



Automated Inspection, Calibration and Measurement Traceability for Sustainable Infrastructure Delivery under Saudi Vision 2030

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Abstract: Saudi Arabia's infrastructure expansion requires assurance systems that match the speed, complexity, and sustainability expectations of Vision 2030. This review examines how automated inspection, digitally enabled calibration, and metrological traceability can be integrated into a coherent quality architecture for infrastructure delivery. The literature indicates that computer vision, uncrewed aerial vehicles, laser scanning, structural health monitoring and digital twins can accelerate defect detection and condition assessment. Still, their decisions remain trustworthy only when the underlying measurements, sensor states, and uncertainty information are traceable. Digital calibration certificates provide a machine-readable mechanism to carry calibration status, uncertainty, and provenance into automated workflows. In contrast, BIM and digital twins provide the asset context needed to convert measurements into engineering decisions. Evidence from construction and asset-management research further shows that automation is not intrinsically sustainable: benefits depend on interoperability, cybersecurity, competence, data governance, risk-based human oversight, and lifecycle use of verified data. The review develops an integrated traceability-to-decision framework for Saudi infrastructure projects, linking calibrated sensing, automated inspection, digital evidence, engineering acceptance and lifecycle feedback. It argues that traceability should be treated as digital infrastructure rather than a laboratory back-office function. It proposes research and policy priorities for scalable implementation across giga-projects, transport, utilities and public assets.

Keywords: Automated Inspection, Calibration, Metrological Traceability, Digital Calibration Certificate, Digital Twin, Infrastructure, Saudi Vision 2030, Sustainability.

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1. INTRODUCTION

Saudi Arabia is delivering an unusually large portfolio of transport, urban, energy, utilities, and public-realm infrastructure while simultaneously pursuing digital transformation and sustainability under Vision 2030. This combination changes the quality-assurance problem. Traditional inspection remains necessary, but episodic visual checks, manually transcribed calibration certificates, and fragmented acceptance records poorly match

projects that generate continuous streams of geometric, material, environmental, and operational data. A more scalable model connects automated inspection with verified measurement systems. Hence, a detected anomaly is not merely visible to software but supported by evidence whose accuracy, uncertainty, provenance, and calibration status can be demonstrated.

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Digital construction research provides many of the technical pieces. Construction digital twins combine models with sensor and operational information, enabling persistent asset representations rather than static handover files [1-3]. Automated inspection studies show that deep learning, mobile mapping, laser scanning, and uncrewed aerial vehicles can identify, localize, and classify concrete defects and bridge damage with increasing speed and repeatability [4-8]. Structural health monitoring extends this logic from discrete inspection events to continuous condition assessment, while machine learning interprets large sensor streams for anomaly detection and prognosis [9,10]. These capabilities support sustainability because earlier defect discovery, targeted maintenance, reduced rework, and longer asset life can lower material use, disruption, safety exposure, and lifecycle cost.

However, automation creates a second-order assurance challenge. An algorithm may be accurate on a benchmark yet still produce unreliable engineering decisions if camera scale is uncertain, positioning is poorly controlled, a displacement sensor has drifted, environmental compensation is missing, or calibration information is detached from the dataset. Metrology research therefore matters to digital infrastructure delivery. Work on digital calibration certificates (DCCs) shows how calibration identity, results, uncertainty, and traceability information can be represented in machine-readable form and exchanged across digital systems [11-16]. The shift from documents designed for human reading to data designed for machine action enables automatic checks of whether a measurement was made with an in-calibration instrument, whether the relevant uncertainty is acceptable for the tolerance being assessed, and whether evidence remains traceable to recognized standards.

This review argues that automated inspection and digital twins should not be treated as separate from calibration and metrological traceability. They form one assurance chain. Inspection generates evidence; calibration establishes measurement fitness; traceability connects values to references through an unbroken documented chain; and digital asset systems preserve context for engineering decisions. This integration is particularly important in Saudi Arabia, where BIM-based sustainability research already highlights the need for information-rich delivery models [17], and recent studies identify both opportunities and implementation barriers for AI-enabled digital twins in the Saudi construction sector [18]. The issue is therefore not whether individual technologies work, but how to govern them as a reliable socio-technical system for sustainable infrastructure delivery.

2. AIM OF THE STUDY

This review aims to develop an evidence-based framework explaining how automated inspection, calibration, and metrological traceability can be integrated with BIM, digital twins, and infrastructure asset management to support reliable and sustainable delivery under Saudi Vision 2030. The review focuses on the assurance pathway from physical measurement to engineering acceptance and lifecycle decision-making, rather than treating automation as an isolated productivity intervention.

