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Original Research Article

Digital Monitoring and Predictive Maintenance of Building Services Systems in Saudi Mega Projects

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Abstract: Saudi Arabia's giga-projects are expanding the scale, density, and technical complexity of building services systems. High-rise districts, hospitality destinations, airports, hospitals, cultural venues, and mixed-use communities require heating, ventilation and air-conditioning (HVAC), electrical, water, fire-safety, vertical transportation, security, and energy systems that remain reliable in harsh climatic and operational conditions. This review paper evaluates how digital monitoring and predictive maintenance can improve the operational performance of building services systems in Saudi mega projects. Following a review-paper structure inspired by recent Springer-style construction technology studies, the article synthesizes 2020-2025 literature on Building Information Modelling (BIM), Internet of Things (IoT), building management systems (BMS), digital twins, automated fault detection and diagnostics (AFDD), machine learning, and facility management. The study proposes a Saudi-oriented Digital Monitoring and Predictive Maintenance Framework (DMPMF) that links asset information requirements, sensor telemetry, analytics, work-order systems, and governance indicators. The review finds that the strongest value is achieved when predictive maintenance is treated not as a stand-alone algorithm, but as an information ecosystem connecting design handover, commissioning, operations, cybersecurity, workforce competence, and sustainability reporting. The paper contributes practical implementation stages, two conceptual visuals, and two synthesis tables for researchers, asset owners, consultants, and facility managers seeking Scopus/Q1-level alignment with Vision 2030 priorities.

Keywords: Digital Monitoring, Predictive Maintenance, Building Services, Digital Twin, BIM, BMS, Saudi Mega Projects, Vision 2030, Facility Management, HVAC.

1. INTRODUCTION

The operation of modern building services has become a strategic concern for Saudi Arabia because the Kingdom is delivering some of the world's most ambitious urban, tourism, healthcare, sports, and mixed-use developments under Vision 2030. In such projects, the value of a building is no longer determined only by its architectural form or initial construction quality. It is increasingly defined by whether mechanical, electrical, plumbing, fire, transport, and control systems can deliver safe, comfortable, low-carbon, and resilient performance over decades of operation. Digital monitoring and predictive maintenance are therefore central to long-term asset value because they transform hidden equipment behavior into measurable, auditable, and actionable intelligence.

Traditional maintenance in large facilities has normally followed reactive or calendar-based routines. These routines are familiar, but they are inefficient for mega projects where equipment populations are large, failure consequences are high, and operating patterns change rapidly. A chiller fault, pump imbalance, air-handling unit control drift, lift malfunction, or electrical distribution anomaly can affect occupant comfort, energy use, safety, water consumption, and business continuity. Recent research on digital twins and fault detection shows that building operations can be improved when live sensor data, asset metadata, BIM context, and analytics are integrated into a lifecycle platform rather than stored in separate systems (Lu *et al*., 2020; Jiang *et al*., 2021; Hosamo *et al*., 2022).

In Saudi mega projects, the problem is intensified by extreme outdoor temperatures, dust exposure, peak cooling demand, complex handover arrangements, and the need to demonstrate environmental performance. Building services must support luxury hospitality, healthcare, commercial, entertainment, transport, and residential functions while reducing unnecessary energy and water waste. Predictive maintenance offers a structured response: monitor the condition of assets continuously, detect abnormal behavior early, forecast failure probability or remaining useful life, prioritize work orders by risk, and feed lessons back into design, commissioning, and procurement.

The purpose of this review is to develop a research-based but implementation-oriented understanding of digital monitoring and predictive maintenance for building services systems in Saudi mega projects. The paper follows a model commonly used in high-quality construction technology journals: it starts with a clear problem statement, defines objectives, explains review methodology, builds a conceptual framework, synthesizes the literature, presents tables and figures, discusses Saudi implementation challenges, and concludes with actionable recommendations. This structure mirrors the attached Springer article, which organizes a technology-integration topic through abstract, introduction, research problem, objectives, methodology, conceptual framework, comparative discussion, results, recommendations, and conclusion (Attia, 2025).

2. Research Problem

Despite rapid adoption of smart-building language across the construction sector, many facilities still struggle to convert digital data into reliable maintenance decisions. The key problem is not the absence of sensors or software. The larger issue is fragmentation: BIM models may remain in design offices, BMS data may remain with controls contractors, Computerized Maintenance Management Systems (CMMS) may hold work orders without diagnostic context, and asset registers may lose accuracy after handover. When these sources are not connected, facility teams receive alarms but lack enough context to identify root causes, forecast consequences, or justify investment decisions.

