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Digital Twins for Quality Assurance and Asset Integrity Management in High-Voltage Electricity Transmission Infrastructure: An Integrated Lifecycle Framework

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Abstract

High-voltage electricity transmission assets are long-lived systems whose operational reliability can be influenced by decisions and quality events occurring during design, manufacture, transport, construction and commissioning. Yet project quality records and operational asset-management information are often separated by organisational and information-system boundaries. This paper proposes a Digital Twin Quality and Asset Integrity Framework (DT-QAIF) that connects construction quality assurance to whole-life asset integrity management. The framework integrates design information, Building Information Modelling (BIM), manufacturing and material records, ITPs, NCRs, geospatial data, condition-monitoring information, inspection history and predictive analytics within a persistent lifecycle digital architecture. Five principal layers are defined: physical infrastructure, data acquisition, digital representation, intelligence and analytics, and engineering decision support. The paper introduces the concept of Quality Heritage—the accumulated quality history inherited by an operational asset from design, manufacture and construction—and a conceptual Digital Asset Integrity Index (DAII) combining Quality Heritage, current condition, environmental/degradation indicators and asset criticality. The framework provides a structured bridge between project quality management and operational asset integrity, supporting traceability, risk-based inspection, predictive maintenance and infrastructure resilience.

Keywords: Digital Twin, Electricity Transmission, Asset Integrity, Quality Assurance, Predictive Maintenance, BIM, Artificial Intelligence, Infrastructure Resilience, Quality Heritage

1. INTRODUCTION

Electricity transmission assets are long-lived critical infrastructure. A tower, foundation, conductor system or associated component constructed today may remain in service for decades. Decisions taken during design, manufacture, transport, storage, construction and commissioning can therefore influence operational performance long after project completion.

Despite this lifecycle relationship, information is frequently fragmented. Design teams create specifications and models; manufacturers generate certificates and inspection records; construction teams produce ITPs, NCRs and photographs; commissioning teams create test results; and operators subsequently manage condition and maintenance data in separate systems. The challenge is not simply to generate more data, but to maintain an authoritative digital thread linking lifecycle information to the physical asset.

Digital twin technology offers a mechanism for connecting physical infrastructure, digital representation, condition information and analytics. Current research demonstrates applications in grid monitoring, predictive maintenance, condition prediction and long-term asset-management decision support [1]–[3]. This paper focuses on a less developed question: how construction quality history can become a persistent input to the operational digital twin.

2. RESEARCH GAP AND CONTRIBUTION

Two assets may achieve final acceptance while having materially different quality histories. One may have been constructed without significant recorded non-conformance, while another may have required foundation remediation, coating repair, delivery-damage assessment or repeated installation corrections. Formal closure confirms that an issue was addressed; it does not necessarily erase the asset's engineering history.

The central contribution of this paper is the concept of Quality Heritage: the accumulated quality history inherited by an operational asset from design, manufacture and construction. The proposed DT-QAIF treats Quality Heritage as a lifecycle variable that can inform inspection prioritisation, condition assessment and predictive maintenance.

3. AIM, OBJECTIVES AND RESEARCH QUESTIONS

The aim is to develop an integrated digital-twin framework connecting construction quality assurance with whole-life asset integrity management for high-voltage electricity transmission infrastructure.

The objectives are to identify lifecycle data requirements; define the digital thread between project QA and operational management; propose a Digital Asset Integrity Index; show how NCR history could influence lifecycle risk assessment; integrate BIM, GIS, condition monitoring and AI; and define requirements for governance, cybersecurity and empirical validation.

The research questions are: (RQ1) How can construction quality information be integrated into transmission-asset digital twins? (RQ2) Can construction non-conformance history improve prediction of future degradation or maintenance demand? (RQ3) What architecture is required to preserve a reliable lifecycle digital thread? (RQ4) How can digital twins support risk-based inspection while maintaining engineering accountability?