3. RESEARCH OBJECTIVES

The study has five objectives. First, it critically synthesizes recent evidence on automated visual, geometric and sensor-based inspection of civil infrastructure. Second, it evaluates how calibration, measurement uncertainty and digital calibration records affect the trustworthiness of automated inspection outputs. Third, it examines the role of BIM, digital twins and asset-information environments in preserving traceability from field evidence to lifecycle decisions. Fourth, it identifies sustainability benefits, trade-offs and governance conditions relevant to Saudi infrastructure delivery. Fifth, it proposes research, managerial and policy priorities for implementing a scalable traceability-by-design architecture across projects and operating assets.

4. Research Questions

Four questions guide the synthesis: How does automation change the reliability and efficiency of infrastructure inspection? Which metrological controls are required to make automated measurements defensible for engineering acceptance? How can calibration and traceability data be integrated with BIM and digital twins across the asset lifecycle? Which institutional, technical, and managerial conditions are necessary for these systems to contribute to sustainable infrastructure outcomes in Saudi Arabia?

5. REVIEW METHODOLOGY

We adopted a structured integrative review design because the topic spans civil engineering, construction informatics, structural monitoring, machine vision, and metrology. The attached reference article informed only the manuscript's broad scholarly organization and its emphasis on transparent review logic; the authors did not reuse its substantive content, claims, or wording. The search strategy focused on concept clusters rather than a single technology. We considered Scopus, Web of Science, ScienceDirect, SpringerLink, Wiley Online Library, IEEE-oriented discovery, Google Scholar for citation tracing, and publisher databases. Search combinations included automated inspection, infrastructure inspection, bridge inspection,

computer vision, UAV, laser scanning, structural health monitoring, digital twin, BIM, calibration, metrological traceability, measurement uncertainty, digital calibration certificate, digital metrology, Saudi Arabia, sustainable construction, and Vision 2030.

The principal evidence window was 2020-2025 to capture the rapid transition toward AI-enabled inspection, digital twins, and machine-readable metrology. We considered earlier literature only where conceptually indispensable, but deliberately concentrated the final reference set within the stated window. Eligible sources were peer-reviewed journal articles or peer-reviewed review papers directly relevant to at least one of four analytical domains: automated infrastructure inspection; sensor or structural condition monitoring; digital twins/BIM for asset information; and calibration or traceability digitalization. We included Saudi-specific studies when they addressed digital construction or sustainable built-environment implementation. We excluded purely promotional technology reports, non-peer-reviewed web material, papers with no clear infrastructure or metrological relevance, and duplicate studies.

Screening was qualitative and did not use fabricated record counts. We first assessed titles and abstracts against the review questions, then evaluated full texts or publisher records as needed. Quality appraisal considered journal peer-review status, methodological transparency, clarity of the sensing or digital architecture, validation context, treatment of uncertainty or limitations, and transferability to infrastructure delivery. Review papers established field-level patterns; empirical studies tested whether those patterns had been demonstrated in field or laboratory applications. The final set contains exactly 30 peer-reviewed references. We checked each bibliographic record and DOI against a publisher page or an authoritative bibliographic record, and we report DOI links in the reference list.

The synthesis used thematic comparison rather than meta-analysis because outcomes are heterogeneous: studies report classification accuracy, defect localization, inspection time, data architecture, interoperability, calibration semantics, asset-management value, and organizational barriers using incompatible metrics. We coded evidence into five themes: sensing and automated inspection; calibration and uncertainty; digital traceability; asset-context integration; and sustainability/governance. The analysis then traced dependencies between themes. For example, computer vision may identify a crack, but dimensional acceptance requires scale and uncertainty; a sensor may stream displacement data,

but trend credibility depends on calibration history; a digital twin may visualize asset condition, but decision integrity depends on whether incoming data retain identity and provenance. This dependency-oriented synthesis is more useful for implementation than ranking technologies independently.

Methodological limitations were actively considered. AI's rapid development means performance reported on controlled datasets can quickly become outdated, while construction environments vary in lighting, access, dust, geometry, and asset type. Metrology literature is technologically mature but often originates from industrial calibration contexts rather than civil infrastructure. Conversely, construction studies often discuss data integration without explicitly addressing SI traceability or uncertainty. Saudi-specific peer-reviewed evidence remains smaller than the global evidence base. These limitations motivate a framework that distinguishes established principles from areas requiring local validation rather than implying universal readiness.