The research problem can therefore be stated as follows: How can digital monitoring and predictive maintenance be structured as an integrated building-services framework for Saudi mega projects, and what technical, organizational, and governance conditions are required for dependable adoption? This question is important because predictive maintenance can fail when algorithms are applied to weak data, when sensors are installed without asset criticality logic, when BIM objects lack maintainable metadata, or when maintenance teams are not trained to interpret analytics. Research between 2020 and 2025 repeatedly emphasizes interoperability, data quality, workforce competence, and lifecycle information management as decisive barriers to digital twin and BIM-enabled facility management (Adewumi *et al*., 2021; Matarneh *et al*., 2022; Al-Kasasbeh *et al*., 2024).

3. AIM AND OBJECTIVES OF THE STUDY

The aim of the study is to develop a review-based framework for digital monitoring and predictive maintenance of building services systems in Saudi mega projects, with emphasis on operational resilience, sustainability, and Vision 2030 alignment.

The objectives are: first, to synthesize recent literature on BIM, IoT, BMS, digital twins, and predictive maintenance for building services; second, to identify the operational data architecture required to connect assets, sensors, analytics, and maintenance workflows; third, to assess the benefits and limitations of predictive maintenance for HVAC, electrical, water, life-safety, and vertical transportation systems; fourth, to propose a Saudi mega-project implementation framework that links reliability, energy efficiency, occupant comfort, asset risk, and governance; and fifth, to provide recommendations for researchers and practitioners seeking stronger evidence-based adoption.

4. REVIEW METHODOLOGY

This study uses a structured narrative review methodology. It is not a statistical meta-analysis because the reviewed literature includes conceptual frameworks, case studies, engineering experiments, systematic reviews, and industryoriented facility management papers with different data structures. Instead, the review applies a transparent synthesis strategy similar to high-quality journal review papers. Searches were designed around five concept groups: building services systems, digital monitoring, predictive maintenance, BIM or digital twin, and Saudi mega-project relevance. Sources were limited to 2020-2025 to meet the currency requirements of emerging digital-construction research.

The review prioritized Scopus- and Web of Science-oriented journal outlets in construction management, energy and buildings, automation in construction, facility management, smart buildings, and built-environment informatics. Inclusion criteria required relevance to at least one of the following: building operations and maintenance, HVAC fault detection, BIM-IoT integration, digital twins for constructed assets, smart facility management, predictive maintenance analytics, or lifecycle information management. Exclusion criteria removed purely industrial manufacturing maintenance papers unless their digital twin logic was transferable to building services. Thematic coding was then applied across six categories: data acquisition, asset information, analytical models, maintenance decision-making, implementation barriers, and Saudi Vision 2030 implications.

Table 1 summarizes the review logic. The method follows the attached model paper's practice of combining descriptive-analytical review with deductive framework development. However, this paper is a review article rather than a project case-study comparison, so it derives its conclusions from cross-literature synthesis rather than from one empirical project dataset.

Table 1: Review methodology and source-selection logic

Review component	Applied approach in this paper
Search period	Literature and standards-oriented sources from 2020 to 2025, with the attached Springer model used for article structure.
Core concepts	Digital monitoring, predictive maintenance, building services systems, BIM, IoT, BMS, CMMS, AFDD, digital twin, facility management.
Inclusion criteria	Studies linked to building operations, HVAC or building-services diagnostics, BIM-IoT integration, asset management, digital twins, or smart facility management.
Exclusion criteria	Manufacturing-only maintenance studies, purely conceptual smart-city papers without building operations relevance, and outdated pre-2020 sources.
Synthesis method	Thematic coding across data acquisition, asset information, analytics, work-order action, governance, and Saudi mega-project application.

5. Conceptual Framework: Digital Monitoring and Predictive Maintenance

Digital monitoring begins with continuous capture of operating data from building services assets. In a Saudi mega-project context, this includes chilled water plants, air-handling units, fan coil units, pumps, heat exchangers, electrical panels, photovoltaic interfaces, water treatment systems, elevators, escalators, fire pumps, smoke control systems, and indoor environmental quality sensors. These assets generate temperature, pressure, flow, current, vibration, humidity, occupancy, valve position, run-hour, energy, alarm, and status data. By itself, this data has limited value unless it is mapped to asset identity, location, design intent, maintenance history, and operational priority.

