Global Academic Journal of Economics and Business

Available online at https://www.gajrc.com
DOI: https://doi.org/10.36348/gajeb.2026.v08i04.019

OPEN ACCESS

ISSN: 2706-9001 (P)
ISSN: 2707-2584 (O)

Original Research Article

Digital Twin Applications for Smart Building Operations, Maintenance and Risk Management in Saudi Mega Projects

Ibad Ullah[1]*
[1]Independent Researcher

***Corresponding Author**
Ibad Ullah
Independent Researcher

Article History
Received: 25.05.2026
Accepted: 18.07.2026
Published: 21.07.2026

Abstract: Saudi Arabia's mega-project portfolio is reshaping the operational logic of the built environment. Smart districts, high-rise mixed-use assets, hospitals, transport hubs, hotels and mission-critical public facilities are expected to perform as continuously optimised systems rather than static construction outputs. This review examines how digital twin applications can improve smart building operations, maintenance and risk management in Saudi mega projects under Vision 2030. The paper synthesises peer-reviewed literature from 2020 to 2025 and develops a building lifecycle framework linking BIM, IoT, building management systems, artificial intelligence, facility management platforms and governance controls. The central argument is that a digital twin becomes valuable only when it converts live building data into verified operational decisions: fault detection, energy optimisation, predictive maintenance, safety alerts, resilience planning, asset lifecycle analysis and executive risk visibility. The review identifies four implementation layers: data foundation, analytical intelligence, operational intervention and governance assurance. Findings show that digital twins can reduce fragmentation between design, construction and facility management; however, success depends on data quality, interoperability, cybersecurity, workforce capability, procurement discipline and ethical use of automation. For Saudi mega projects, the strongest value is expected in MEP-intensive assets where energy, cooling, lifts, water systems, fire safety, indoor environmental quality and equipment availability directly affect public value. The paper proposes a practical roadmap for staged adoption, beginning with priority assets and moving toward portfolio-level digital twin governance. It concludes that digital twins should be treated as socio-technical operating systems for smart buildings, not merely 3D visual models.

Keywords: Digital Twin, Smart Buildings, Saudi Mega Projects, Facility Management, Predictive Maintenance, Risk Management, Vision 2030, Building Information Modeling, MEP Systems.

1. INTRODUCTION

Saudi Arabia is investing in an unprecedented generation of mega projects, including smart cities, entertainment districts, tourism destinations, healthcare campuses, transport nodes and mixed-use urban developments. These projects are expected to support economic diversification, quality of life, sustainability and institutional performance under Vision 2030. Yet their operational complexity is very different from conventional building portfolios. A smart building in a mega-project environment may contain thousands of sensors, linked building management systems, digitally controlled HVAC equipment, vertical transport, access control, fire systems, water networks, elevators, renewable energy assets, security systems and occupant-facing applications. The operational challenge is therefore not only to construct assets quickly, but to maintain safe, reliable, efficient and adaptive performance after handover. Digital twin technology addresses this challenge by creating a dynamic, data-linked representation of a physical asset or system. Unlike a static BIM model, a digital twin connects geometry, asset registers, sensor streams, operational rules, maintenance history, performance analytics and decision dashboards. Recent reviews describe digital twins in construction and facility management as mechanisms for real-time data acquisition, analysis and decision support across the asset lifecycle (Boje *et al*., 2020; Deng *et al*., 2021; Opoku *et al*., 2021; Madubuike *et al*., 2022; Hakimi *et al*., 2024). In smart buildings, the digital twin can monitor equipment health, simulate energy demand, detect abnormal patterns, prioritize maintenance orders, test emergency scenarios and support long-term risk governance (Ghansah, 2024; Mousavi *et al*., 2024; Piras *et al.,* 2024).

The Saudi context gives this topic strategic urgency. Mega projects such as NEOM, Red Sea developments, Qiddiya, Diriyah and urban regeneration programmes are designed around intelligent infrastructure, high service expectations and sustainability commitments. The uploaded reference model on applied AI in NEOM construction also emphasises that advanced analytics, machine learning, robotics, IoT and digital twins can improve project efficiency, safety, sustainability and cost control in Saudi mega-project settings (Allouzi and Aljaafreh, 2024). Building on that model, this paper shifts the focus from AI in construction execution to digital twin applications in post-construction operations, maintenance and risk management. The review is important because many digital transformation initiatives fail when technology is treated as a procurement item rather than an operating capability. A high-quality digital twin requires reliable data architecture, clear ownership, cybersecurity controls, trained facility teams, updated asset information and measurable performance indicators. Without these conditions, the twin may become an attractive dashboard with limited operational authority. With them, it can become the control layer that links building performance with maintenance strategy, risk appetite and Vision 2030 outcomes.