6. Thematic Literature Review and Critical Analysis

Automated inspection is shifting civil-infrastructure assurance from periodic observation toward data-rich condition assessment. Image-based methods are particularly mature. Liu and Yeoh showed that crack-pattern recognition can move beyond simple crack detection toward condition-relevant characterization [5], while Chow *et al.*, integrated mobile data capture, deep learning, LiDAR-based reconstruction, and BIM mapping to link detected concrete defects to structural elements [4]. Such integration matters because isolated image labels have limited engineering value unless the defect can be located, measured, and associated with an asset component. UAV research extends coverage to difficult and hazardous locations. Jeong *et al.*, combined UAV imagery with machine learning and visibility enhancement for bridge inspection [6], and Zhang *et al.*'s review found progress toward automation but also substantial residual dependence on human intervention across the inspection chain [7]. Ye *et al.*, similarly showed how UAV and smartphone imagery with deep learning can support post-earthquake bridge condition assessment [8]. The critical pattern is that data acquisition has become easier and faster, while engineering assurance has become autonomous.

The bottleneck is not only algorithm performance. Automated inspection is a measurement process. When a crack width, deflection, alignment, surface deviation, or thermal anomaly is used for acceptance, the result must relate to tolerance and uncertainty. This requirement is

often implicit in computer-vision literature, but explicit in metrology. Mustapää *et al.*, emphasize that collaborative sensor systems require attention to traceability and calibration metadata [11]. Gadelrab and Abouhoggail show why conventional certificate formats become inadequate when calibration information must participate in automated processes [12]. Research on DCC architectures, PDF/A-3 transitional solutions and metrological e-infrastructure demonstrates a progression from digitized documents to structured, machine-interpretable evidence [13-16]. The distinction is fundamental: a scanned certificate may be electronically stored, but it cannot reliably drive automated validity checks, uncertainty propagation, or asset-state qualification.

Digital calibration therefore acts as a trust layer for automated infrastructure sensing. Machine-readable certificates can carry instrument identity, calibration results, conditions, uncertainty, and digital authentication. Nummiliukki *et al.*, demonstrated an industrial proof of concept in which DCC information moves through a digitalized calibration environment [19]. At the same time, Engel describes the broader GEMIMEG-II architecture for machine-actionable metrology [20]. Smith *et al.*, show that DCC structures can hold richer uncertainty information than conventional certificates, including Monte Carlo outputs [21]. More recent work focuses on interoperable trust ecosystems, reusable software and harmonized semantics [22-25]. These studies collectively suggest that traceability can become executable: information systems can determine whether evidence meets defined metrological rules before admitting it into a quality decision.

Digital twins provide the complementary asset context. Boje *et al.*, identify semantic and dynamic-data requirements for a construction digital twin [1]; Jiang *et al.*, distinguish digital twins from BIM and cyber-physical systems while mapping civil-engineering applications [2]; and Opoku *et al.*, show that construction applications span monitoring, structural integrity, facilities management and other lifecycle functions [3]. In engineering asset management, Li *et al.*, argue that digital twins can evolve from technical representations toward socio-technical and environmental decision systems [26]. Yu *et al.*'s digital-twin-based bridge monitoring illustrates how measured responses and numerical models can be combined for fatigue evaluation [10]. The strongest implication for traceability is that the twin should not merely receive values; it should receive qualified values with identity, time, location, calibration state, and uncertainty attached.

This concept can be described as traceability by design. At the sensor layer, instruments and

imaging systems require fit-for-purpose calibration or verification. At the acquisition layer, time synchronization, environmental conditions, scale, coordinate reference, and data integrity must be controlled. At the analytics layer, AI models require versioning, validation domain, and confidence information. At the decision layer, measured or inferred quantities must be compared with engineering tolerances using explicit decision rules. At the asset layer, accepted evidence and its provenance should persist in the BIM/digital twin so that later inspections can be compared on a like-for-like basis. Figure 1 summarizes this chain. The architecture reduces the risk that sophisticated analytics create false confidence from unqualified data.