The proposed Digital Monitoring and Predictive Maintenance Framework (DMPMF) has six layers. The first is the asset-information layer, where BIM, COBie-style data drops, equipment tags, space identifiers, and commissioning records define the digital identity of maintainable assets. The second is the sensing and controls layer, where BMS/BAS points, IoT devices, smart meters, and gateways generate near-real-time telemetry. The third is the data integration layer, where protocols such as BACnet, Modbus, MQTT, APIs, and data lakes harmonize operational data. The fourth is the analytics layer, where rule-based FDD, statistical monitoring, machine learning, deep learning, and physics-informed models identify abnormal behavior and forecast risk. The fifth is the action layer, where CMMS and mobile workforce tools convert analytics into inspected, approved, and closed work orders. The sixth is the governance layer, where cybersecurity, data quality, model ownership, Saudi Building Code alignment, ESG reporting, and performance dashboards provide accountability.

Figure 1 presents the architecture in an Apple-inspired visual style. It shows that predictive maintenance is a feedback loop rather than a one-way technology pipeline. Sensors feed digital twins and analytics; analytics feed maintenance action; maintenance outcomes update risk models; and governance dashboards translate technical performance into executive evidence. This lifecycle view is consistent with studies arguing that BIM, digital twin, and cyber-physical systems become valuable when static geometry is linked with dynamic operational data (Douglas *et al*., 2021; Shahzad *et al*., 2022).

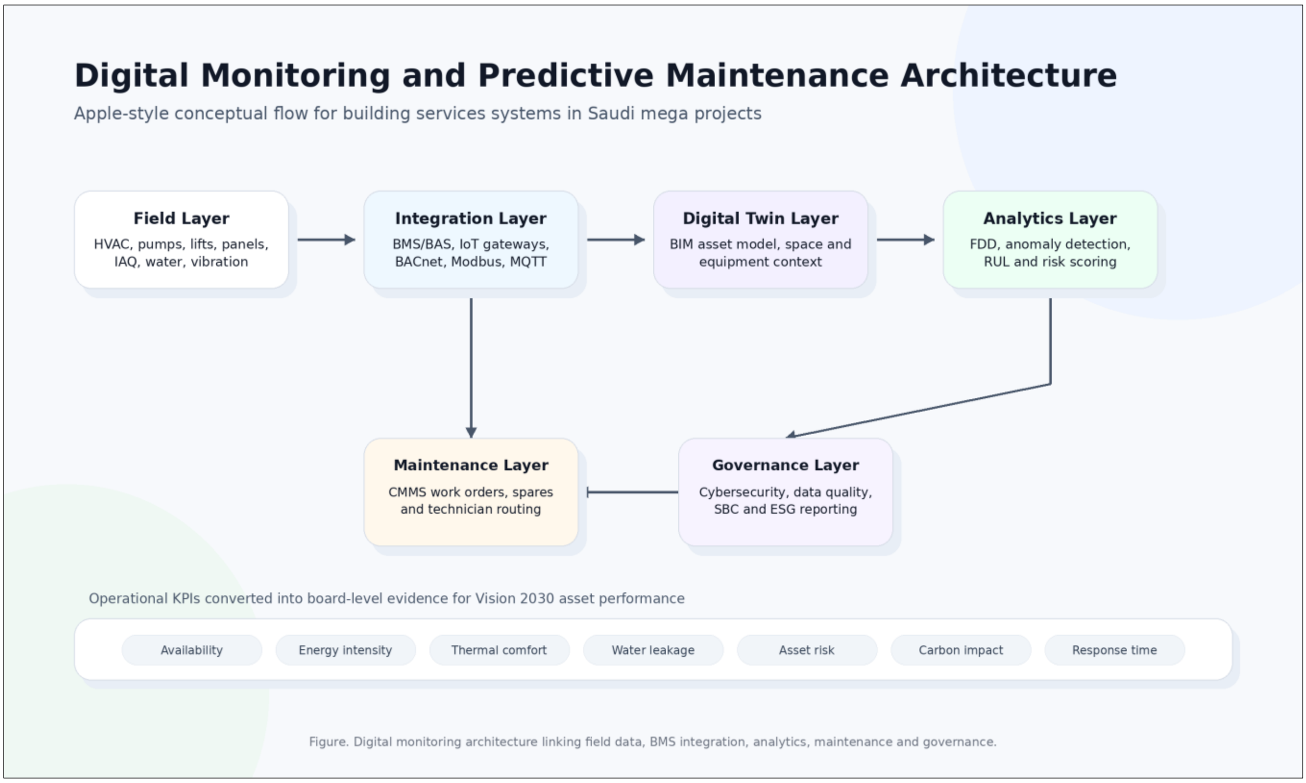

Figure 1: Digital monitoring and predictive maintenance architecture for building services systems in Saudi mega projects

