TRANSPORTATION INFRASTRUCTURE ENGINEERING

Predictive Maintenance and Infrastructure Resilience in Saudi Metro Facilities: Integrating Asset Condition Monitoring, Failure-Risk Assessment, and Maintenance Optimisation for Vision 2030

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Abstract

Saudi metro facilities form an interconnected service environment in which mechanical, electrical, civil and digital assets must function together to protect passengers and sustain dependable operations. Conventional fixed-interval maintenance offers administrative simplicity but cannot consistently distinguish benign deterioration from emerging failures with disproportionate safety or service consequences. This review examines how asset condition monitoring, failure-risk assessment and maintenance optimisation can be combined within a facility-centred decision framework relevant to Saudi Vision 2030. A structured critical synthesis of thirty DOI-indexed publications dated 2020–2025 examines metro station assets, building services, railway infrastructure, resilience, digital twins and maintenance scheduling. Evidence indicates that predictive models are promising when sensor measurements are interpreted alongside functional dependencies, failure consequences, intervention access and uncertainty. However, reported classification performance is rarely transferable without local validation, and monitoring alone does not establish an operational maintenance strategy. The proposed framework connects asset registers, trusted observations, probabilistic risk interpretation, constrained intervention scheduling and feedback from completed work orders. Particular attention is given to cooling demand, passenger circulation, fire protection, power continuity, drainage and the restricted access windows of operating stations. The review concludes that Saudi metro operators should prioritise explainable, consequence-aware decisions and measurable service resilience over algorithmic sophistication, while developing governance for data quality, cybersecurity, workforce competence and long-term asset renewal.

Keywords: condition monitoring; failure risk; infrastructure resilience; maintenance optimisation; predictive maintenance; Saudi metro; station facilities; Vision 2030

1 Introduction

Urban metro reliability is often described through train punctuality, yet the passenger experiences a broader infrastructure system. A train may arrive to schedule while a failed escalator excludes mobility-impaired users, a ventilation fault compromises platform comfort, or a drainage incident renders an entrance unavailable. Consequently, facility condition must be treated as an integral determinant of transport performance rather than an ancillary property service. Railway research has made substantial progress in sensing, diagnosis and digital integration, although evidence remains uneven across track, vehicles, stations and their interdependent services [2–4]. A facility-centred perspective asks not merely whether equipment is likely to fail, but which loss of function would matter, to whom, for how long and under which operating conditions.

Saudi Arabia offers a strategically important setting because sustained investment in metropolitan mobility places long-term performance alongside construction delivery. Riyadh Metro began phased public operation in December 2024, with all six lines operating by January 2025, according to the Royal Commission for Riyadh City. Its scale makes service continuity dependent on repeated maintenance decisions across buildings, tunnels, depots, plant rooms and interchange stations. Vision 2030 establishes the policy context through improved urban accessibility, quality of life, resource efficiency and institutional capability. These policy ambitions cannot be translated into claimed maintenance savings without measured baseline data. Instead, they justify examining how reliability engineering may contribute to public value, operational assurance and more sustainable asset stewardship.

Three established maintenance logics coexist in metro facilities. Corrective maintenance responds after functional loss; preventive maintenance uses scheduled inspections or replacement intervals; and predictive maintenance updates intervention decisions from observed condition and forecast deterioration. These approaches are complementary rather than mutually exclusive. Routine tests remain indispensable for life-safety equipment even when sensor streams are available, while run-to-failure can be proportionate for inexpensive, non-critical components with accessible spares. The central engineering problem is the allocation of scarce labour, possession time and capital to asset failures whose probabilities and consequences differ. Recent rolling-horizon maintenance research demonstrates why risk-informed planning should adapt as new observations and operational constraints emerge [7].