The sustainability contribution comes mainly from lifecycle efficiency rather than digitalization itself. Reliable automation can reduce repeat site visits, unnecessary access systems, destructive testing, and premature replacement. Persistent condition histories can support risk-based maintenance, extend asset life, and direct materials and labor to locations where intervention is justified. Jäkel *et al.*, show how digital-twin information can support operational sustainability assessment of bridges [27], and Jiao *et al.*, link digital twins with sustainable operation and maintenance of building infrastructure [28]. Yet these benefits are conditional. Sensors, UAV fleets, computing, and data centers consume resources; model maintenance demands skills; and false positives can cause unnecessary intervention. Sustainable performance therefore depends on whether the assurance system reduces whole-life resource use more than its own digital burden.

Saudi Arabia provides a compelling implementation context. Hasanain and Nawari propose BIM-enabled approaches for a sustainable built environment aligned with national transformation priorities [17]. Alnaser and Elmousalami report that Saudi construction professionals see important benefits in AI-enabled digital twins but also identify implementation challenges across organizational, technical, and governance dimensions [18]. These findings imply that Saudi traceability architecture cannot import a traceability architecture as a purely technical package. It must fit procurement models, regulatory responsibilities, laboratory accreditation, data-hosting rules, contractor capability, and asset-owner information requirements. The objective should be a national-quality ecosystem in which project evidence can move across designers, contractors, testing laboratories, supervising consultants and operators without losing meaning or trust.

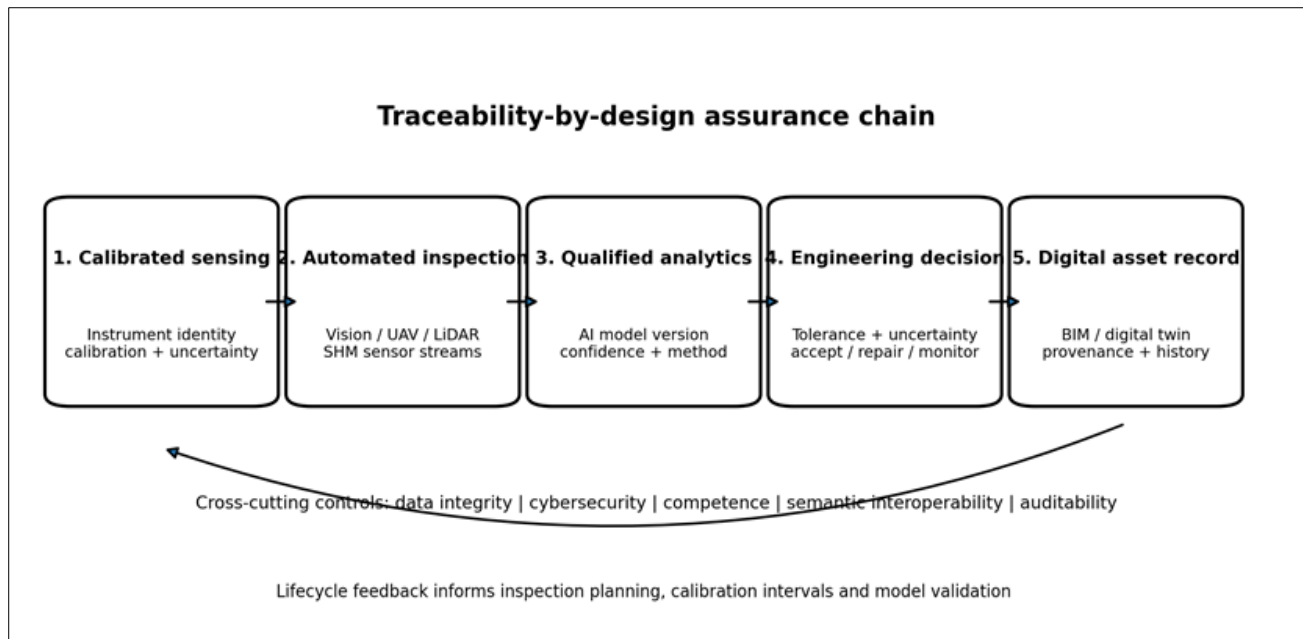


Figure 1: Traceability-by-design assurance chain linking calibrated sensing to persistent digital asset evidence

Table 1 compares the principal technology layers and their assurance dependencies. The comparison highlights a recurring asymmetry: sensing and visualization technologies are developing rapidly, whereas formal treatment of calibration, uncertainty and machine-readable provenance is less visible in construction implementation. Closing that asymmetry is central to

reliable automation. A project may have a high-resolution digital twin yet still have weak evidence if it cannot defend incoming measurements. Conversely, excellent calibration records have limited value if they remain detached from asset location, inspection context, and acceptance decisions.