6. Building Services Systems Relevance

HVAC systems are the highest-priority building services category for Saudi mega projects because cooling demand dominates operational energy and directly affects occupant experience. Faults such as simultaneous heating and cooling, stuck dampers, fouled coils, leaking valves, chilled water flow imbalance, short cycling, sensor drift, and poor scheduling can remain hidden in daily operation while increasing energy use and accelerating equipment degradation. Reviews of data-driven HVAC fault detection identify supervised learning, unsupervised anomaly detection, Bayesian methods, rule-based models, and deep learning as major approaches, but they also warn that model reliability depends on high-quality labels and transferable data (Chen *et al*., 2020; Shao *et al*., 2023).

Electrical systems require monitoring of load profiles, power quality, transformer condition, switchgear temperature, backup generation, uninterruptible power supplies, and renewable energy interfaces. Predictive maintenance in this domain is strongly connected to safety and business continuity. A developing smart district cannot rely only on periodic inspection because abnormal thermal signatures, harmonic distortion, or load imbalance may signal future failure. Water and plumbing systems are equally important because Saudi projects must manage leakage, pumping efficiency, greywater or treated water reuse, and water quality in large public and hospitality assets. IoT-based metering and pressure monitoring can identify leakage patterns earlier than manual inspection.

Vertical transportation and life-safety systems add another risk dimension. Elevators, escalators, fire pumps, smoke control fans, access control, and emergency power systems require high availability and strict maintenance evidence. Predictive maintenance can prioritize inspection based on run hours, abnormal motor signatures, door-cycle patterns, and alarm sequences. However, these systems must be integrated carefully because safety-related assets require validated procedures, audit trails, and human approval. Therefore, predictive maintenance should support professional judgment rather than replace it.

7. Data Architecture and Analytical Techniques

The analytical value chain begins with data quality. Many smart-building projects fail because sensor points are inconsistent, naming conventions differ across contractors, and the relationship between equipment and spaces is unclear. BIM-IoT integration research highlights the need to link dynamic sensor data with static building information, but also reports challenges in semantic mapping, model updating, and ownership responsibility (Adewumi *et al.,* 2021; Tang *et al*., 2020). For Saudi mega projects, this means that asset information requirements should be specified before construction completion, not invented after handover.

Predictive maintenance models may be divided into four groups. Rule-based models use engineering thresholds and fault logic, such as identifying low chilled water delta-T or excessive fan energy. Statistical models detect drift from normal operation using control charts or regression. Machine learning models classify or predict faults from labeled patterns, while deep learning models can identify complex temporal signals from high-frequency data. Hybrid models combine physics, domain knowledge, and data-driven learning. The strongest practice is often hybrid because building services are governed by physical laws, but their behavior is affected by occupancy, weather, controls, and maintenance practices.

The output of analytics should not be a vague alarm. It should produce a risk-ranked decision: probable fault, affected asset, confidence level, operational impact, energy penalty, safety relevance, recommended inspection, required spare part, and expected urgency. Pruvost *et al*., (2023) note that predictive maintenance supported by digital twins can improve diagnosis, prediction, and decision-making, but only when the twin contains sufficient functional information. Similarly, building digital twin reviews emphasize component monitoring, anomaly detection, operational optimization, predictive maintenance, and scenario simulation as interconnected applications rather than separate tools (Bortolini *et al*., 2022; Al-Kasasbeh *et al*., 2024).

8. FINDINGS AND THEMATIC SYNTHESIS

The review identifies five major findings. First, predictive maintenance produces the highest practical value when deployed around critical and repetitive assets, especially chillers, pumps, air-handling units, lifts, and electrical distribution components. These assets provide enough data to train models and carry enough operational risk to justify the investment. Second, digital twins are most useful when they integrate asset metadata, topology, live telemetry, and maintenance records. A visual 3D model without operational semantics is insufficient for predictive maintenance.