An important gap lies between attractive predictive dashboards and decisions that can withstand scrutiny. Models trained on clean historical records may overlook missing alarms, changes in equipment duty, undocumented repairs or coupled failures. Reviews of digital twins and railway artificial intelligence identify persistent problems with interoperability, validation and the conversion of analytical output into operational value [4,8,9]. Station facilities complicate this gap because fault symptoms may propagate across several systems. An overheating pump motor, for example, can indicate bearing degradation, a blocked strainer, altered fluid demand or an instrumentation error. A credible maintenance programme must preserve these competing explanations until evidence permits a defensible decision.

1.1 Aim, review questions and contribution

The aim is to develop an evidence-grounded, risk-sensitive maintenance architecture for Saudi metro facilities that explicitly connects observed asset condition to infrastructure resilience. Four questions organise the analysis: which monitoring variables are informative for major facility functions; how should uncertain faults be translated into consequence-weighted priorities; how can interventions be scheduled without creating avoidable service disruption; and which governance arrangements permit responsible deployment? The contribution differs from a technology catalogue by specifying decision interfaces, escalation rules and validation requirements. It also separates immediate equipment reliability from wider service resilience, defined here as the capacity to sustain, adapt and restore essential passenger functions following disruption [5,6].

The framework further distinguishes leading indicators, which signal changing exposure before loss of function, from lagging indicators, which record completed failures or disruptions. This separation enables governance teams to challenge whether predictions are prospective. It also clarifies the scope of resilience: prevention is valuable, but redundancy, safe degraded operation, rapid restoration and

learning after incidents remain necessary even where forecasting models perform well under conditions.

2 Review design and analytical method

A structured, critical integrative review was chosen because the proposed decision framework draws on distinct empirical traditions rather than a single comparable intervention. Relevant evidence includes facility fault diagnosis, railway risk modelling, condition monitoring, scheduling, built-environment digital twins and resilience assessment. The review corpus comprises thirty identifiable publications from 2020–2025, each assigned a persistent digital object identifier. Sources were located by targeted title, topic and citation searches, then screened for direct relevance to at least one stage of the intended monitoring-to-action sequence. The review is not presented as an exhaustive database census, and no unrecorded search totals or screening counts are asserted.

Selection favoured peer-reviewed studies that disclosed an identifiable analytical contribution, such as a tested fault classifier, a maintenance optimisation formulation, a system architecture or an explicit synthesis of deployment barriers. Station and building-services research was given precedence for equipment behaviour; transport research was used to interpret system effects and constrained operating windows. Studies addressing geographically different networks were retained only when the transferable principle could be distinguished from context-specific assumptions. The thirty papers were coded against asset domain, data requirements, analytical method, operational decision, validation setting and limitations. Contradictions were interpreted, not averaged, because metrics and data populations differed.

The synthesis proceeds through five analytical stages. First, it defines the functional boundaries of a metro facility and its principal failure dependencies. Second, it contrasts available measurements with the physical conditions they can legitimately infer. Third, it examines diagnosis, forecast uncertainty and risk construction. Fourth, it reviews maintenance optimisation under safety, access and resource constraints. Finally, it translates these findings into a staged governance and evaluation framework. Each stage is informed by triangulation across facility, railway and infrastructure research; specific performance figures are attributed to individual studies rather than generalised to Saudi operations [1,15,25].

This design has limitations intrinsic to purposive evidence selection. Negative industrial results may remain unpublished, terminology varies between facilities engineering and railway operations, and laboratory benchmarks underrepresent dynamic passenger demand. Furthermore, citation counts and journal prestige do not establish field transferability. Accordingly, the proposed architecture is a reasoned synthesis rather than a tested Riyadh deployment. All suggested thresholds, priority categories and evaluation measures are described as design proposals requiring operator calibration. This distinction prevents the review from presenting hypothetical efficiency gains, invented asset populations or simulated metro observations as empirical findings.

