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Review Article

IoT-Enabled Structural Health Monitoring for Smart Cities in Saudi Arabia under Vision 2030: Integrating Embedded Sensor Networks, Real-Time Data Acquisition, and Cloud-Based Infrastructure Intelligence

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Abstract: Structural health monitoring is increasingly relevant to smart cities because deterioration, changing loads and climatic exposure cannot always be captured through periodic inspection. This review evaluates how embedded sensors, synchronised acquisition, wireless communications, edge analytics and cloud-based infrastructure intelligence can form a trustworthy evidence chain for bridges, buildings and associated urban assets. A structured, critical synthesis of 30 traceable publications from 2020–2025 is organised around sensing reliability, network performance, diagnostic inference, lifecycle decision-making and Saudi deployment requirements. The review distinguishes measurement continuity from diagnostic validity and identifies three persistent weaknesses: uncertain sensor provenance, insufficient separation of environmental variation from damage, and weak translation of alerts into auditable maintenance actions. It develops an asset-centred architecture with local safety safeguards, governed data exchange, uncertainty-aware analytics and human engineering review. For Saudi Arabia, the framework prioritises heat-tolerant instrumentation, long-term calibration, communications resilience and cross-organisational asset governance. The contribution is a set of testable implementation criteria rather than unverified claims of performance or a new empirical dataset. Under Vision 2030, effective monitoring should be judged by reproducible condition evidence and defensible intervention decisions, not simply the number of connected devices.

Keywords: Structural Health Monitoring, Internet of Things, Embedded Sensing, Edge Computing, Cloud Intelligence, Bridge Monitoring, Saudi Vision 2030, Infrastructure Resilience.

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1. INTRODUCTION

Urban infrastructure becomes intelligent only when observations can be converted into decisions that maintain safety, service continuity and long-term value. Structural health monitoring (SHM) provides a basis for this conversion by tracking quantities associated with structural behaviour, including acceleration, strain, displacement, cable tension and environmental exposure. Internet of Things (IoT) connectivity expands traditional monitoring beyond isolated loggers by allowing remote acquisition, diagnostic computation and coordinated asset oversight. Yet connectivity alone does not establish structural safety. A sensor can report precisely while measuring the wrong location, drifting with temperature or losing synchronisation with neighbouring devices [1–4].

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Saudi Arabia provides an important setting for examining this distinction. Vision 2030 has stimulated digital transformation and ambitious urban development, while established cities continue to operate bridges, public buildings and transport corridors with heterogeneous ages and maintenance records. Research on Saudi urban computing identifies opportunities for integrated services but also stresses institutional and implementation barriers [5]. Recent work on urban digital twins likewise highlights the significance of interoperability, infrastructure readiness and secure data governance rather than treating simulation as a substitute for asset knowledge [6]. Such considerations make structural intelligence an engineering and organisational issue simultaneously.

The central problem is not a shortage of sensing technologies. It is the absence of a clearly governed path from physical response to defensible maintenance action. A bridge acceleration anomaly, for example, may reflect temperature, traffic loading, imperfect sensor attachment, equipment damage or genuine stiffness change. Without independent context and uncertainty estimates, an automated alert risks becoming either misleading reassurance or an expensive false alarm. Bayesian assessment, collaborative diagnosis and monitoring-system reliability studies demonstrate why the quality of interpretation matters at least as much as data availability [7–9].

This review asks three questions. First, which sensor and acquisition arrangements produce sufficiently comparable measurements for long-term urban deployment? Secondly, how should edge, network and cloud functions be allocated to protect timeliness, data integrity and diagnostic reliability? Thirdly, what governance conditions allow monitoring outputs to influence inspection priorities, maintenance planning and public infrastructure resilience in Saudi Arabia? Its distinct contribution is an integrated evidence-to-action framework spanning instrumentation, information systems and engineering accountability, rather than another catalogue of connected devices.