Third, automated fault detection must be connected to maintenance workflows. If analytics are not linked to CMMS work orders, technician feedback, and spare-parts planning, detected faults may become another unmanaged alarm stream. Fourth, energy and maintenance should be integrated. Many building service faults increase energy use before they cause equipment breakdown. Therefore, predictive maintenance supports both reliability and sustainability. Fifth, organizational readiness is as important as technology. Staff need training in BMS interpretation, data quality, failure modes, BIM navigation, cybersecurity, and performance reporting.

Table 2 maps building services categories to data sources, algorithms, and Saudi mega-project benefits. It shows that the same digital infrastructure can support multiple outcomes: reduced downtime, improved comfort, lower energy intensity, water conservation, safety compliance, better procurement planning, and more credible ESG reporting. The review also finds that predictive maintenance should be implemented through staged maturity rather than sudden full automation. Figure 2 therefore presents a five-stage roadmap: instrument, connect, diagnose, predict, and optimize.

Table 2: Building services predictive maintenance matrix for Saudi mega projects

Building services category	**Key monitored data**	**Predictive analytics focus**	**Saudi mega-project benefit**
HVAC and district cooling interfaces	Temperature, flow, pressure, valve position, energy, vibration, occupancy	FDD, abnormal energy drift, chiller and pump risk, remaining useful life	Reduced cooling downtime, lower energy intensity, improved comfort during hot-climate operation
Electrical distribution	Load, power quality, thermal condition, breaker status, generator and UPS alarms	Anomaly detection, thermal risk, load imbalance and reliability trend analysis	Higher business continuity for hotels, hospitals, airports, arenas, and mixed-use districts
Water and plumbing	Flow, pressure, tank level, pump status, leakage alarms, water quality	Leak detection, pump degradation, abnormal demand pattern recognition	Water conservation, faster leakage response, improved sustainability reporting

Building services category	Key monitored data	Predictive analytics focus	Saudi mega-project benefit
Vertical transportation	Run hours, motor signatures, door cycles, fault codes, waiting-time indicators	Failure probability, usage-based maintenance, risk-based dispatching	Improved guest and resident experience in high-rise and transit-connected assets
Life-safety systems	Fire pump status, smoke fan status, emergency power, panel alarms, inspection records	Compliance risk tracking, condition-based testing support, overdue task prioritization	Strong safety assurance and auditable maintenance evidence