3 Saudi metro facilities as interdependent assets

A practical asset boundary includes heating, ventilation and air conditioning; escalators and lifts; electrical distribution and standby supplies; fire detection and suppression; sump pumps and drainage; lighting; station controls; communications; and building fabric. Their criticality is determined by functional location and redundancy, not equipment category alone. The loss of a fan

serving a minor storeroom has different consequences from the loss of smoke extraction in a crowded interchange. Similarly, an escalator outage may be inconvenient where accessible alternatives remain operational but exclusionary where vertical circulation redundancy is inadequate. Failure consequence must therefore be mapped to location, passenger exposure, recovery alternatives and regulatory obligations.

Dependency mapping is essential because common-cause failures undermine simple asset rankings. A power disturbance can stop pumps, lifts, air handling units and local communications simultaneously. A blocked drain may damage electrical cabinets, while poor cooling can accelerate control-equipment degradation. Digital asset records should preserve relationships among upstream power feeds, controlled equipment, protective devices, adjacent spaces and operational functions. Built-environment twin research supports this move from isolated equipment representations towards connected lifecycle information, but also documents fragmented data exchange and uncertain maintenance ownership [10,19,23]. A useful representation need not begin as a sophisticated three-dimensional replica; a trustworthy relational asset model is more fundamental.

The Saudi operating environment adds contextual considerations without licensing deterministic claims about local failure rates. High ambient temperatures increase the importance of cooling duty and electrical thermal margins, while airborne dust can affect filters, heat-transfer surfaces and electromechanical assemblies. Short maintenance windows, public accessibility, energy consumption and crowded interchanges must be incorporated into local planning assumptions. These factors require seasonal baselines and station-specific engineering review. Rather than impose a single national predictive threshold, operators should compare equipment within matched duty classes and incorporate manufacturer requirements, commissioning records and measured exposure histories before altering inspection intervals.

Table 1. Facility asset functions, condition evidence and risk interpretation.

Asset domain	Candidate condition indicators	Potential functional consequence	Assessment safeguard
Cooling and ventilation	Temperature differential; current; filter pressure; vibration	Thermal discomfort; reduced ventilation; equipment overheating	Seasonal/load adjustment; confirm airflow
Escalators and lifts	Motor current; vibration; stops; fault codes; duty cycles	Loss of accessible circulation; crowding; entrapment risk	Maintain mandated testing and accessible alternatives
Power and standby supply	Battery status; temperature; breaker operations; power quality	Simultaneous loss of dependent services	Validate redundancy and controlled isolation
Fire and life-safety	Functional tests; fan status; detector diagnostics; damper position	Compromised evacuation or smoke control	Statutory tests override predictive deferment
Drainage and pumps	Water level; flow; pressure; motor current	Flooding; access closure; electrical damage	Cross-check sensor faults against physical levels
Station fabric and access	Inspection defects; leakage; deformation; ingress records	Restricted access; secondary equipment deterioration	Pair observation with safety and accessibility audit

Asset domain	Candidate condition indicators	Potential functional consequence	Assessment safeguard
Communications and controls	Link quality; device errors; latency; configuration changes	Lost visibility; delayed response; dependent service failures	Separate advisory analytics from safety control

Source: author synthesis of the cited literature; categories are illustrative, not site measurements.

4 Condition monitoring and diagnostic interpretation

Condition monitoring is useful only when measured variables are causally connected to credible failure mechanisms. Vibration features may indicate bearing wear or misalignment in rotating equipment; electrical current signatures may reveal abnormal motor loading; and temperature differentials can expose inefficient cooling or restricted flow. However, each signal responds to operating regime as well as damage. Anomaly detection should therefore account for load, season, occupancy, start-up transients and control mode. Reviews of building HVAC diagnostics show that the main challenge is not obtaining more measurements indiscriminately but preserving sensor context, clear fault definitions and comparable assessment criteria [15,18].