2. AIM, OBJECTIVES AND RESEARCH QUESTIONS

The aim of this review is to develop a structured understanding of how digital twin applications can enhance smart building operations, maintenance and risk management in Saudi mega projects. The study has five objectives. First, it clarifies the concept of digital twins for smart buildings and distinguishes it from BIM, dashboards and isolated IoT systems. Second, it synthesises recent literature published between 2020 and 2025 on digital twin applications in facility management, energy management, predictive maintenance, safety and risk governance. Third, it identifies the operational value of digital twins for MEP-intensive assets in Saudi mega projects. Fourth, it proposes a lifecycle framework that connects digital twin data flows with maintenance decisions and risk controls. Fifth, it outlines adoption challenges and practical recommendations for project owners, consultants, contractors and facility management teams. The review is guided by four research questions. How are digital twins being applied in smart building operations and facility management? Which maintenance and risk management functions can be improved by integrating BIM, IoT, AI and building management data? What barriers may limit implementation in Saudi mega projects? How can digital twin adoption be governed so that it supports safety, sustainability, lifecycle value and stakeholder confidence?

3. METHODOLOGY

This paper adopts a narrative systematic review methodology suitable for a conceptual review paper intended for Scopus and Web of Science style publication. The method follows three stages: search, screening and synthesis. The search stage focused on peer-reviewed journal articles, review papers and selected conference papers published from 2020 to 2025. Keywords included digital twin, smart building, facility management, predictive maintenance, BIM, IoT, building energy management, risk management, construction digital twin, asset lifecycle and Saudi mega projects. The screening stage prioritised sources that discussed digital twins in the architecture, engineering, construction and facility management domain. Sources were retained when they addressed at least one of the following: building operations, maintenance, energy, safety, risk, data governance, interoperability, lifecycle asset management or smart city implementation. Studies that used digital twin only as a generic Industry 4.0 term without built-environment relevance were excluded. The synthesis stage used thematic coding. Literature was grouped into six themes: conceptual foundations, enabling technologies, operations and energy, maintenance and asset health, risk and resilience, and implementation governance. The method is review-based and does not claim field measurement from Saudi projects. Instead, it develops a transferable conceptual framework for Saudi mega-project owners and facility managers by aligning international evidence with the operational needs of Vision 2030 infrastructure. This approach is appropriate because digital twin adoption in smart buildings remains fragmented, and review-based frameworks are useful for connecting emerging knowledge with practical implementation (Deng *et al.*, 2021; Madubuike *et al.,* 2022; Omrany *et al.,* 2023; Liu *et al.*, 2024).

4. Literature Review: Digital Twins in the Built Environment

Digital twin research in the built environment has developed rapidly since 2020. Early work positioned construction digital twins as an extension of BIM that includes semantic data, sensors and dynamic feedback loops (Boje *et al.,* 2020). This is significant because BIM traditionally supports design coordination and asset information, while digital twins support operational awareness and decision automation. Deng *et al.,* (2021) describe the transition from BIM to digital twins as a progression from static representation to intelligent building representations across lifecycle stages. Opoku *et al.*, (2021) identify key application areas including structural integrity, facilities management, monitoring, logistics and energy simulation. Madubuike *et al.*, (2022) further show that digital twins have potential in design, construction, operation and maintenance, but implementation remains limited by interoperability, data exchange and organisational readiness. Recent reviews expand this discussion. Omrany *et al.*, (2023) identify virtual design, project planning, asset management, safety, logistics and energy as important digital twin application domains in construction. Khallaf *et al.*, (2022) classify applications into facility management, energy, structural health monitoring, disaster management and smart cities. Yang *et al.*, (2024) describe architecture, applications, trends and challenges, noting that poor data quality, weak integration and data security remain barriers. Mousavi *et al.*, (2024) provide a broad review of digital twin definitions, capabilities and challenges in AEC, while Liu *et al.*, (2024) review digital twin technology across buildings, landscapes and urban environments. For smart building facility management, the literature is more specific. Hakimi *et al.*, (2024) explain that digital twins enable real-time data acquisition, transfer, analysis and utilisation for smart facility management. Ghansah (2024) identifies enablers, applications and challenges at the facility management stage, highlighting the need for systematic reference models, real-time data integration and effective visualisation. Ahmad *et al.*, (2023) argue that facility management is increasingly shaped by data from automation systems and sensor networks. Piras *et al.,* (2024) propose built-environment digital twin frameworks for energy and operational decisions, and Piras *et al.*, (2025) demonstrate how IoT components, automation flows and dashboards can support smart building monitoring. In parallel, AI-enhanced digital twin research shows that machine learning can support fault detection, predictive maintenance, energy optimisation and occupant-centric control (Palley *et al.*, 2025; Ghaemi *et al.*, 2025; Elias and Issa, 2025). The literature therefore suggests a shift from digital twin as visual replica toward digital twin as an operational intelligence environment. In Saudi mega projects, this distinction is critical. A digital twin that only displays a 3D model cannot manage chilled water faults, fire system readiness, elevator availability, indoor air quality or crowd movement risk. A decision-ready twin must integrate live data, asset hierarchies, operational thresholds, maintenance workflows and accountable governance.