Table 1: Technology layers, assurance dependencies and sustainability pathways in integrated digital inspection

Layer	Typical technologies	Primary value	Critical assurance dependency	Sustainability pathway
Sensing	Cameras, UAVs, LiDAR, SHM sensors	Faster and safer evidence capture	Calibration/verification, scale, synchronization, environment	Fewer repeat visits; reduced access and survey burden
Analytics	CNNs, ML, change detection	Defect recognition and condition inference	Model validation, domain limits, confidence, uncertainty	Earlier intervention; reduced rework and failure risk
Traceability	DCC, digital signatures, identifiers	Machine-checkable provenance and calibration status	Interoperable schemas, uncertainty fields, authentication	Less duplicated testing; defensible reuse of evidence
Asset context	BIM, digital twins, CDE/asset systems	Links evidence to components and lifecycle history	Semantic mapping, persistent IDs, version control	Targeted maintenance; longer asset service life
Decision/governance	Acceptance rules, dashboards, audit trails	Consistent risk-based action	Tolerance-to-uncertainty rules, human oversight, cybersecurity	Avoided unnecessary repair/replacement; accountability

A second issue is interoperability. DCC research increasingly emphasizes harmonized schemas, secure exchange and shared semantics [22-25]. Infrastructure projects face a similar challenge across BIM platforms, common data environments, inspection applications, laboratory systems and asset-management software. Interoperability must therefore cover both geometry and quality meaning. A crack measurement should carry units, uncertainty, method, equipment, location, date, operator or autonomous-agent identity, calibration status and decision outcome in forms that downstream systems can interpret. This approach also improves auditability: regulators and owners can reconstruct why an element was accepted, repaired or monitored without relying on disconnected PDFs and spreadsheets.

Cybersecurity and algorithm governance form another critical layer. Digitally signed certificates and trusted data spaces can protect identity and integrity, but secure transport does not prove that a measurement method is fit for purpose. Similarly, an accurate AI model can fail when deployed outside its validated domain. Governance must therefore combine cryptographic trust, metrological trust and engineering trust. Cryptographic trust asks whether data are authentic and unchanged; metrological trust asks whether values are traceable and uncertainty is acceptable; engineering trust asks whether the method and decision rule are appropriate for the asset and failure mode. Sustainable infrastructure delivery requires all three.

A further challenge concerns the difference between detection and measurement. Many AI inspection systems are optimized to answer categorical questions, such as whether cracking, spalling, or corrosion is present. Engineering acceptance often asks a harder quantitative question: how large is the defect, where is it relative to a design feature, how has it changed, and is the measured change significant relative to uncertainty? This distinction determines whether an automated result can support a contractual or safety decision. Coordinate metrology research is useful here because it treats machine interpretability and traceability as prerequisites for automated quality control, not optional metadata [24]. The same principle applies to photogrammetry and laser scanning: camera calibration, control geometry, point-cloud registration, and environmental effects should be linked to the reported result. For repeated inspections, the system must also preserve the measurement configuration so that apparent

deterioration is not confused with a change in sensor, algorithm, or coordinate frame.

Measurement uncertainty should consequently be treated as decision information. If a measured value is far from an acceptance limit, modest uncertainty may have little practical effect. If it lies near the limit, uncertainty can determine whether the correct action is acceptance, rejection, or further investigation. Smith *et al.*, demonstrate that digital calibration structures can carry detailed uncertainty information in machine-readable form [21], while emerging DCC interoperability work seeks to make such information usable across systems [25]. Infrastructure platforms could exploit this capability by assigning measurement-quality states to inspection records. A green state might indicate that traceability and uncertainty are clearly adequate; an amber state might require human review because uncertainty is material to the decision; and a red state might block acceptance because calibration, provenance, or method validation is missing. Such logic would make uncertainty operational rather than leaving it buried in certificate attachments.

The asset-information model also needs a stable semantic structure. Digital-twin research repeatedly identifies interoperability and lifecycle continuity as unresolved issues [1-30]. A useful infrastructure schema would separate the physical object, the inspection event, the measurement result, the instrument, the calibration record, the analytical model, and the engineering decision while linking them through persistent identifiers. This separation lets you revise a defect interpretation without overwriting the original observation, and evaluate a calibration update without losing historical context. It also supports forensic audit because it can reconstruct the state of evidence at the time of a decision. For Saudi giga-projects involving many packages and international suppliers, persistent identifiers are particularly important: asset evidence may pass through several organizations before handover, and semantic continuity is more durable than reliance on a single proprietary platform.