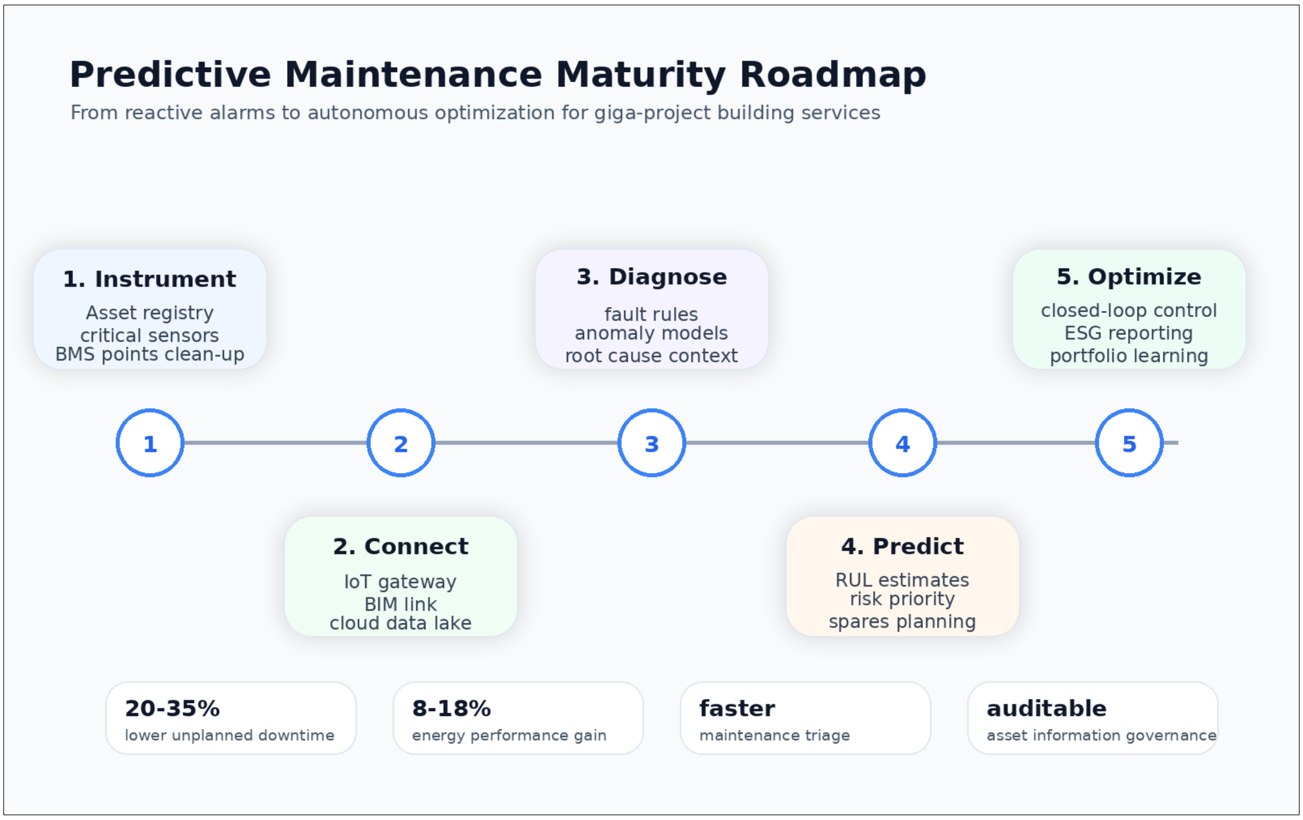

Figure 2: Predictive maintenance maturity roadmap from instrumentation to autonomous optimization.

9. DISCUSSION: SAUDI MEGA-PROJECT IMPLEMENTATION

Saudi mega projects present a rare opportunity to embed predictive maintenance from the design and construction stages. Many global facilities attempt to retrofit digital twins after years of operation, when asset data is incomplete and documentation is scattered. In contrast, new Saudi developments can specify maintainable BIM objects, naming standards, sensor requirements, cybersecurity rules, and performance dashboards before handover. This is aligned with Vision 2030's emphasis on infrastructure modernization, environmental stewardship, digital transformation, and quality of life.

However, implementation must be realistic. A mega-project may include thousands of assets and millions of BMS data points, but not every point requires advanced analytics. The first step is asset criticality ranking. Assets should be classified by safety impact, comfort impact, energy impact, business continuity, replacement cost, redundancy, and access difficulty. Predictive maintenance should start with high-criticality assets and repetitive equipment families where learning can be transferred. This prevents overinvestment in low-value analytics and helps facility teams build confidence.

Another Saudi-specific issue is climate. High ambient temperature, dust, humidity variation in coastal locations, and intense cooling periods increase stress on HVAC equipment. Models trained in temperate climates may not transfer directly to Saudi operating conditions. Therefore, local baselines are needed. During the first operational year, data should be used to establish normal performance envelopes across seasons, occupancy patterns, and special events. Once baselines mature, models can compare current behavior to expected behavior and identify abnormal drift.

Procurement strategy also matters. Contracts should require open data access, clear point naming, API availability, asset register quality, commissioning data, training, and post-handover support. If vendors lock operational data into proprietary systems, predictive maintenance becomes costly and fragile. Open standards and a common data environment are essential. Cybersecurity must also be embedded because connected building services systems can expose operational risk if remote access, identities, patches, and network segmentation are poorly managed.

10. RECOMMENDATIONS

The first recommendation is to define asset information requirements at project inception. Owners should specify which maintainable assets require BIM parameters, sensor points, warranty data, spare parts, failure modes, commissioning values, and maintenance procedures. This will reduce information loss during handover. The second recommendation is to adopt a digital monitoring hierarchy. Not every asset needs the same sensing depth. Critical chillers, pumps, switchgear, and lifts need high-resolution condition monitoring, while lower-risk components may only need run-hour and alarm tracking.

The third recommendation is to create a unified building services data model. BMS points, BIM objects, CMMS asset IDs, and space identifiers should follow a controlled naming and tagging convention. The fourth recommendation is to start with hybrid analytics. Rule-based FDD can capture known engineering faults, while machine learning can identify patterns that are difficult to encode manually. The fifth recommendation is to integrate analytics into maintenance workflows. Every predictive alert should be traceable to an inspection result, action taken, technician feedback, and model update.