4.1 Conceptual Distinction between BIM, BMS and Digital Twins

A recurring problem in practice is the assumption that any 3D model, dashboard or sensor platform is automatically a digital twin. This review adopts a stricter interpretation. BIM provides structured geometric and asset information, but it may remain static after handover if it is not updated by operational events. A building management system controls and monitors mechanical and electrical equipment, but it normally lacks complete spatial context, lifecycle logic and cross-system simulation. A dashboard visualises data, but it may not contain a calibrated model of how assets should behave. A digital twin integrates these elements into a continuously updated representation that can describe, diagnose, predict and recommend. The difference is therefore functional rather than aesthetic. A model becomes a twin when it maintains an operational relationship with the physical building and influences decisions through validated feedback loops (Boje *et al.*, 2020; Deng *et al.*, 2021; Sacks *et al.,* 2020). This distinction matters for Saudi mega projects because technology budgets can be wasted when visual sophistication is confused with operational maturity. The procurement question should not be whether a project has a digital twin, but whether the twin can answer operational questions: Which assets are drifting from normal behaviour? Which faults create the highest business risk? Which maintenance actions will reduce downtime? Which energy sequences waste cooling load? Which emergency systems are outside compliance? A useful twin should therefore be assessed through decision quality, response speed, data reliability and measurable performance improvement.

5.1 Saudi Mega-Project Context and Operational Priorities

Saudi mega projects present distinctive digital twin requirements because they combine large scale, harsh climatic conditions, complex stakeholder ecosystems and high public expectations. Extreme summer temperatures increase dependence on cooling reliability and energy optimisation. Tourism, entertainment and transport assets require strong crowd comfort, safety and continuity of service. Healthcare, research, hospitality and mixed-use facilities require stable indoor environmental quality, rapid maintenance response and rigorous compliance records. District-level assets may also share utilities, mobility systems, security infrastructure and public realm services. In this context, the smart building is not an isolated object. It is part of a connected urban system where failure in one asset can affect adjacent services and user experience. Digital twins can support this environment by creating a common operational picture across buildings, infrastructure and service providers. They can also help owners compare performance between assets, detect recurring contractor issues and improve capital planning. Vision 2030 emphasises efficiency, accountability, sustainability and quality of life, and digital twins can operationalise these goals when they are linked to measurable KPIs rather than generic innovation claims. The uploaded NEOM-oriented AI reference model argues that intelligent technologies can enhance efficiency, sustainability, safety and project success in Saudi mega developments; the present review extends that logic into operations by arguing that the same intelligent foundation must continue after handover (Allouzi and Aljaafreh, 2024).

6.1 Performance Indicators for Digital Twin Value

Digital twin benefits should be measured through operational indicators. For energy, indicators include energy use intensity, peak demand, chilled water efficiency, equipment coefficient of performance and carbon-related metrics. For maintenance, indicators include mean time between failures, mean time to repair, preventive maintenance compliance, fault recurrence, work order closure time and maintenance cost per asset. For risk, indicators include critical asset availability, overdue statutory inspections, safety event response time, unresolved alarms and emergency system readiness. For occupant experience, indicators include comfort complaints, indoor air quality deviations, lift waiting time and service satisfaction. These indicators help prevent a common implementation weakness: investing in technology without proving value. Reviews of digital twin and facility management literature repeatedly emphasise decision support, asset management, energy optimisation and lifecycle value, but they also note that practical evidence and standardised evaluation remain insufficient (Khallaf *et al*., 2022; Omrany *et al*., 2023; Hakimi *et al*., 2024). Saudi owners should therefore build benefit measurement into the pilot stage. Baseline performance should be recorded before implementation, and post-implementation improvements should be verified through auditable data. This approach strengthens the business case and supports continuous improvement.

5. Digital Twin Architecture for Smart Building Operations

A smart building digital twin requires layered architecture. The first layer is the physical asset layer, including HVAC plants, pumps, chillers, air handling units, lighting, meters, lifts, fire systems, access systems, water networks and structural components. The second layer is the data acquisition layer, which collects information through IoT sensors, meters, supervisory control and data acquisition systems, building management systems, computerised maintenance management systems, CAFM platforms and occupant feedback channels. The third layer is the model layer, where BIM geometry, asset registers, system schematics, spatial information and operational metadata are connected. The fourth layer is the analytics layer, where AI, rules engines, simulation models, fault detection and optimisation algorithms convert data into predictions. The fifth layer is the decision layer, where dashboards, alerts, work orders, risk heat maps and executive reports support action. The sixth layer is the governance layer, which defines data quality, cybersecurity, responsibility, audit trails and change control. This layered architecture is consistent with research showing that digital twins depend on data integration, simulation, analytics and visualisation rather than one technology alone (Boje *et al*., 2020; Deng *et al*., 2021; Madubuike *et al*., 2022; Yang *et al*., 2024). For Saudi mega projects, the architecture should be implemented at three scales. At asset scale, a twin monitors one building or critical system such as a central cooling plant.