Calibration strategy itself can become risk-based. Fixed intervals are simple to administer but may under-control harsh applications or over-calibrate stable instruments. A digital assurance environment can combine calibration history, drift, utilization, environmental exposure, check-standard results, and consequence of measurement error to inform interval review. This does not remove laboratory accreditation requirements; rather, it gives asset owners a stronger evidence base for deciding when additional verification is necessary. The same logic applies to sensors embedded for long-

term monitoring, where retrieval for conventional calibration may be impractical. Redundant sensing, reference checks, in-situ verification and model-based diagnostics can provide evidence of continuing fitness, but these approaches need explicit uncertainty models and documented acceptance criteria. Structural-health-monitoring research shows the analytical potential of intelligent sensing [9,10], yet its use in regulated acceptance will depend on how these metrological questions are resolved.

Organizationally, integrated assurance changes responsibilities. Quality teams traditionally control inspection and test plans; surveyors control geometric measurement; laboratories control calibration; BIM teams control model information; and asset managers inherit selected records at handover. Automated traceability cuts across these boundaries. Without governance, each group may optimize its own system while the end-to-end evidence chain remains fragmented. A project-level digital assurance plan should therefore define data ownership, validation authority, exception handling and preservation rules before mobilization. It should also specify which decisions may be automated and which require signed professional review. This is consistent with the broader engineering-asset-management view that digital twins are socio-technical systems rather than merely technical replicas [26]. The design of roles, incentives and escalation paths is therefore as important as the selection of sensors or software.

Finally, plan evidence reuse from construction through operations. Commissioning measurements, alignment records, material-condition evidence and baseline imagery have substantial value for later diagnostics, but only when their provenance remains interpretable. If operating teams receive only a folder of reports, they largely lose the opportunity for longitudinal comparison. If they receive qualified observations linked to asset objects, later inspections can automatically retrieve the baseline, identify changes, and determine whether the same or an equivalent measurement process was used. This creates a direct bridge between construction quality and asset-management sustainability. It turns handover from document transfer into the transfer of a traceable measurement history, which better aligns with the lifecycle ambitions of digital twins and sustainable infrastructure management [27,28].

7. DISCUSSION

The literature supports a shift from document-centric quality control toward evidence-centric assurance. In the conventional model, inspection reports, calibration certificates, test

sheets, and BIM files are separate deliverables assembled retrospectively. In the integrated model proposed here, traceability metadata travel with the measurement and are checked before the evidence influences a decision. This changes calibration from a periodic compliance activity into an active digital control. It also changes the digital twin from a visualization platform into a governed evidence environment.

Figure 2 presents the resulting closed-loop model. Calibrated sensing and automated inspection generate qualified observations; analytics transform observations into defect or condition indicators; engineering rules convert indicators into acceptance, repair, or monitoring decisions; the digital twin stores both asset state and evidence provenance; and operational outcomes feed back into inspection planning, calibration intervals, and model validation. The loop is deliberately not fully autonomous. Human review remains necessary where failure consequences are high, data quality is marginal, uncertainty approaches tolerance, or the AI encounters conditions outside its validated domain. The appropriate goal is risk-proportionate automation, not elimination of professional judgment.

This synthesis also clarifies the relationship between sustainability and quality. Rework prevention is a direct sustainability mechanism because avoided defects reduce material, energy, transport, and schedule waste. Traceable dimensional control can reduce over-conservative corrective work when uncertainty is understood. Condition-based maintenance can defer replacement while maintaining safety. Better evidence can also improve handover, preventing the common loss of commissioning and calibration knowledge between project and operations. These mechanisms are stronger than generic claims that digital technologies are inherently green. They link measurement reliability to resource decisions across the asset lifecycle.

For Vision 2030 projects, scale creates both leverage and risk. Large programs can standardize data requirements, approved inspection methods, and calibration semantics across supply chains, producing network effects and reusable digital assurance components. Yet scale also amplifies inconsistency when each project defines its own naming, certificate format, or AI validation approach. The strategic opportunity is therefore to establish common minimum requirements for machine-readable metrological evidence while allowing project-specific methods above that baseline. This would align innovation with accountability rather than forcing a choice between them.