For chillers, air handlers and variable-refrigerant systems, candidate inputs include supply and return temperatures, valve positions, differential pressure, fan speed, compressor current, refrigerant indicators and energy consumption. Combining physical rules with learned residuals can distinguish persistent degradation from normal control response. Studies of multistage fault diagnosis and machine-learning approaches have reported promising performance for their particular datasets, but accuracy depends on test design, fault prevalence and instrumentation quality [16,20,22]. A Saudi metro pilot should begin with operator-defined fault hypotheses, test sensor calibration under high-load operation and evaluate whether alerts reveal a maintainable cause before acquiring additional hardware.

Escalators require a different measurement logic because their availability is experienced directly by passengers. Motor current, gearbox vibration, brake behaviour, operating hours, fault codes and load cycles can support health indicators, provided safety inspection is never displaced by a model score. Zwetsloot and colleagues described escalator health analytics linking observations with remaining-life estimation, demonstrating the value of relating refurbishment to measured condition rather than age alone [25]. Such evidence is especially relevant to interchange facilities, yet the model's results should not be transplanted without considering manufacturer configuration, passenger flows and the effects of preventative adjustment. The correct decision may be targeted inspection rather than immediate replacement.

For pumps, drainage and water-related assets, pressure, flow, vibration, wet-well level and motor current can reveal degradation only when expected hydraulic demand is known. Research on hydraulic anomaly detection and sensor remaining-life estimation highlights two distinct risks: equipment faults and measurement faults [26,29]. A false high-level reading can trigger unnecessary maintenance, whereas a failed low-level sensor can conceal flooding. Facility analytics should consequently incorporate cross-sensor consistency checks, inspection confirmation and controlled tests of protective functions. When data are sparse, physically interpretable thresholds supported by maintenance history may offer a safer starting point than opaque multi-input prediction.

Electrical and control assets need equally explicit boundaries. Transformer temperature, breaker operations, power-quality disturbances and uninterruptible supply battery condition can signal

threats to dependent services; however, safety interlocks and emergency functions must remain governed by certified procedures. Railway connectivity studies emphasise latency, availability and cybersecurity as prerequisites for remote analysis [12,13]. Diagnostic analytics should operate as advisory functionality outside approved safety control loops unless formally engineered and authorised. A digital system must not silently convert a statistical anomaly into an automatic intervention on equipment whose disconnection would create greater risk than continued supervised operation.

4.1 Diagnostic evidence, data bias and uncertainty

Prediction tasks should be distinguished precisely. Detection asks whether behaviour is abnormal; diagnosis estimates the likely fault mechanism; prognosis estimates time to a functional limit; and maintenance recommendation compares possible actions. The station-facilities study by Alothman and colleagues used tree-based learning to predict failure categories, maintenance need and status, illustrating the practical relevance of structured maintenance records [1]. Its reported classifier performance remains specific to the underlying cases and labels. It does not establish the future failure probability of every asset, nor does it demonstrate that a predicted maintenance need automatically yields the best operational schedule.

Failure labels are often generated by work orders, and work orders reflect human practices rather than a neutral record of physical truth. A technician may close a recurring alarm as resolved when the underlying cause persists; changes to defect coding can simulate performance improvements; and replacement decisions censor the natural progression of degradation. Models evaluated using random splits of records from the same unit may inadvertently exploit asset identity, seasonal patterns or post-failure information. Operators should use time-separated validation, group testing by station or equipment family, inspect leakage pathways and record performance across rare but consequential faults. Calibration and alert lead time matter at least as much as overall classification accuracy.



Figure 1. Proposed facility monitoring, risk assessment and accountable maintenance decision loop (original conceptual schematic).

5 From failure probability to service risk

Failure likelihood alone cannot determine maintenance priority. A rational risk estimate relates a defined failure mode, a forecast time horizon, exposure conditions and the severity of its consequences. Consequence may include injury potential, loss of accessible journeys, service interruption, emergency response burden, repair cost and environmental effects. Probabilities should be treated as uncertain estimates conditional on available evidence. Where detailed data do not exist, structured engineering judgement can establish provisional ordinal risk bands, with explicit confidence labels. The progression towards probabilistic methods should be justified by whether finer estimates change an actual intervention decision, not by the apparent sophistication of the calculation.