At district scale, it connects clusters of buildings, public spaces, utilities and mobility interfaces. At portfolio scale, it gives the owner visibility across multiple assets and contractors. This hierarchy is useful because mega projects often include phased delivery, multiple operators and long operational lifecycles. Data handover from construction to operations becomes a major success factor. If asset tags, warranties, manuals, commissioning data, model attributes and maintenance procedures are incomplete, the operational twin starts with weak foundations. Owners should therefore define digital twin information requirements before construction completion, not after facility teams inherit the asset.

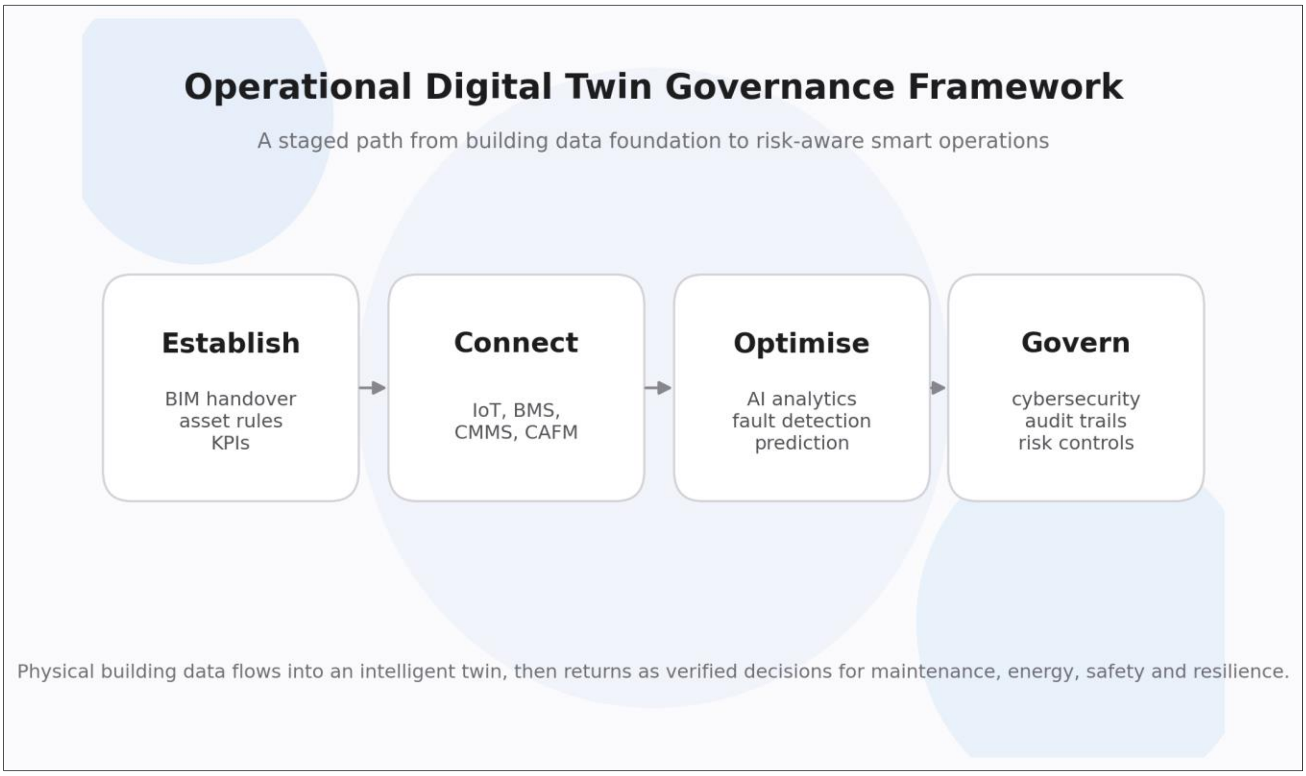

Figure 1: Operational Digital Twin Governance Framework for Saudi smart buildings.

Table 1: Digital twin layers and smart building operational functions

Layer	**Core data or function**	**Operational decision supported**	**Saudi mega-project relevance**
Physical asset	MEP equipment, spaces, structures and utilities	System condition and operating state	Focuses on cooling, life safety, water, lifts and emergency power
Data acquisition	IoT, meters, BMS, CMMS, CAFM and occupancy data	Live monitoring and anomaly detection	Supports desert-climate performance and service continuity
Model and context	BIM, asset registers, location, warranties and manuals	Asset traceability and lifecycle planning	Improves handover from contractors to operators
Analytics	AI, rules, simulation and predictive models	Fault diagnosis, energy optimisation and maintenance timing	Reduces downtime and supports sustainability KPIs
Governance	Cybersecurity, ownership, audit trails and change control	Risk accountability and reliable decision-making	Builds investor, regulator and public confidence