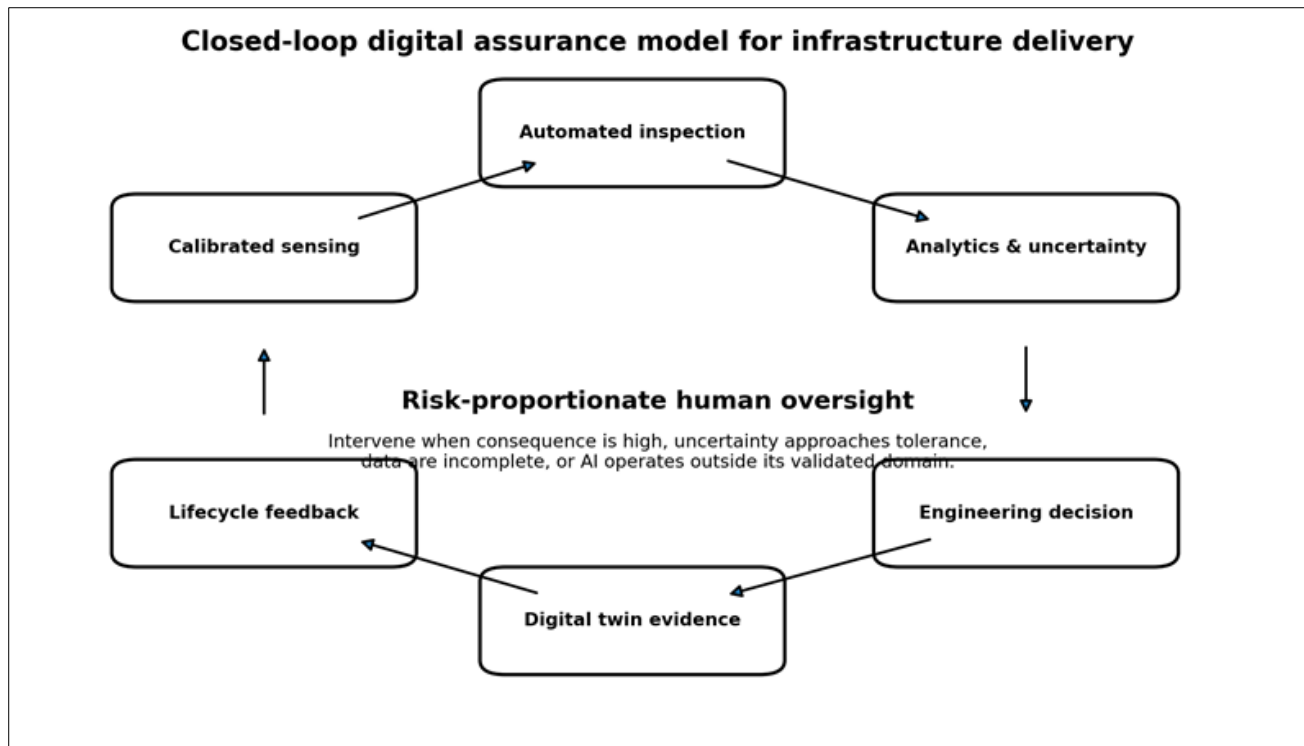


Figure 2: Closed-loop assurance model with risk-proportionate human oversight

A practical consequence is that evidence quality must be assessed before data aggregation. When low-quality measurements are merged into dashboards, the visual coherence of the result can conceal weak provenance. A traceability-first workflow instead evaluates instrument status, environmental validity, uncertainty, time synchronization, and method suitability at source. Only qualified records proceed to analytics.

8. Research Gaps and Future Research

Four research gaps are especially important. First, civil-infrastructure studies rarely quantify how calibration uncertainty propagates through AI-based measurement and final acceptance decisions. Future experiments should report end-to-end uncertainty budgets for image-derived dimensions, photogrammetric deformation, laser-scan geometry, and sensor-based condition indicators. Second, DCC research has advanced machine-readable calibration, but mappings between DCC fields and BIM/digital-twin object schemas remain underdeveloped. Semantic links should be tested for common infrastructure instruments and inspection classes.

Third, field validation under Saudi conditions is limited. Heat, dust, glare, long transport corridors, large concrete surfaces, and mixed contractor ecosystems can affect sensors, imagery, communications, and maintenance practice. Demonstration projects should compare automated and conventional inspection while tracking accuracy, safety exposure, rework, carbon-relevant resource

use, and lifecycle cost. Fourth, governance research should define thresholds for human intervention and AI revalidation. A practical maturity model could distinguish advisory automation, supervised acceptance, and bounded autonomous acceptance according to failure consequence, uncertainty ratio, data completeness, and model confidence.