2. Review design and Interpretive Method

A structured critical literature review was adopted because the purpose was to integrate engineering mechanisms and deployment decisions, not to estimate a pooled treatment effect. The evidence base comprises 30 identifiable publications dated 2020–2025, each paired with a digital object identifier. They cover wireless structural sensing, synchronised acquisition, cloud architecture, condition inference, digital twins, energy autonomy, sensor faults and Saudi smart-city implementation. Engineering case studies were read alongside conceptual and review articles so that proposed benefits could be distinguished from tested capabilities. Comparative claims were restricted to what the publications evaluated; findings were not pooled or extended to other structures without explicit engineering justification.

Sources were selected purposively through targeted searches for combinations of structural monitoring, wireless sensors, edge computing, cloud platforms, damage detection, digital twins, bridge reliability and Saudi urban development. Inclusion required clear relevance to civil infrastructure or a transferable decision mechanism, an identifiable publication year within the requested interval and a traceable DOI. Purely promotional accounts, unverified performance claims and papers outside that interval were excluded. This is an interpretive, bounded synthesis: it does not claim exhaustive database coverage, formal risk-of-bias scoring or fabricated screening totals.

Each source was examined against five analytical questions: what is measured; how measurement uncertainty enters; where computation occurs; what decision the output supports; and what conditions limit transfer to other assets. Claims were classed as demonstrated application, methodological proposal or context-specific interpretation. Cross-cutting mechanisms were then assembled into a layered architecture and an operational assurance pathway. Comparisons remain qualitative because the underlying experiments use different assets, sampling rates, damage definitions and success criteria. Consequently, no numerical improvement in Saudi asset safety or maintenance cost is attributed to this review itself.

3. Instrumentation and Embedded Sensor Networks

A defensible system starts with the physical quantity most closely linked to the intended failure mechanism. Accelerometers are suitable for identifying dynamic characteristics and changes in vibration response, whereas strain gauges can follow local demand and fatigue-sensitive details. Fibre-optic sensing offers distributed or multiplexed measurements and may be advantageous where electromagnetic interference or long cable runs complicate conventional instrumentation. Displacement sensors, inclinometers and positioning systems provide complementary observations of deflection, movement and rotation. No modality is universally superior: sensitivity, drift, installation access, sampling requirements and interpretation determine practical suitability [10–12].

Sensor placement should follow structural load paths and plausible deterioration modes, not the convenience of installing a gateway. Sparse arrays can identify global changes but may miss local cracking, bearing distress or corrosion-related section loss. In contrast, dense arrays increase maintenance burden, transmission demand and the number of opportunities for sensor faults. Optimisation studies show that model uncertainty, especially uncertain boundary conditions and modal properties, changes the value of candidate locations [13, 14]. A robust design therefore combines engineering judgement, preliminary structural models and sensitivity analysis before the first device is installed.

Embedded sensing creates a further distinction between measurement access and measurement representativeness. Sensors cast into a new element may provide stable contact and protection, but can be difficult to replace or recalibrate. Surface-mounted devices are accessible yet vulnerable to accidental impact, delamination, water ingress and changes in attachment stiffness. The installation record should capture asset identifier, orientation, depth or mounting method, calibration certificate, firmware version and baseline conditions. Traceable metadata are indispensable when recordings from multiple maintenance contractors must remain comparable over decades. A streaming number without such provenance cannot support reproducible engineering interpretation.

Low-cost microelectromechanical accelerometers expand feasible monitoring coverage, although their noise floors and drift behaviour must be evaluated against the expected response. Research on compact IoT sensing and instrumented drive-by bridge assessment demonstrates promising acquisition models while also illustrating that the moving vehicle, vehicle speed and route become part of the measurement system [1-15]. Such arrangements can help prioritise inspection across a network, but they should not be represented as interchangeable with permanent, bridge-mounted instrumentation where precise modal tracking is required.

In practical terms, system acceptance should begin before procurement with a failure-mode register. For each structure, engineers can identify the deterioration mechanism, observable response, required detection lead time and independent verification route. This procedure discourages collecting high-frequency data where the corresponding failure process is slow or weakly observable. It also exposes assumptions that a procurement proposal might otherwise conceal: whether a bearing movement can be distinguished from temperature expansion, whether a crack can be inferred from global acceleration, and whether enough baseline information exists to separate sensor drift from structural change. Each assumption should become a documented commissioning test.