6. Applications in Operations, Maintenance and Risk Management

The first major application is operational monitoring. Digital twins can combine real-time performance data with spatial and asset context, allowing facility teams to see how building systems behave under actual occupancy, weather and event conditions. In Saudi Arabia, where cooling demand is a major operational issue, twins can compare chiller load, indoor temperature, humidity, air quality, occupancy and energy demand to detect inefficiency and comfort risk. Building energy management research shows that AI-enabled digital twins can learn from occupancy behaviour and support autonomous optimisation while balancing energy efficiency and comfort (Ghaemi *et al*., 2025; Palley *et al.,* 2025). The second application is predictive maintenance. Instead of maintaining equipment only by calendar schedule or after failure, a digital twin can use vibration, temperature, pressure, runtime, fault codes and historical maintenance records to predict degradation. For MEP systems, this can improve availability of chillers, pumps, lifts, fire pumps, generators and water treatment assets. Elias and Issa (2025) frame AI-driven digital twins as systems that integrate sensor data, facility management systems and predictive analytics for maintenance decisions. The third application is fault detection and diagnostics. A twin can identify abnormal equipment behaviour, compare it with expected operating envelopes and recommend corrective action. For example, an air handling unit may show normal runtime but abnormal energy use because of a stuck damper, dirty filter or control sequence error.

The twin can connect sensor evidence to maintenance workflows, reducing time wasted on manual troubleshooting. The fourth application is risk management. Smart building risk includes equipment failure, fire safety non-compliance, crowding, indoor air quality problems, water leakage, cybersecurity breach, energy instability and business interruption. Digital twins support risk management by linking hazards to location, asset criticality, probability, consequence and control status. Construction safety research also indicates that digital twin integration with sensor technology can improve real-time risk monitoring and safety decision support (Luo *et al*., 2024). For operational buildings, the same principle can be applied to emergency readiness, evacuation simulation and critical asset resilience. The fifth application is lifecycle asset planning. Owners can use digital twin records to evaluate whether equipment should be repaired, upgraded or replaced. This is important for Saudi mega projects because assets are expected to remain globally competitive for decades. Twin-based lifecycle analysis can connect maintenance cost, energy cost, carbon impact, downtime, warranty status and user experience. The sixth application is stakeholder transparency. Executives, regulators, investors, facility managers and service providers often view building performance through different reports. A portfolio twin can create shared performance evidence, reducing disputes and improving accountability.