Future research should also test whether traceable digital evidence improves sustainability outcomes, not just inspection productivity. Longitudinal studies are needed to establish whether verified condition data actually extends maintenance intervals, reduces unnecessary replacement, and improves asset availability. This would connect digital-quality research to measurable Vision 2030 outcomes.

9. Practical, Managerial and Policy Implications

Project owners should specify traceability requirements at procurement rather than requesting calibration evidence only at audit or handover. Information requirements should define which measured quantities are acceptance-critical, required uncertainty-to-tolerance ratios, permitted automated methods, calibration status checks, metadata fields, and retention periods. Contractors should integrate instrument registers with inspection applications so that expired or unsuitable equipment is flagged automatically. Testing and calibration laboratories should prepare for machine-readable

outputs and secure interfaces instead of treating PDF certificates as the final digital state.

Managers should establish a digital assurance role spanning quality, BIM, surveying, testing, cybersecurity, and asset management. Fragmented ownership is a major implementation

risk because no single discipline otherwise controls the complete evidence chain. Competence programs should therefore cover not only AI tools but also measurement uncertainty, decision rules, data provenance, and limitations of automated models. Table 2 translates the framework into staged implementation priorities.

Table 2: Staged implementation roadmap for traceable automated inspection in Saudi infrastructure programs

Stage	Priority action	Owner focus	Evidence requirement	Expected outcome
1. Define	Classify acceptance-critical measurements	Asset owner / designer	Tolerance, required uncertainty, retention rule	Clear assurance basis before procurement
2. Connect	Link instrument register, DCC and inspection IDs	Contractor / laboratory	Unique equipment ID, calibration status, method metadata	Automatic pre-use validity checks
3. Qualify	Validate automated method in project conditions	Quality / engineering / digital teams	Accuracy, uncertainty, failure modes, human-review triggers	Bounded and defensible automation
4. Integrate	Attach qualified evidence to BIM/digital-twin objects	Information manager / asset team	Persistent asset ID, location, time, provenance	Auditable lifecycle evidence
5. Improve	Use operational outcomes to refine inspection/calibration	Operator / regulator / program owner	Trend history, false-positive/negative review, recalibration triggers	Longer asset life and scalable learning

At policy level, Saudi regulators and major asset owners could accelerate adoption through common requirements for digital calibration identifiers, interoperable units and uncertainty fields, secure certificate validation, and persistent linkage between test evidence and asset objects. Pilot programs should focus on high-value repetitive use cases such as concrete geometry, bridge visual inspection, rail and road asset monitoring, MEP commissioning, and environmental sensors. National guidance should remain technology-neutral: requirements should define evidence quality and traceability outcomes rather than mandating particular vendors. This would encourage innovation while preserving comparability and auditability across the infrastructure portfolio.

10. Limitations

This review integrates heterogeneous bodies of literature and therefore cannot provide a pooled estimate of productivity, accuracy, or sustainability benefit. Many inspection studies evaluate specific datasets or assets, while metrology studies often address industrial rather than construction use cases. The Saudi evidence base is expanding but remains smaller than the international literature. The review also focuses on peer-reviewed publications and does not attempt to catalog every relevant technical standard, procurement specification, or regulatory document. Consequently, treat the proposed framework as a research-informed architecture requiring project-level validation, not as a substitute

for discipline-specific standards or statutory acceptance procedures.

11. CONCLUSION

Automated inspection can make infrastructure assurance faster, safer, and more continuous, but automation alone does not make evidence trustworthy. The decisive requirement is an unbroken chain linking physical observations to calibrated instruments, quantified uncertainty, authenticated provenance, engineering decision rules and persistent asset context. Recent advances in DCCs show that calibration and traceability information can become machine-readable and actionable. At the same time, digital twins provide a lifecycle environment in which qualified evidence can be retained and reused. Bringing these developments together creates a practical route from isolated digital tools to traceability-by-design.

For Saudi Vision 2030, this integration can support sustainable delivery by preventing rework, enabling targeted maintenance, extending asset life and improving accountability across complex supply chains. The strongest implementation model is not full autonomy but risk-proportionate automation governed by metrological, cybersecurity, and engineering controls. A shared national baseline for interoperable traceability metadata, combined with project-specific validation of automated methods, would allow Saudi infrastructure programs to scale digital innovation without weakening assurance. The

next research frontier is therefore not simply better defect-detection algorithms; it is demonstrably reliable decision systems in which every critical measurement can be understood, verified, and traced throughout the asset lifecycle.

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