Dependencies create an important distinction between component criticality and functional criticality. Two identical pumps may carry different consequences if one serves a redundant drainage arrangement while the other protects an underground area with limited escape routes. A feeder breaker can appear healthy yet represent a single point of failure for several safety-related systems. Failure-mode analysis should therefore trace initiating events to lost functions and plausible common causes. Network resilience studies demonstrate the importance of combining restoration of physical infrastructure with the management of disrupted services rather than evaluating a failed element independently [5,6]. In a metro station this principle applies to rerouting passengers, activating standby equipment and managing capacity during repairs.

A useful risk register records failure mode, current evidence, causal uncertainty, affected function, consequence scenario, response deadline and permissible temporary controls. For high-consequence hazards, predefined engineering limits and statutory tests override model preferences. For moderate consequences, trend slope, predicted deterioration horizon and maintenance opportunity can guide prioritisation. Low-consequence components may remain on planned inspection if additional monitoring would cost more than its information value. Table 1 specifies indicative monitoring and consequence links, while Figure 2 shows conceptually why the best intervention window balances degradation, disruption and premature replacement. Neither representation claims measured Saudi failure rates.

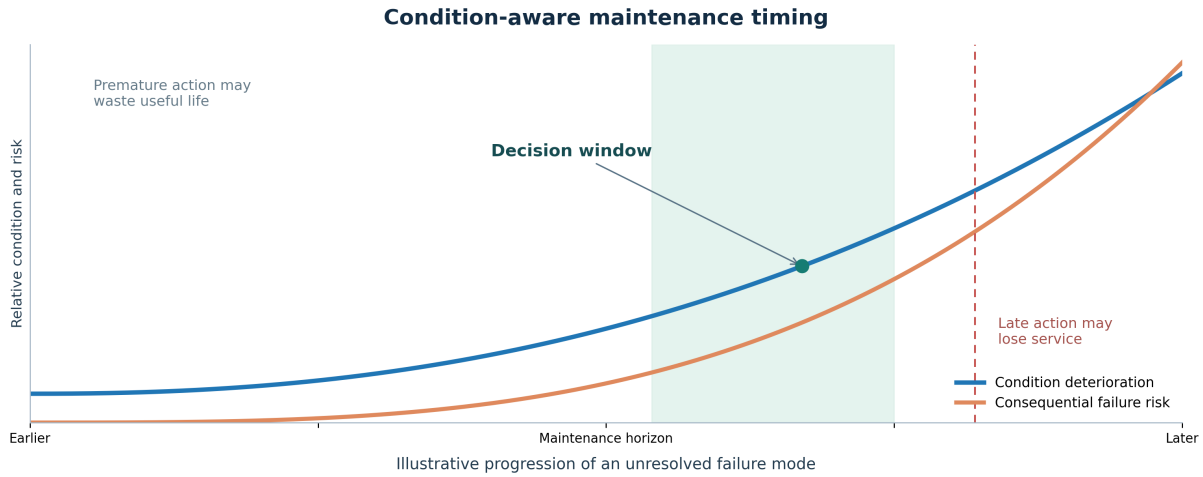


Figure 2. Conceptual maintenance decision window. The curves are explanatory, not observations or estimated Saudi metro failure probabilities.

6 Maintenance optimisation under operating constraints

The purpose of optimisation is to turn evidence into an executable, auditable work programme. A maintenance decision is constrained by engineering access, service demand, technician competence, spare availability, isolation requirements and dependencies between tasks. A nominally optimal replacement date is unusable if it coincides with an event-driven passenger peak or requires simultaneous isolation of both redundant systems. Rolling-horizon optimisation addresses this tension by repeatedly revising assignments as faults, resources and forecasts change [7]. Railway catenary maintenance allocation research offers a complementary example of treating workforce and material resources explicitly instead of assuming unlimited repair capacity [11].