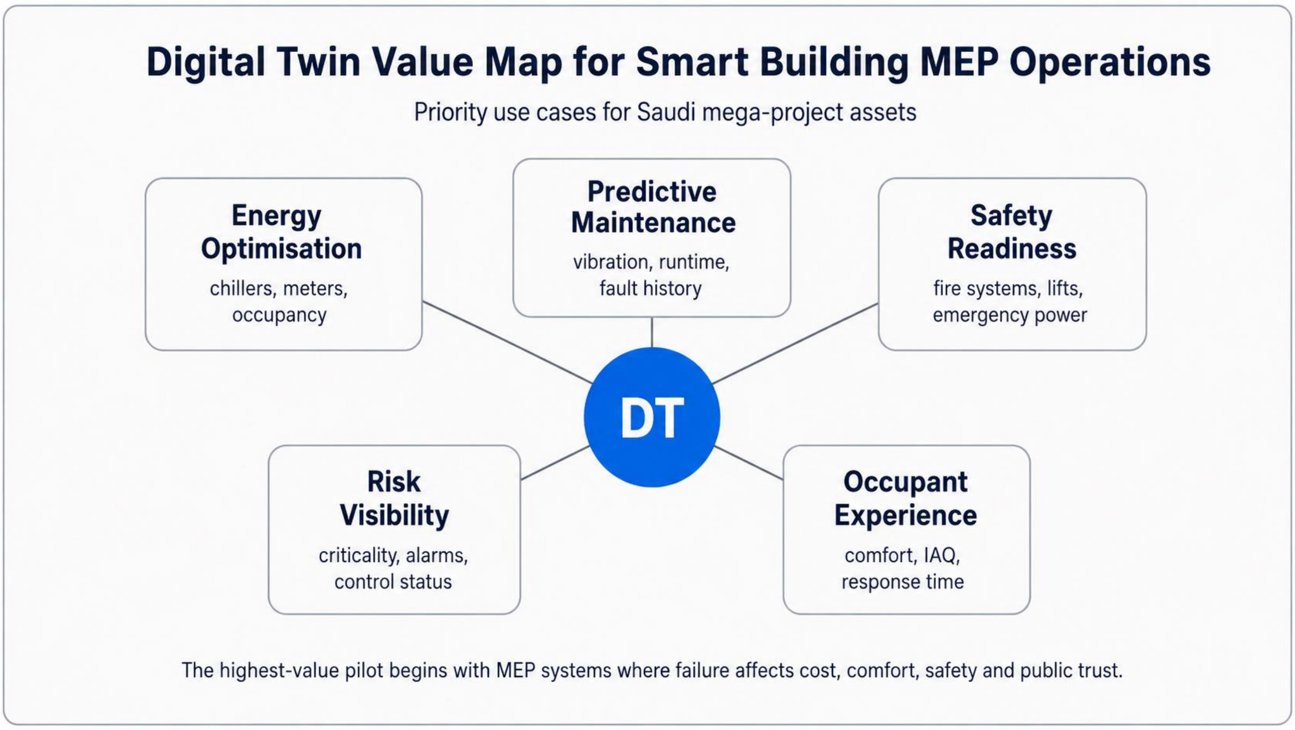

Figure 2: Digital Twin Value Map for MEP-centred smart building operations

7. Proposed Framework for Saudi Mega Projects

The proposed framework is titled the Operational Digital Twin Governance Framework for Saudi Smart Buildings. It has four phases: Establish, Connect, Optimise and Govern. The Establish phase creates the digital foundation. Project owners define asset information requirements, naming conventions, BIM handover standards, sensor strategy, cybersecurity rules and operational KPIs before handover. The Connect phase integrates BIM, BMS, CMMS, IoT, energy meters, access systems and maintenance data into one controlled environment. The Optimise phase applies analytics to energy, comfort, equipment health, fault detection, maintenance prioritisation and risk alerts. The Govern phase institutionalises ownership, audit trails, data quality reviews, privacy controls, vendor management and continuous improvement. The framework differs from conventional technology adoption because it treats the digital twin as an operating model. It links technical components with business decisions. For example, a chiller fault is not only a sensor event; it is an energy, comfort, cost and risk issue. A fire pump test is not only a maintenance action; it is a compliance and public safety control. A lift outage is not only an asset failure; it affects accessibility, crowd movement and user satisfaction. This logic is well aligned with smart facility management literature, which emphasises real-time data utilisation, decision support and operational integration (Ahmad *et al*., 2023; Hakimi *et al*., 2024; Ghansah, 2024).

In Saudi mega projects, the framework should begin with critical assets rather than full digital replication of everything. Priority should be given to MEP systems with high operational cost, safety importance or public visibility: district cooling plants, HVAC, elevators, fire systems, water systems, emergency power, indoor environmental quality and energy meters. After value is proven, the twin can expand to space management, occupant experience, sustainability reporting and portfolio optimisation. This staged strategy reduces cost, improves adoption and prevents over-complex implementation.

7.1 MEP-Centred Priority Use Cases

A practical Saudi deployment should prioritize MEP systems because they concentrate operational cost, safety exposure and user experience risk. District cooling plants, chillers, pumps, air handling units, fire pumps, generators, lifts and water systems generate continuous data and are linked to clear service outcomes. A digital twin can compare expected and actual performance, rank faults by criticality, recommend maintenance timing and test the impact of control changes before they are applied. This MEP-centred approach also helps facility managers avoid information overload. Instead of creating a complete twin of every component at once, the owner can begin with systems where downtime, energy waste or compliance failure has visible consequences. The approach is consistent with predictive maintenance and smart building studies that emphasise sensor integration, analytics and actionable decision support (Piras *et al*., 2025; Elias and Issa, 2025).

8. Challenges, Limitations and Governance Requirements

Digital twin adoption faces technical, organisational and governance barriers. Data quality is the most common limitation. If asset registers are incomplete, sensors are poorly calibrated or naming conventions differ between contractors, the twin may produce unreliable insights. Interoperability is another barrier because BIM, BMS, CMMS, CAFM, IoT platforms and vendor systems often use different data structures. Yang *et al*., (2024) identify poor data quality, integration difficulty and data security as core challenges in construction digital twins. Ghansah (2024) similarly highlights reference model gaps, real-time data integration and visualisation as major smart building challenges. Cybersecurity is especially important in smart buildings because digital twins can connect operational technology with enterprise networks. A compromised twin could expose asset data, disrupt building services or create safety risks. Saudi mega-project owners should therefore classify systems by criticality, apply network segmentation, monitor access rights and maintain audit trails. Organisational readiness is equally important. Facility managers, engineers, IT teams and vendors must understand how to interpret twin outputs and act on them. A digital twin cannot replace professional judgement; it should improve evidence quality and speed of response. Procurement models can also create difficulty. If contractors deliver models that are useful for design but not operations, facility teams inherit digital information that lacks maintainable value. Contracts should define operational data requirements, sensor responsibilities, update obligations, acceptance testing and long-term support.

Ethical and social considerations also matter. Digital twins may process occupancy patterns, movement data, access logs and environmental conditions. This data can improve safety and comfort, but privacy, consent and proportionality should be addressed. Finally, there is a risk of over-automation. Decision-making should include human oversight, especially for life safety, emergency response and high-cost interventions. The requirement of governance is therefore clear: the digital twin must be reliable, secure, explainable and accountable.