4. DIGITAL TWINS IN INFRASTRUCTURE AND POWER SYSTEMS

A digital twin is more than a static three-dimensional model. It is a digital representation connected to its physical counterpart by structured information flows that support understanding, simulation, prediction or decision-making. UK infrastructure research highlights the potential of digital twins to improve whole-life efficiency, resilience and maintenance planning [4].

In power systems, recent work has applied digital twins and AI to asset management, long-term planning and transmission equipment condition prediction [1], [2]. Recent reviews also emphasise architectures, enabling tools, predictive maintenance, grid applications and the governance challenges of utility-scale implementation [3].

For high-voltage transmission, candidate assets include lattice towers, poles, foundations, conductors, insulators, fittings, earth wires, optical ground wires, earthing systems and substation interfaces.

5. PROPOSED DT-QAIF ARCHITECTURE

The DT-QAIF contains five principal layers. Layer 1 is the physical infrastructure itself. Each critical asset should be connected to a unique identifier linking location, design, materials, inspections, NCRs, commissioning and subsequent maintenance.

Layer 2 acquires lifecycle data. Construction-stage information may include material certificates, supplier inspections, delivery records, ITPs, photographs, surveys, coating records, foundation records and commissioning evidence. Operational information may include visual inspection, drone imagery,

thermal data, LiDAR, corrosion indicators, weather exposure, condition sensors, maintenance interventions and defect history where technically justified.

Layer 3 provides the digital representation by integrating BIM, GIS, document repositories and condition-monitoring information. Layer 4 applies analytics such as anomaly detection, image classification, deterioration modelling, remaining-life estimation and predictive maintenance. Layer 5 converts outputs into engineering decision support through maps, dashboards, alerts, asset-health indicators and risk-ranked recommendations.

6. QUALITY HERITAGE

Quality Heritage is defined here as the structured history of quality-relevant events associated with an asset before operational handover. It may contain design revisions and concessions; manufacturing inspection and material certification; transport and delivery condition; construction inspection results; NCRs, repairs and rework; photographs; commissioning findings; and final acceptance evidence.

The concept does not imply that every historical NCR represents a future defect. Rather, it proposes that selected categories of quality history should remain available for evidence-based lifecycle analysis instead of becoming dormant within archived project records.

7. DIGITAL ASSET INTEGRITY INDEX

A conceptual Digital Asset Integrity Index is proposed as:

7.1 DAII Formulation

DAII = f(QH, CC, ED, CR), where QH is Quality Heritage, CC is current condition, ED represents environmental exposure and degradation indicators, and CR is asset criticality. A weighted implementation may be expressed as DAII = w1QH + w2CC + w3ED + w4CR. The weights and thresholds must be empirically calibrated before operational use.

8. EXAMPLE TRANSMISSION-TOWER APPLICATION

Consider a tower whose foundation was accepted after remediation and whose protective coating required local repair during construction. Years later, inspection identifies increasing coating deterioration under elevated environmental exposure. A conventional age-based inspection regime may treat this tower similarly to neighbouring assets. DT-QAIF would preserve the construction history and allow the combination of historical coating repair, current deterioration and exposure conditions to influence inspection priority.

This example illustrates the value of linking information that normally exists in separate lifecycle systems. The framework does not assume causation; it creates the data structure required to test whether historical quality events add predictive value.

9. BIM-GIS-IOT-AI INTEGRATION

BIM provides component geometry, specification and design identity; GIS provides location, terrain and environmental context; condition-monitoring technologies provide time-dependent physical information; and AI supports anomaly detection, image classification and prediction. The quality record provides lifecycle provenance.

The resulting digital twin can therefore be expressed conceptually as: BIM + GIS + condition data + AI + quality records = lifecycle asset intelligence. Real-time sensing should be applied proportionately: not every asset requires continuous telemetry, and digital-twin maturity should reflect criticality, failure consequence and decision value.