A suitable objective is multi-criteria rather than a simple minimisation of repair expenditure. It can include expected failure consequence, planned intervention cost, disruption exposure, energy inefficiency and the penalty for postponing safety-critical work. Decision variables represent task selection, start time, resource assignment and possible grouping with other access-dependent jobs. Constraints preserve minimum required service capacity, segregation of unsafe simultaneous isolations, maximum response time for critical alarms and compliance inspection intervals. The formulation must distinguish hard safety constraints from negotiable preferences. Where consequence probabilities are poorly supported, scenario ranking or robust optimisation is more defensible than calculating falsely precise monetary expected losses.

Opportunity-based maintenance can reduce repeated closures by coordinating related activities, but coupling tasks has a risk. Completing an additional low-priority replacement during a scarce possession may prolong isolation or introduce a new commissioning defect. A proposed work bundle should be evaluated against available skill mix, material readiness, contingency time and a defined return-to-service test. The planning horizon can therefore contain three decisions: immediate protective action where risk is intolerable; scheduled corrective or preventive work within a safe interval; and deliberate deferment with monitoring where remaining risk is acceptable. Deferred work requires an owner, expiry date and stated re-evaluation trigger.

Service resilience broadens this calculus beyond asset uptime. The preferred intervention may preserve a station's essential functions through temporary operating arrangements even when individual equipment remains unavailable. Examples include activating a standby pump, opening an alternative accessible route or limiting plant load until replacement parts arrive. Such responses should be assessed against passenger safety, fatigue of backup equipment and recovery time. Network resilience literature identifies restoration sequencing and demand management as interacting decisions [6]. For station facilities, the insight is that successful optimisation should measure uninterrupted access and critical-function continuity, not merely the number of maintenance tasks closed.

7 Integrated monitoring–risk–decision architecture

The proposed architecture contains six connected capabilities. A functional asset register identifies equipment, location, duties and dependencies. A condition layer collects calibrated measurements, inspection results, alarms and work-order histories. A quality layer timestamps observations, checks completeness and flags conflicting evidence. A diagnostic layer combines engineering rules with appropriately validated statistical models. A risk layer translates probable fault trajectories into consequences for passenger and service functions. Finally, a planning layer produces interventions, assigns resources and records outcomes for reassessment. Figure 1 depicts the loop. This structure

synthesises railway monitoring strategies and digital-twin literature while avoiding the assumption that a visual model alone produces operational intelligence [2,9,14].

Interoperability should be addressed before predictive model procurement. Each asset needs a persistent identifier shared across maintenance management, building controls, procurement and engineering documents. Measurements require units, sensor locations, sampling intervals, calibration records and known operating states. Fault codes require controlled definitions and a record of classification changes. Without these foundations, a well-performing algorithm can generate recommendations that cannot be traced to the asset requiring work. Studies of digital integration across the built environment emphasise the difficulty of reconciling design models, live operational data and asset-management records [19,23,27]. Governance should therefore specify authoritative systems and reconciliation responsibility.

The diagnostic interface should communicate evidence rather than a bare red warning. For each recommendation it ought to show the affected asset, observed departure from normal behaviour, plausible failure modes, confidence or uncertainty, relevant historical precedents and consequences if no action is taken. Engineers must be able to reject an unsuitable recommendation, record the reason and request additional inspection. Such human supervision is particularly important when classes are imbalanced, assets are rarely failed or the model encounters equipment outside its validated duty range. A user-facing explanation need not expose every numerical parameter, but it must enable an accountable maintainer to understand what changes the decision.