Power autonomy is essential for remote structures, elevated crossings and dispersed urban assets. Batteries impose an ongoing access and replacement obligation; solar or vibration harvesting can reduce this burden but depend on local environmental energy and duty cycles. Reviews and experimental studies of bridge energy harvesters indicate technical feasibility under suitable excitation, while whole-system implementations stress the need to consider energy conversion, storage and communications together [16–18]. In Saudi conditions, high ambient temperatures may accelerate battery ageing, making thermal qualification, enclosure design and conservative maintenance intervals more important than nominal manufacturer endurance.

Table 1: Sensing alternatives and engineering deployment considerations

Modality	Primary observation	Reliability constraint	Appropriate application
MEMS accelerometers	Global response, mode changes	Timing, noise floor, thermal drift	Bridges, towers; verify modal sensitivity
Foil strain gauges	Local strain and fatigue demand	Bond integrity, thermal compensation	Critical joints and retrofit details
Fibre-optic sensors	Multiplexed strain and deformation	Interrogator cost, fibre continuity	Long members and difficult wiring
Displacement / tilt	Movement, settlement, rotation	Reference stability, mounting geometry	Bearings, joints, walls and foundations
Environmental probes	Heat, humidity, corrosion context	Calibration drift, exposure durability	Context normalisation, not damage proof
Optical / remote sensing	Surface geometry and movement	Lighting, visibility, registration	Targeted inspection and access-limited assets

4. Real-Time Acquisition, Time Alignment and Communication

Continuous monitoring requires more than continuous connectivity. It requires time-stamped, quality-controlled observations acquired at rates appropriate to the physical process. Dynamic modal analysis depends on sampling frequency, antialias filtering and synchronisation among channels; slowly varying strain or displacement may require a different acquisition schedule. Research on synchronised IoT monitoring shows how distributed sensor nodes can be coordinated without a fully wired network, but synchronisation error remains a design variable rather than a negligible implementation detail [2]. Instrument specifications should therefore state allowable timing offset, jitter, packet loss and recovery behaviour.

Connectivity choices must be made from required data volume, power budget, geographic coverage and tolerance for delay. Short-range networks may support local node clustering; cellular or narrowband links can connect remote gateways; fibre or fixed Ethernet suits assets with reliable physical access. Long-range low-power communication is attractive for health indicators and event notifications, but raw high-rate vibration streams may exceed its practical throughput. A novel cable-monitoring device illustrates an alternative: identify modal quantities locally and transmit compact engineering features instead of every sampled waveform [19]. This reduces traffic but makes transparent algorithm versioning and retention of representative raw windows crucial.

Fault tolerance should operate at several layers. A node should buffer measurements during outages, a gateway should validate schema and timestamps, and a receiving service should record missing intervals instead of silently reconstructing a complete-looking series. Store-and-forward behaviour protects continuity, although delayed data must be distinguished from live status in engineering dashboards. Network health indicators should include packet delivery, sensor heartbeat, clock drift, storage fill level and retransmission count. These operational metrics are not secondary IT diagnostics; they determine whether absence of an alarm means a stable structure or an unavailable monitoring channel [4-9].

Operational resilience includes recovery after rare events. Following flooding, unusual wind, impact or a power interruption, sensors may be damaged at the same moment that their information becomes most valuable. Redundant reference channels, local non-volatile buffering and a rapid post-event functionality check can protect the credibility of subsequent assessments. Recovery procedures should specify which measurements remain admissible, when temporary visual inspection is required, and what evidence authorises a return to normal monitoring status. These provisions reduce the risk that network availability is mistaken for proof of structural stability at the point of greatest uncertainty.

Data quality controls should be physically interpretable. Accelerations may contain saturation, spikes, dropped samples, aliasing or orientation errors; strain data may exhibit offset drift or thermal sensitivity. Automated screening can flag implausible ranges, sudden baseline shifts and conflicting neighbouring channels, but must retain the unaltered original measurements for later scrutiny. Reconstruction algorithms provide options for incomplete time series; recent studies report neural approaches for missing sensor data, yet imputed values must carry explicit flags and uncertainty rather than being presented as direct observations [20, 21]. This separation preserves evidential integrity during retrospective investigations.