Table 2: Implementation risks and governance controls for digital twins in Saudi smart buildings

Risk area	Problem	Governance control	Success indicator
Data quality	Incomplete asset data, weak tagging or sensor errors	Define asset information requirements and data validation rules	High data completeness and fewer false alerts
Interoperability	BIM, BMS, IoT and FM systems do not exchange data	Use open standards, APIs and integration testing before handover	Stable data flow across systems
Cybersecurity	Operational technology may be exposed to network threats	Segment networks, control access and monitor audit logs	No critical unresolved access exceptions
Adoption	Teams may not trust or use twin outputs	Train facility, IT and contractor teams using operational scenarios	Twin alerts converted into work orders
Over-automation	Critical decisions may be delegated without review	Maintain human approval for safety and high-cost actions	Clear decision authority and incident traceability

9. DISCUSSION

The review shows that digital twins are most valuable when they close the gap between construction information and operational decisions. Saudi mega projects are not only large; they are service environments where building performance affects tourism, investment, public safety, sustainability and national reputation. Conventional facility management often depends on reactive maintenance, fragmented reports and delayed visibility. Digital twins can shift the model toward continuous diagnosis and proactive control. However, this transformation requires owners to think beyond software procurement. The digital twin should be embedded into asset management strategy, commissioning, handover, maintenance contracts and executive reporting. This paper also shows that the strongest early business case lies in MEP operations. Cooling, energy, water, fire protection, lifts and emergency systems are expensive, data-rich and risk-sensitive. They generate measurable KPIs such as downtime, energy intensity, response time, fault recurrence, comfort complaints and maintenance cost. These KPIs can be used to prove value before expanding the twin to broader smart city functions. The Saudi context adds an additional dimension: alignment with Vision 2030. Digital twin adoption can support efficiency, accountability, sustainability and quality of life when it is governed properly. It can also help owners manage complex supplier ecosystems by creating a shared evidence base. The implication for researchers is that future studies should move from broad conceptual claims to measured case evidence in Saudi building portfolios. The implication for practitioners is that digital twins should begin with clear operational problems, not with the ambition to model everything at once.

10. RECOMMENDATIONS

First, Saudi mega-project owners should define digital twin requirements before construction handover, including asset data standards, system interfaces, cybersecurity requirements and performance KPIs. Second, they should prioritise high-value MEP use cases such as chiller optimisation, fault detection, lift availability, fire system readiness, water leakage, indoor air quality and emergency power. Third, project teams should adopt a phased roadmap: pilot one critical facility, validate results, standardise lessons and scale to district or portfolio level. Fourth, contracts should require maintainable BIM data, sensor calibration records, commissioning evidence, warranties, manuals and update responsibilities. Fifth, facility managers should be trained in data interpretation, not only dashboard navigation. Sixth, owners should establish a digital twin governance board linking facilities, IT, cybersecurity, procurement, sustainability and risk management. Seventh, digital twin outputs should feed real maintenance workflows through CMMS or CAFM integration so that alerts become accountable work orders. Eighth, privacy and ethical controls should be applied wherever occupant or movement data are used. Ninth, performance should be reviewed through measurable indicators such as downtime reduction, energy savings, response time, asset availability, risk closure and user satisfaction. Finally, Saudi universities, consultants and mega-project developers should collaborate on local case studies to build evidence suited to desert climate, large-scale developments and Vision 2030 infrastructure priorities.

11. CONCLUSION

Digital twins can become a strategic operating capability for smart buildings in Saudi mega projects. Their value is not limited to visual modelling; it lies in linking physical assets, live data, analytics and governance into one decision environment. The review found strong evidence that digital twins can support operations, predictive maintenance, energy management, risk monitoring, safety readiness and lifecycle planning. For Saudi mega projects, the most immediate value is expected in MEP-intensive assets where failure affects cost, comfort, safety and public trust. However, successful adoption requires disciplined data management, interoperability, cybersecurity, trained teams, contractual clarity and human oversight. The proposed Operational Digital Twin Governance Framework provides a staged pathway from digital foundation to connected systems, optimisation and accountable governance. When implemented carefully, digital twins can help Saudi mega projects move from asset delivery to performance excellence. This aligns with Vision 2030 by supporting smarter infrastructure, sustainable operations, transparent management and resilient public value. Future research should test the framework through empirical case studies in Saudi smart buildings, comparing operational performance before and after digital twin implementation. Longitudinal evidence would also clarify investment returns, governance maturity, and operational resilience across diverse Saudi facility types.

REFERENCES

- Ahmad, A., Mobaraki, A., & Pärn, E. A. (2023). Digital twin in facility management operational decision-making: A systematic review. Journal of Facilities Management, 21(5), 733-752.
- Allouzi, M., & Aljaafreh, M. (2024). Applied AI in NEOM construction projects: The potential impact of AI in enhancing projects success. Acta Informatica Malaysia, 8(1), 32-44.

