the significant force deviations and associated deflection changes observed after cable replacement would immediately trigger high-criticality alerts and Emergency Safeguards workflows. While the adjustment strategy would still rely on expert judgement and detailed structural analysis, smart contracts would ensure timely escalation, controlled operational states, and complete traceability of each adjustment step and validation outcome.

The key contribution of BLOCK-MIND in this application is therefore not the automation of engineering decisions, but the formalization of the decision pathway from monitoring evidence to intervention intent. The rationale linking detected anomalies to specific response classes (summarized in the class-level playbooks of Table 2) is made explicit, repeatable, and verifiable. While detailed engineering assessments and intervention designs remain case-specific and off-chain, their initiation, approval, and completion are governed through structured and auditable workflows.

Applied retrospectively, the major damage events and rehabilitation actions of the Yonghe Bridge can be reinterpreted as outcomes of such a monitoring-driven decision process. Applied prospectively, the framework provides a consistent methodology to anticipate escalation, improve the timeliness of assessments, reduce ambiguity in responsibility allocation, and enhance the traceability of management actions throughout the service life of the bridge.

4 DISCUSSION AND CONCLUSIONS

This paper introduced BLOCK-MIND, a digital framework that formalizes the connection between SHM-based diagnostics and bridge management actions through a closed-loop and verifiable decision process. By integrating AI-based monitoring, Digital Twins, and blockchain technologies, the framework addresses a key limitation of current practice, namely the absence of structured, transparent, and traceable mechanisms linking sensing to intervention.

The application scenario based on the Yonghe Cable-Stayed Bridge shows how monitoring evidence can be interpreted using physics-informed structural indicators and mapped to predefined response classes, without automating safety-critical engineering decisions. In this context, blockchain and smart contracts are employed not as decision-makers, but as governance tools that certify alerts, decisions, and interventions, thereby supporting accountability and long-term traceability across stakeholders.

Beyond the specific case considered, BLOCK-MIND reflects a broader trend in civil engineering toward highly integrated digital frameworks that combine sensing, modelling, decision logic, and governance. Such approaches are increasingly required to manage the growing complexity of

infrastructures and to respond to the ongoing digitalization of the built environment. Rather than focusing on isolated tools, future bridge management systems are expected to rely on holistic, interoperable platforms capable of linking data, models, and decisions within a unified process.

Future work will focus on the detailed implementation and quantitative validation of the proposed framework, as well as on its extension to network-level infrastructure management. Expanding BLOCK-MIND from individual assets to bridge networks or transportation corridors would enable coordinated risk assessment, prioritization of interventions, and resilience-oriented decision-making at system scale, further aligning the framework with the needs of modern infrastructure agencies.

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