5. Edge–Cloud Allocation and Infrastructure Intelligence

A city-scale system benefits from layered computation because structural events, communication delays and analytical workloads have different tolerances. At the sensor, preprocessing may include calibration, windowing and basic fault detection. At the gateway or edge server, event triggers and rapid anomaly screens can operate during intermittent wide-area connectivity. The cloud is better suited to historical comparison, model training, fleet analytics and controlled collaboration among owners and engineers. Published edge, fog and cloud arrangements demonstrate the practicality of distributing monitoring services rather than concentrating all operations in a single remote application [3].

The engineering requirement is graceful degradation. Loss of cloud access should not disable local recording or safety-critical threshold evaluation. Conversely, edge models should not silently make irreversible interventions outside their validated domain. Adaptive edge-intelligence research presents methods that combine node-level processing and network coordination, while showing why latency gains must be balanced with model assurance and sensor limitations [22]. An appropriate system distinguishes immediate operational warnings from advisory indications that require expert review, preserving the responsibility of competent engineers for structural safety decisions.

A cloud data platform should organise information by persistent asset identifiers, structural component, measured quantity, timestamp, units and acquisition lineage. A useful record contains both sensor observations and contextual information such as inspection findings, drawings, maintenance history, load restrictions and environmental conditions. Cloud infrastructure then provides a controlled analytical workspace, not merely an inexpensive store for telemetry. Versioned models, access logs and reproducible computations permit conclusions to be revisited when an inspection discovers previously unknown deterioration or when a sensor fault is subsequently confirmed.

A related issue concerns continuity across contractors and software versions. Infrastructure data frequently outlive the original platform supplier. Without explicit units, coordinate conventions, time standards, calibration identifiers and ownership rules, a historical database may become unusable even while files remain technically accessible. Open interchange formats and export testing should consequently form part of contract acceptance. Model changes need a reproducible change log and a comparison with prior outputs so that revised algorithms do not retrospectively change the apparent condition of an asset without explanation. Such controls make long-term monitoring valuable for engineering investigation rather than only for immediate visual reporting.

Digital twins are relevant where measured behaviour is connected to a model that can be updated and interrogated. Studies have linked optical measurements to bridge dynamic response and explored the incorporation of real-time data into structural simulation [23, 24]. Yet fidelity depends on assumptions about materials, supports, loads and boundary conditions. A visually persuasive three-dimensional model is not automatically a calibrated engineering twin. Computational approaches using sparse motion data illustrate how observations can update model representations, but the limits of observability should remain explicit [25]. Visualisation must communicate confidence and missing evidence rather than conceal them.