The sixth recommendation is to establish a Saudi mega-project performance dashboard that combines availability, energy intensity, carbon impact, comfort complaints, water leakage, safety-critical overdue tasks, and maintenance response time. The seventh recommendation is to invest in workforce competence. Facility managers, engineers, technicians, and client representatives need training in BIM-FM, BMS analytics, data literacy, cybersecurity, and reliability-centered maintenance. The eighth recommendation is to maintain human oversight. Predictive systems should recommend, prioritize, and explain; accountable professionals should approve safety-critical actions.

11. Limitations and Future Research

This review is limited by the uneven maturity of published evidence. Many studies demonstrate promising prototypes, but fewer provide long-term operational results across complete building portfolios. Future research should therefore focus on longitudinal Saudi case studies that compare reactive, preventive, condition-based, and predictive maintenance outcomes over several years. There is also a need for benchmark datasets from hot-climate buildings so that algorithms can be tested under local conditions. Another gap concerns economic evidence. Owners need transparent models for return on investment, including avoided downtime, energy savings, deferred replacement, reduced complaints, and improved asset life.

Future research should also investigate interoperability between BIM, BMS, CMMS, GIS, and digital twin platforms in large mixed-use districts. Technical studies should examine explainable AI for facility teams because black-box predictions are less likely to be trusted in safety-critical environments. Finally, governance research is needed on data ownership, cybersecurity, contractual responsibility, and regulatory alignment for smart building operations in the Kingdom.

11.1 Implementation Note

Implementation priority should remain evidence led. Owners should begin with a pilot package that covers a limited but representative group of high-value assets, such as chillers, primary pumps, air-handling units, switchgear, fire pumps, and selected elevators. The pilot should document the baseline failure history, alarm volume, energy intensity, technician response time, spare-parts availability, and occupant complaint trends before advanced analytics are switched on. This baseline prevents exaggerated claims and gives the project team a defensible comparison point. After three to six months of operation, diagnostic alerts should be compared with technician findings so that false positives, false negatives, sensor faults, and unclear recommendations can be corrected. The pilot should then be expanded only when measurable value is demonstrated.

A second priority is commissioning for data, not only commissioning for performance at one point in time. Conventional commissioning proves that systems can operate under test conditions, but predictive maintenance requires stable naming, calibrated sensors, trend logging, asset relationships, alarm rationalization, and access to historical data. Saudi mega projects should therefore include digital commissioning checklists that verify whether every critical asset has a unique identifier, correct location, correct BMS mapping, accepted operating envelope, relevant failure modes, and a maintenance procedure attached to the CMMS. This information must be reviewed jointly by designers, contractors, controls specialists, commissioning authorities, and facility managers before practical completion.

A third priority is governance of analytics. Predictive models should be treated as maintained assets in their own right. Each model needs an owner, version history, training data description, validation method, performance threshold, review interval, and retirement rule. If a model continues to create low-quality alerts, it should be retrained or removed. If a model affects safety-critical decisions, it should produce explainable reasoning and require human approval. This governance is essential in Saudi giga-project environments where systems may be operated by multiple contractors, tenants, hotel operators, public agencies, or specialist service providers. A clear responsibility matrix avoids disputes when an alert is ignored, a fault is missed, or a warranty claim depends on operating evidence.

A fourth priority is integration with sustainability targets. Predictive maintenance should not be evaluated only by reduced breakdowns. It should also be assessed by avoided energy waste, improved indoor air quality, water savings, lower carbon intensity, fewer emergency callouts, and extended equipment life. For example, a chilled water valve fault may not immediately stop service, but it may increase pumping energy and reduce comfort. A leaking domestic water system may not appear as a catastrophic failure, but it can weaken sustainability performance and increase operational cost. Linking maintenance analytics with environmental reporting creates a stronger business case for owners and supports Vision 2030-aligned performance transparency.

A fifth priority is change management. Facility teams may distrust predictive systems if they appear suddenly, use unfamiliar language, or produce alerts that do not match field experience. Successful adoption requires co-design with maintenance supervisors and technicians. Dashboards should show practical information: what asset is affected, why the system thinks a fault exists, what evidence supports the recommendation, what action is suggested, and what happens if the issue is deferred. Training should be delivered through live building examples rather than generic software demonstrations. Technician feedback should be captured after every work order so the system learns from local conditions.