Cybersecurity and operational assurance are part of data integrity rather than external appendices. Remote telemetry must be segmented from safety control networks; privileged access, configuration changes and model updates require logging. Devices should retain safe local functionality if connectivity is lost. Research on train-ground intrusion detection and flexible railway networks shows why digital transport services cannot assume uninterrupted, trustworthy communications [12,13]. In facility applications the primary response to doubtful telemetry is controlled fallback to established inspection and protective routines, not an unverified automated shutdown. Recovery procedures should include restoring missing records and documenting decisions made during degraded digital operation.

8 Implementation and evaluation pathway for Saudi operators

Implementation should start with a limited operational case whose consequences, maintenance burden and available data are understood. A pilot encompassing one high-duty cooling plant, a representative escalator group and a drainage arrangement would sample different failure mechanisms without claiming to represent an entire network. The operator should first define the loss-of-function scenarios, determine asset boundaries and audit twelve or more months of available records where feasible. Missing history should be documented rather than imputed as evidence of fault-free operation. Baseline metrics must be frozen before deployment, including intervention lead time, false alarms, service-impacting failures and time spent returning equipment to operation.

The first analytical release should favour interpretable thresholds and limited models where maintainers can validate causal relationships. A pilot review board should compare sensor alerts with manual inspections, trace the path from alert to work order and check that work actually changes the failure mechanism. Performance should be examined by asset class, station, season and operating regime. Temperature-related drift may make an acceptable winter threshold unreliable during peak cooling demand. For uncommon failures, precision, missed-event review and warning

lead time are more informative than a headline accuracy figure. Building fault-diagnosis research similarly stresses the value of topology, expert knowledge and realistic validation conditions [17,21].

Once reliable diagnosis is demonstrated, the second phase can introduce consequence scoring and constrained scheduling. A safety representative should approve hazard scenarios, operations managers should identify workable isolation periods, and maintainers should validate labour durations and spare lead times. Table 2 proposes controls, decision owners and evaluation indicators for each stage. Change control matters because upgraded plant, revised passenger circulation or altered service frequency can invalidate earlier assumptions. After deployment, drift checks should compare input distributions and forecast errors with the original validation period; significant change should trigger model review rather than silent threshold adjustment.

A mature programme requires learning from outcomes. After each intervention, the work order should record confirmed fault mechanism, replaced component, actual downtime, testing results and any effect on adjacent equipment. Near misses and rejected alerts are equally informative because they reveal weaknesses in risk interpretation. Asset managers should assess trends quarterly, distinguish avoided failures from changes in reporting practice and identify cases in which monitoring cost exceeds its decision value. Organisational capability includes trained reliability engineers, cybersecurity personnel, facilities supervisors and procurement teams capable of specifying interoperable data. Without ownership of these interfaces, digital investment risks creating parallel dashboards instead of stronger maintenance governance.

Table 2. Implementation governance and evidence required for each decision stage.

Decision stage	Suggested audit indicator	Accountable function	Evidence of acceptability
Asset register	Configuration accuracy; dependency coverage	Asset manager	Complete and traceable identifiers
Sensor and data quality	Data completeness; calibration exceptions	Facilities engineering	Reconciled anomalies and documented missingness
Diagnostic validation	Precision; missed critical faults; alert lead time	Reliability engineer	Prospective, station-separated evaluation
Risk review	Consequences; uncertainty; control adequacy	Safety and operations	Approved hazard and priority rationale
Maintenance planning	Work-window adherence; backlog risk; repeat isolations	Maintenance planner	Feasible plans with controlled deferments
Recovery and resilience	Function loss duration; accessible-route continuity	Station operations	Passenger-facing service restoration evidence
Model and cyber governance	Drift events; access violations; fallback tests	Digital systems and cybersecurity	Documented change control and safe fallback

Source: author synthesis of the cited literature; categories are illustrative, not site measurements.