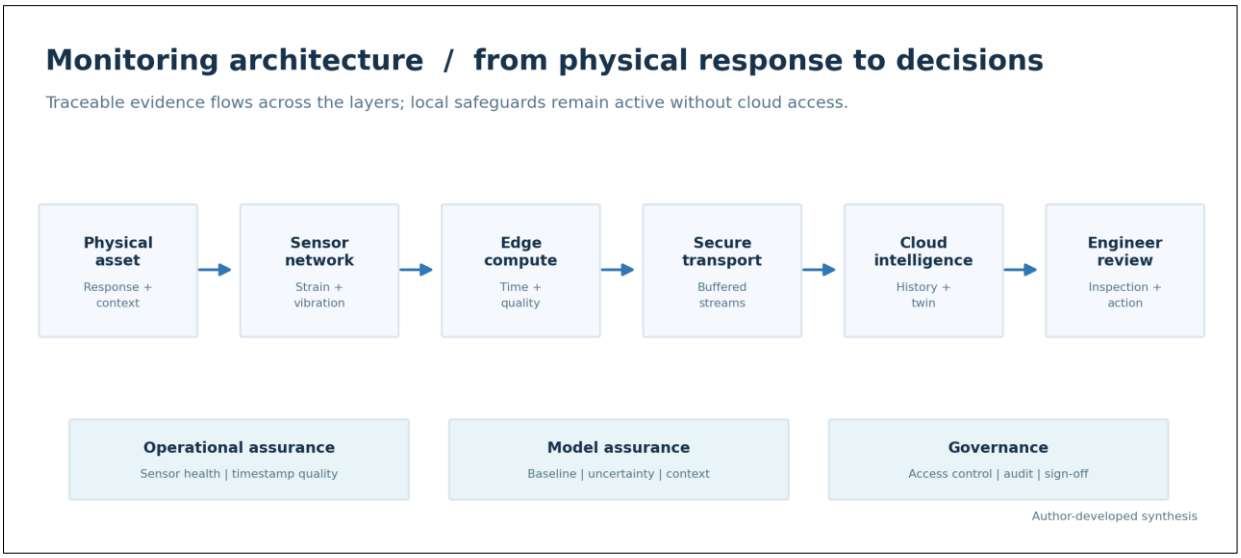


Figure 1: IoT-to-decision architecture with cross-layer assurance controls. Original conceptual figure

6. From Changing Signals to Credible Diagnostics

The most difficult inference is distinguishing damage from ordinary variability. Traffic, wind, temperature, occupancy and operational schedules change measured vibration even when physical condition is stable. Thermal effects can generate systematic movements and modal changes that resemble deterioration; temperature-sensitive anomaly identification research illustrates the importance of treating environment as an explanatory variable [26]. Baseline models should therefore capture seasonal and operational regimes, not rely on one commissioning-day recording. Where early healthy-state data are unavailable, engineers should document the limitations of any transferred baseline.

Data-driven methods can recognise complex patterns, but a lower classification error in a controlled experiment does not establish field reliability. Reviews of deep learning-based SHM identify applications in image analysis, vibration-based diagnostics and sensor-data recovery, while highlighting generalisation and practical deployment barriers [27]. Hybrid convolutional and recurrent models can identify temporal damage signatures, yet the diagnostic meaning of learned features is sometimes opaque [28]. Training data, damage labels

and loading regimes therefore require careful documentation before such systems influence asset restrictions or emergency responses.

Transfer methods are attractive when damage-labelled observations are scarce, a common constraint because well-maintained structures seldom provide examples of every possible failure. Bayesian transfer approaches and unsupervised diagnosis can support probabilistic inference, but their credibility depends on explicit assumptions concerning similarity among structures [7]. An anomaly score should not be relabelled as a probability of collapse without a defensible physical and probabilistic model. Engineers need accessible evidence explaining which channels changed, whether the change persists after environmental correction, and whether independent measurements corroborate the diagnosis.

Interpretation also benefits from a distinction between detection, localisation, severity assessment and prognosis. Detection establishes that a measured state differs from expectation. Localisation seeks the affected component or region. Severity assessment relates that change to structural capacity or serviceability, while prognosis estimates future evolution under uncertain loading and environment. Each stage requires additional evidence and may have a different attainable accuracy. Procurement documents should not use these four terms interchangeably. A demonstrator that detects a frequency shift has not necessarily shown that it can reliably quantify a crack, forecast residual life or justify reopening a restricted structure.

Uncertainty must accompany alarms throughout the decision chain. Measurement error concerns instrumentation; model uncertainty concerns assumed geometry and stiffness; operational uncertainty concerns loads and environmental exposure; and diagnostic uncertainty concerns alternative explanations. A monitoring study may provide strong evidence that response has changed without identifying its cause or consequence. Bayesian deterioration assessment and the value-of-information literature show why these distinctions matter for selecting inspections and interventions [8, 9]. The preferred outcome is not the maximum number of alerts, but timely identification of changes that meaningfully alter engineering decisions.

7. Maintenance Integration, Assurance and Cyber Resilience

An operational platform should connect diagnostic evidence to a named decision owner. When a threshold is exceeded, the system should create a case with sensor traces, baseline comparison, environmental context, uncertainty statement and recommended verification action. An asset engineer can then request recalibration, targeted inspection, non-destructive testing, load assessment or closer monitoring. Human–machine collaboration research demonstrates the value of integrating automated classification with structural expertise when damage examples are incomplete [29]. This workflow prevents isolated dashboard alarms from becoming an unrecorded substitute for a formal maintenance process.