A sixth priority is portfolio learning. Saudi mega projects often include multiple buildings, districts, or asset classes delivered in phases. Once the first buildings are occupied, their operational evidence should inform later phases. Repeated pump failures may indicate a specification issue, a controls sequence problem, poor installation practice, or unsuitable maintenance intervals. Repeated comfort complaints may show that design assumptions about occupancy or solar gain require revision. When digital monitoring is connected to design and procurement governance, predictive maintenance becomes a continuous improvement mechanism across the whole development program, not merely a facilities tool.

A final priority is realistic maturity planning. Full autonomous optimization should not be promised at the start. A more credible pathway begins with clean asset registers, calibrated monitoring, and reliable alarm management. It then moves toward automated fault detection, risk-based maintenance planning, predictive analytics, and eventually closed-loop optimization where appropriate. This staged pathway protects budgets, improves trust, and allows owners to select technologies based on evidence. It also reduces the risk of technology theatre, where attractive dashboards are presented without dependable data, maintenance integration, or measurable operational value.

An eighth priority is cybersecurity and operational continuity. Connected building services systems should be segmented from corporate networks, protected with role-based access, monitored for unusual activity, and updated through controlled change procedures. Remote access by vendors should be time limited, logged, and approved. Cybersecurity is not separate from maintenance because a compromised controller, gateway, or cloud integration can create service disruption, safety concerns, or unreliable data. Predictive maintenance platforms should therefore follow secure-by-design principles and include backup operating procedures for cases where analytics or connectivity are unavailable.

A ninth priority is procurement alignment. Owners should avoid purchasing isolated products that cannot exchange data. Tender documents should require open interfaces, exportable histories, documented point lists, clear ownership of generated data, and compatibility with the project's information management standards. Suppliers should be evaluated not only on dashboard appearance but on data quality functions, integration capability, model transparency, support arrangements, and evidence from comparable facilities. Long-term value depends on whether a platform can survive operator changes, building expansions, and future technology upgrades.

A tenth priority is performance verification. The project should define measurable indicators before implementation: unplanned downtime, mean time between failures, mean time to repair, energy use intensity, alarm reduction, preventive task compliance, spare-parts stock accuracy, occupant complaints, and cost of emergency callouts. These indicators should be reported monthly and reviewed by both technical and executive teams. Where benefits are not visible, the cause should be investigated: poor data, unsuitable algorithms, weak maintenance processes, or unrealistic expectations. This closes the loop between technology investment and operational accountability.

Finally, research collaboration should be encouraged between Saudi developers, universities, engineering consultants, technology vendors, and facility management companies. Shared anonymized datasets would help validate fault detection models for hot-climate operation and reduce dependency on imported assumptions. Academic partners can test explainable algorithms, while operators can provide practical failure evidence that rarely appears in design documents. This collaboration would create local knowledge, support professional capability, and strengthen the credibility of Saudi smart building research in international journals. It would also help move the sector from isolated pilot projects toward repeatable, standards-based predictive maintenance practice.

For client-side governance, a digital operations steering committee should be created before handover. It should include asset management, facilities, IT, cybersecurity, sustainability, finance, and project delivery representatives. The committee should approve data standards, review monthly performance, resolve vendor access issues, and decide which analytics are scaled. This prevents predictive maintenance from being owned by one department alone and ensures that reliability, cost, comfort, and environmental performance are considered together. This governance structure is especially important where buildings are handed over in phases and multiple operators share one digital infrastructure. It also protects continuity, trust, evidence.

12. CONCLUSION

Digital monitoring and predictive maintenance can transform building services management in Saudi mega projects if they are implemented as a lifecycle information system rather than as isolated software. The review shows that the core success factors are accurate asset data, interoperable BMS and IoT telemetry, BIM-linked context, reliable analytics, CMMS workflow integration, trained people, and governance dashboards. For HVAC, electrical, water, life-safety, and vertical transportation systems, predictive maintenance can support fewer failures, lower energy waste, faster maintenance decisions, and stronger sustainability reporting.

The proposed DMPMF provides a practical framework for aligning facility operations with Vision 2030 priorities. It enables asset owners to move from reactive alarms to risk-based decision-making and from fragmented handover data to continuous performance intelligence. The strongest conclusion is that predictive maintenance is not only a technical upgrade; it is an organizational capability. Saudi mega projects that build this capability early will be better positioned to protect asset value, improve user experience, reduce environmental impact, and demonstrate world-class operational excellence.

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