9 Discussion: resilience, sustainability and transferability

The reviewed evidence supports a conditional rather than universal case for predictive maintenance. Station-facility classifiers show that work-order data can support differentiated forecasts [1]; HVAC studies demonstrate how measured operating patterns may reveal faults [15–17]; escalator and pump research extends prognosis to passenger circulation and drainage systems [25,26,29]. Yet these studies investigate different populations, labels and performance measures. Their apparent success

cannot be pooled into a single expected improvement for Riyadh Metro. The defensible conclusion is narrower: technically credible monitoring can improve the timing and targeting of investigation when it is embedded in asset knowledge and an operational decision process.

A second insight concerns system boundaries. Traditional equipment reliability may prioritise a component with a high observed failure rate, whereas resilience prioritises functions that lack acceptable substitutes. For example, frequent minor lighting defects may consume considerable maintenance labour, but a rare failure involving emergency ventilation can carry much greater consequences. The maintenance portfolio therefore needs both efficiency measures and explicit protection of severe, low-frequency scenarios. Research on network restoration and built-environment twins reinforces the importance of cross-system coordination, yet the local governance arrangements required to implement it remain comparatively underexamined [6,10,24].

Environmental performance offers additional but carefully bounded value. Condition-responsive maintenance may prevent inefficient cooling, avoid avoidable component replacement and support longer useful lives; conversely, new sensors, networking and computing systems consume energy and create their own renewal obligations. An environmental assessment should therefore compare whole-life outcomes rather than presume that greater digitalisation is inherently greener. Research on HVAC fault detection and digital building maintenance provides mechanisms for improved operational control but does not establish a universal carbon reduction rate [20,22,30]. Saudi deployment should connect energy reporting with verified asset performance and explicitly account for additional monitoring infrastructure.

10 Research limitations and future directions

This review does not include proprietary Saudi metro failure histories, station-level work orders or independently audited pilot outcomes. Consequently, it cannot validate hazard probabilities, recommend numerical alert thresholds or certify a particular optimisation algorithm for operational use. The purposeful literature set also privileges accessible academic publications over confidential operator practice. Publication and reporting biases remain possible, especially for unsuccessful predictive projects. The proposed model should therefore be treated as a testable design framework. Future studies could establish cross-station datasets with harmonised failure codes, compare prediction against simpler inspection rules and report the organisational cost of maintaining trustworthy asset information.

Further work should evaluate rare-event calibration, uncertainty-aware remaining-life forecasts, multi-asset common-cause modelling and causal assessment of interventions. Prospective trials should specify decision rules before observing outcomes, distinguish model development from independent validation and measure passenger-facing function rather than equipment accuracy alone. Comparative assessment should include changes in unplanned loss of accessibility, disruption duration, lifecycle cost and technician workload. Research on data-driven facility management and digital asset representations identifies scalability and practical integration as persistent research needs [23,27,28]. A multi-site Saudi study would add value by testing these requirements under local climate, equipment and service conditions.

11 Conclusion

Predictive maintenance becomes operationally meaningful when a credible observation changes a justified maintenance decision. For Saudi metro facilities, that change must be assessed against passenger safety, accessibility, redundant capacity, restricted work windows and the consequences of interruption. This review has shown how station equipment diagnostics, probabilistic failure interpretation, maintenance optimisation and resilience planning can be joined without assuming that data volume or model complexity guarantees improvement. The resulting framework prioritises functional asset mapping, calibrated monitoring, transparent uncertainty, consequence-weighted action and feedback from verified repairs. It preserves mandatory inspections and human authority where failure consequences are severe.

The principal practical implication is a phased programme of engineering assurance rather than wholesale automation. Operators should establish reliable asset identities, select bounded pilots, measure performance against defined baselines and extend models only when their recommendations withstand independent field assessment. Scheduling should incorporate service availability and recovery arrangements as explicitly as repair effort. These measures align with Vision 2030 by supporting durable urban mobility infrastructure and accountable use of public resources. The key research task now is to validate whether such integrated decisions improve critical-function continuity in operating Saudi metro stations, using transparent evidence rather than asserted savings or untested performance claims.

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