Sensor systems themselves require inspection. Electronics age, cables corrode, enclosures leak and mounting conditions change; fault-aware value-of-information analysis demonstrates that a degraded monitoring system can weaken downstream decisions [9]. Asset owners should schedule calibration checks, test event reporting, review data completeness and periodically challenge diagnostic assumptions. Independent reference measurements are particularly useful after repairs, extreme weather or device replacement. A record of failed checks should reduce confidence in subsequent conclusions until the underlying problem is resolved, rather than simply disappear from management reports.

Cybersecurity forms part of measurement assurance because unauthorised modification of telemetry, calibration values or alert thresholds can misrepresent physical risk. Segmented networks, device identity management, encrypted communications, signed firmware, least-privilege access and immutable audit trails provide complementary safeguards. Cloud users should be granted access according to asset responsibility, while raw sensor evidence and engineering decisions should have distinguishable retention and approval rules. Cross-agency access must not imply unrestricted access to critical infrastructure data. An incident response plan needs to cover both system recovery and the engineering consequences of uncertain measurements.

A credible alert protocol should also distinguish informational deviations, inspection triggers and urgent operational warnings. Informational deviations may warrant trend observation, while inspection triggers require a responsible engineer to assess supporting evidence within an agreed service window. Urgent warnings should be reserved for validated conditions with clear operational consequences and approved escalation authority. Repeated false alerts can cause alarm fatigue, whereas thresholds set too conservatively may conceal developing damage. Threshold governance must therefore combine

physical safety margins, historical noise distributions, changing exposure conditions and post-event review. Every exception should generate a record that supports later recalibration of the process.

Performance indicators should reflect the complete monitoring service. Device availability and transmission uptime are necessary but insufficient. More informative measures include calibrated-channel coverage, proportion of usable time windows, rate of investigated anomalies, time to engineering acknowledgement, evidence completeness, inspection findings and closure quality. Decision outcomes should be reviewed against pre-deployment baselines, asset criticality and total ownership costs. Only such evaluation can reveal whether a connected monitoring investment actually improves maintenance prioritisation or merely increases data volume.

8. Deployment Considerations for Saudi Smart Cities

Saudi deployments must accommodate severe heat, airborne dust, intense solar exposure, occasional heavy rainfall and highly variable access conditions. These factors affect sensor housings, adhesive bonds, cable glands, batteries, cooling requirements and enclosure ingress protection. Coastal assets may also face aggressive chloride exposure, while inland installations can experience substantial daily thermal gradients. These are engineering design considerations rather than evidence that a particular Saudi infrastructure portfolio has already achieved measured deterioration reductions. Qualification plans should test calibration stability, thermal cycling, ingress protection, replaceability and communication reliability under the expected site conditions.

The portfolio is also heterogeneous. A new smart district can reserve conduit routes, sensor niches, network cabinets and digital asset identifiers during design. An operating urban bridge may require traffic management, restricted work windows and reversible attachments. Historic or architecturally sensitive structures may need non-contact measurements and a different tolerance for installation. A review of non-contact bridge sensing shows the value of complementary optical and remote methods, alongside constraints concerning line of sight and environmental interference [30]. Deployment strategies should therefore separate new-build readiness from retrofit complexity.

Saudi urban computing research identifies the need to translate digital ambition into workable cross-institutional arrangements [5]. In the monitoring domain, this means agreeing who owns sensors, who maintains gateways, who is permitted to update a structural model and who signs an inspection decision. Urban digital-twin literature relevant to the Kingdom similarly emphasises data governance and practical readiness [6]. Central platforms can help combine information across municipal, transport and developer assets, but shared dashboards should not erase legally distinct duties, engineering standards or asset-specific risk tolerances.