10. PREDICTIVE MAINTENANCE AND LIFECYCLE DECISION-MAKING

Maintenance strategies can be reactive, preventive, condition-based or predictive. Digital twins support a transition towards condition-based and predictive approaches by combining current condition with historical and contextual variables.

A conceptual failure-probability model may be expressed as P(Failure) = f(A, C, E, L, QH), where A is age, C current condition, E environmental exposure, L loading or operational variables, and QH Quality Heritage. The research hypothesis is that adding QH to conventional condition variables may improve prediction for selected asset and defect classes.

11. DIGITAL THREAD FROM CONSTRUCTION TO OPERATION

The proposed lifecycle sequence is: design digital model; manufacturing quality records; delivery inspection; construction ITPs; NCR and corrective-action history; commissioning; digital handover; operational digital twin; condition monitoring; predictive maintenance; renewal or replacement.

A robust digital thread requires persistent identifiers, controlled metadata, configuration management and data ownership. Handover should transfer not only final drawings and certificates but also structured quality knowledge that remains relevant to lifecycle decision-making.

12. QUALITY ASSURANCE OF THE DIGITAL TWIN

A digital twin cannot support reliable decisions if its underlying information is inaccurate, incomplete, inconsistent or obsolete. The digital twin itself therefore requires quality assurance covering completeness, accuracy, traceability, timeliness, configuration control, validation and authorised change.

This creates an important role for quality professionals in digital engineering: assuring the integrity of digital information and the processes by which it is created, updated, interpreted and used.

13. CYBERSECURITY AND GOVERNANCE

Greater digital connectivity increases the consequences of unauthorised access, manipulated sensor data, model corruption, incorrect automated recommendations and loss of sensitive infrastructure information. Security must therefore be incorporated by design.

Controls should include role-based access, authentication, encryption, logging, backup and recovery, network segmentation where relevant, data lineage, model/version control and incident-response arrangements. Engineering accountability must remain explicit even where analytics or automated alerts are used.

14. PROPOSED EMPIRICAL VALIDATION

Future research should select a representative sample of transmission assets and assemble anonymised construction NCRs, ITPs, commissioning records, material records, inspection history and maintenance data. Unique identifiers would connect lifecycle information to each asset.

Two predictive models could then be compared. Model A would use conventional variables such as age, environment and present condition. Model B would use the same variables plus Quality Heritage. If Model B demonstrates statistically and practically meaningful improvement in prediction of degradation, maintenance demand or defect recurrence, the central hypothesis would receive empirical support.

Validation should include sensitivity analysis, missing-data assessment, bias checks, calibration, cross-validation and economic evaluation. Correlation between an old NCR and later degradation must not be treated as proof of causation without appropriate engineering analysis.

15. DISCUSSION

The novelty of DT-QAIF is not the use of digital twins in power systems alone. The proposed contribution is the integration of construction quality heritage into whole-life digital asset intelligence. This addresses a persistent organisational separation between project delivery and asset operation.

Closed project records can still contain useful lifecycle information. By retaining selected quality history as structured asset data, operators may improve traceability, inspection prioritisation, organisational learning and future design feedback.

16. LIMITATIONS AND FUTURE WORK

The framework is conceptual. Not all quality events will be relevant to future asset condition, and not every component warrants a high-fidelity digital twin. Future studies should identify which NCR categories have lifecycle significance, calibrate the DAII, test computer-vision integration, evaluate interoperability between project and operational systems, and quantify cost-benefit at different levels of twin maturity.

17. CONCLUSION

This paper proposes a Digital Twin Quality and Asset Integrity Framework for high-voltage electricity transmission infrastructure. Its central concept, Quality Heritage, preserves selected design, manufacturing and construction quality history as a lifecycle asset variable. Combined with current condition, environmental exposure and criticality, this history can support a Digital Asset Integrity Index and future predictive-maintenance research. Empirical validation is required, but the framework provides a structured bridge between project quality assurance, digital engineering and whole-life asset resilience.

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