Prioritisation should start with consequence and uncertainty. High-occupancy structures, essential transport crossings and assets with known deterioration can justify higher instrumentation effort than relatively simple low-consequence facilities. Candidates for pilot deployment should have accessible drawings, baseline condition surveys and a clearly defined maintenance decision to improve. The pilot must collect data through representative hot and cooler periods before damage-sensitive thresholds are trusted. Commissioning should include a simulated outage, a device replacement, a misleading alarm and a formal decision handover, not merely a demonstration that cloud charts update.

External validity is particularly important for emerging-city infrastructure. A pilot performed on an accessible demonstration bridge cannot establish identical feasibility for a complex flyover, a remote overpass or a heavily occupied high-rise. Moving from pilot to portfolio requires evidence about installation time, safe access, communications shadowing, maintenance workload and the availability of qualified local personnel. Standardised acceptance templates can support scaling, but the selected sensors and diagnostic models should remain asset specific. This balance between common information governance and local structural engineering judgement is central to a sustainable monitoring service.

Implementation under Vision 2030 should be framed as a capability-building pathway, not a promise that digitalisation itself guarantees resilience. Procurement specifications ought to mandate open data structures, long-term device support, ownership of raw observations and exportable engineering evidence. Local teams need training in instrumentation, structural dynamics, security, statistical interpretation and asset management. Contracting should reward usable, validated information and timely corrective decisions rather than sensor counts. These provisions position connected monitoring as a sustainable operating capability rather than a technology installation that becomes obsolete when a supplier changes.

Table 2: Evidence-to-action acceptance gates for operational monitoring

Assurance stage	Required evidence	Acceptance indicator	Accountable role
Measurement acceptance	Calibration, timestamp and asset ID	Usable-channel share; clock-offset record	Instrument owner
Transport resilience	Buffering and authenticated delivery	Missing-data duration; recovery verification	Network and OT lead
Analytical validity	Baseline context and documented model	Context-adjusted false escalation review	SHM analyst
Engineering escalation	Corroboration and uncertainty statement	Time to qualified assessment	Structural engineer
Maintenance closure	Inspection record and intervention trace	Confirmed findings; closure audit	Asset manager

9. Integrated Framework and Evaluation Propositions

Figure 1 presents a layered architecture joining the physical asset to a governed engineering response. Its organising principle is evidential continuity: every analytical conclusion should be linked backwards to an identified sensor, a known calibration state, a timestamped observation and relevant environmental context. Local edge services preserve essential monitoring during communications failures, whereas cloud services maintain longitudinal trends and coordinated information. Each processing transition creates a documented quality gate. This arrangement accommodates heterogeneous sensor vendors without assuming that identical sampling or transmission methods are appropriate for every asset.

Figure 2 converts this architecture into an assurance sequence. A measurement is not promoted directly into a damage claim; it passes through data-quality review, environmental adjustment, model-based or statistical interpretation, uncertainty assessment and an explicit intervention decision. Escalation can occur immediately when a validated extreme threshold is crossed, but normal diagnostic routes require independent corroboration. The framework yields four evaluation propositions: provenance quality improves interpretability; robust edge functions reduce evidence loss during outages; explicit environmental correction reduces avoidable false alarms; and recorded engineer review improves the traceability of maintenance decisions.

Table 1 compares sensing options against field constraints, while Table 2 translates the conceptual pathway into measurable acceptance criteria. Neither table assigns invented numerical performance scores. A future evaluation should use a matched before-and-after operational design, with consistent asset risk classes and reporting intervals. Appropriate endpoints include usable data availability, time between anomaly and verified inspection, false-escalation burden, detected defects confirmed independently and maintenance decisions changed by monitoring evidence. Financial evaluation should include installation, licensing, calibration, battery replacement, communications, cybersecurity and data stewardship costs across the entire asset lifecycle.

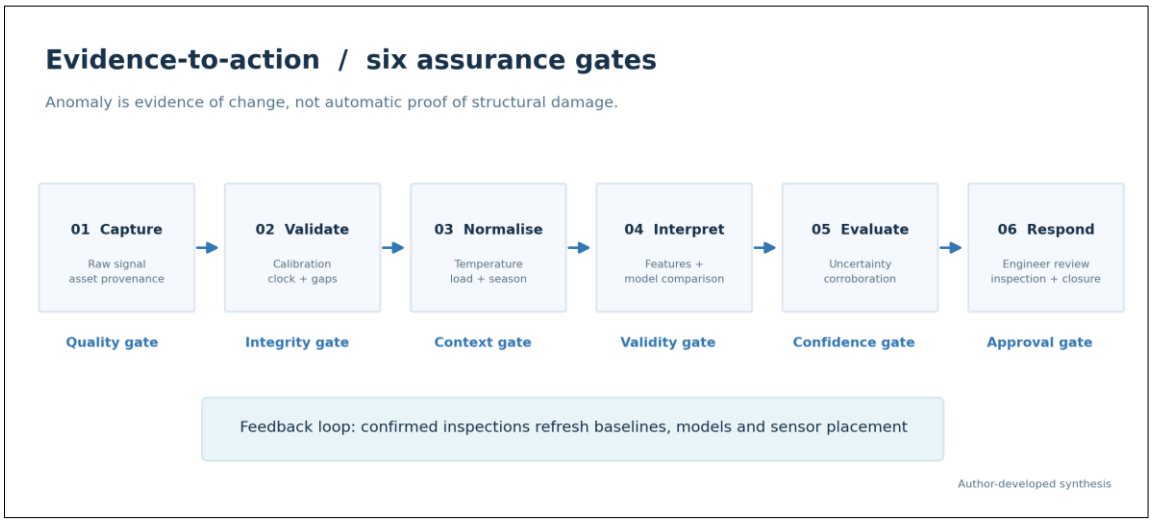


Figure 2: Structural data assurance from observation to engineering intervention. Original conceptual figure

10. DISCUSSION AND RESEARCH AGENDA

The reviewed studies establish the technical feasibility of many individual components, but evidence for an integrated, long-lived municipal decision system remains thinner. Controlled comparisons are difficult because bridges, buildings and tunnels differ in dynamics, failure mechanisms and operational constraints. An accurate classifier on a benchmark dataset cannot substitute for site-specific validation, and a successful wireless demonstration does not establish decade-long reliability. The practical research challenge is to test coupled performance across sensing, inference and engineering response, especially when devices drift or infrastructure is temporarily disconnected.

Three research priorities follow. First, field studies should publish uncertainty-aware performance across seasons and exceptional loading, including negative findings and sensor failures. Secondly, cross-asset trials should test whether common schemas can preserve engineering context without forcing unlike structures into misleading uniform indicators. Thirdly, decision studies should measure whether evidence changes inspection timing, intervention effectiveness and whole-life cost. Saudi research could be particularly valuable in examining extreme temperature effects, coastal exposure and the relationship between new-build digital readiness and retrofit constraints.

Limitations of this review are explicit. The 30-source synthesis is purposive rather than exhaustive; methodological diversity prevents meta-analysis; and Saudi-specific structural monitoring deployments are not represented as a validated national dataset. The architecture is therefore a reasoned design proposition, not a certified standard. Its strongest claim is conceptual: an IoT system contributes to infrastructure intelligence when measurement lineage, diagnostic uncertainty, human accountability and lifecycle maintenance are designed as one service.

11. CONCLUSION

IoT-enabled structural health monitoring can strengthen smart-city infrastructure management when connected sensors are embedded in a reliable engineering decision process. This review has integrated sensing modalities, synchronised acquisition, energy-aware communications, edge–cloud computing, uncertain diagnostics and asset governance into a single evidence-to-action framework. It argues that trustworthy monitoring depends less on uninterrupted data streaming than on calibrated measurement, transparent limitations and defensible intervention pathways. For Saudi Arabia, climate qualification, asset-specific baselines, interoperable records and competent local stewardship should be treated as deployment prerequisites. Vision 2030 creates an opportunity to coordinate these capabilities across new and existing infrastructure, but actual safety and lifecycle benefits must be demonstrated through independently verified operational outcomes. Future research should therefore prioritise long-duration field validation, fault-tolerant diagnostics and evidence of better maintenance decisions over increasingly complex dashboards.

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