- Alnaser, A. A., Alqahtani, F., & Alaloul, W. S. (2025). Benefits and challenges of AI-based digital twin adoption in Saudi Arabia's construction industry. Applied Sciences, 15(9), 4675.
- Baghdadi, A., Alaloul, W. S., & Musarat, M. A. (2025). A comprehensive review of digital twin implementation in the construction industry. International Journal of Computer Integrated Manufacturing, 38(9), 1084-1105.
- Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic construction digital twin: Directions for future research. Automation in Construction, 114, 103179.
- Deng, M., Menassa, C. C., & Kamat, V. R. (2021). From BIM to digital twins: A systematic review of the evolution of intelligent building representations in the AEC-FM industry. Journal of Information Technology in Construction, 26, 58-83.
- Elias, C., & Issa, R. R. A. (2025). AI-driven digital twins for predictive maintenance. Proceedings of the European Conference on Computing in Construction, 6, 369-377.
- Ghaemi, A., De Wilde, P., & Li, H. (2025). AI and digital twin applications in building energy management. Proceedings of the IEEE International Conference on Smart Building Systems, 1-6.
- Ghansah, F. A. (2024). Digital twins for smart building at the facility management stage: A systematic review of enablers, applications and challenges. Smart and Sustainable Built Environment, 14(4), 901-930.
- Hakimi, O., Liu, H., & Abudayyeh, O. (2024). Digital twin-enabled smart facility management: A bibliometric review. Frontiers of Engineering Management, 11(1), 32-49.
- Khallaf, R., Khallaf, M., & Anumba, C. J. (2022). Review of digital twins for constructed facilities. Buildings, 12(11), 2029.
- Liu, W., Zhang, Y., Li, X., & Chen, K. (2024). A systematic review of digital twin technology in the architecture, engineering and construction industry. Buildings, 14(11), 3475.
- Luo, Q., Li, H., & Zhang, Y. (2024). Applications of digital twin technology in construction safety risk management: A literature review. Engineering, Construction and Architectural Management, 32(6), 3587-3615.
- Madubuike, O. C., Anumba, C. J., & Khallaf, R. (2022). A review of digital twin applications in construction. Journal of Information Technology in Construction, 27, 145-172.
- Mousavi, Y., Behzadan, A. H., & Rashidi, A. (2024). Digital twin technology in built environment: A review of definitions, applications and challenges. Smart Cities, 7(5), 101.
- Omrany, H., Chang, R., Soebarto, V., Zhang, Y., Ghaffarianhoseini, A., & Zuo, J. (2023). Digital twins in the construction industry: A comprehensive review of current implementations, enabling technologies, and future directions. Sustainability, 15(14), 10908.
- Opoku, D. G. J., Perera, S., Osei-Kyei, R., & Rashidi, M. (2021). Digital twin application in the construction industry: A literature review. Journal of Building Engineering, 40, 102726.
- Palley, B., Pour Rahimian, F., & Goulding, J. (2025). Integrating machine learning and digital twins for operation and energy management in smart buildings: A review. Smart Cities, 9(6), 202.
- Piras, G., Muzi, F., & Di Benedetto, A. (2024). Digital twin framework for built environment: A review of key enablers and energy applications. Energies, 17(2), 436.
- Piras, G., Muzi, F., & Di Benedetto, A. (2025). Smart buildings and digital twin to monitor the indoor environment and optimise energy systems. Applied Sciences, 15(9), 4939.
- Qiu, S., Chen, Z., & Zhang, X. (2025). Exploring the impact of digital twin technology in sustainable infrastructure management. Journal of Civil Engineering and Management, 31(2), 135-153.
- Revolti, A., Adibfar, A., & Hensen, J. L. M. (2024). From building information modelling to construction digital twin: A conceptual framework. Automation in Construction, 164, 105456.
- Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., & Girolami, M. (2020). Construction with digital twin information systems. Data-Centric Engineering, 1, e14.
- Signorini, M., Dejaco, M. C., & Re Cecconi, F. (2025). Put out fires in facility management through the digital twin. CIB W070 Conference Proceedings, 1, 1985.
- Wang, M., Zhang, H., & Li, J. (2024). Opportunities and threats of adopting digital twin in construction: A systematic review. Buildings, 14(8), 2349.
- Wang, Z., Zhang, X., & Ouyang, J. (2021). Trends in digital twinning for design, operation and maintenance of buildings. IEBB Technical Report, Delft University of Technology.
- Yang, Z., Tang, C., Zhang, T., Zhang, Z., & Doan, D. T. (2024). Digital twins in construction: Architecture, applications, trends and challenges. Buildings, 14(9), 2616.
- Zahedi, F., Rahimian, F. P., & Seyedzadeh, S. (2024). Digital twins in the sustainable construction industry: A systematic review. Buildings, 14(11), 3613.
- Zhou, Y., Zhao, J., & Chen, J. (2023). Technologies for digital twin applications in construction. Automation in Construction, 150, 104832.
- Saudi Vision 2030. (2025). Vision 2030 annual report and national transformation priorities. Government of Saudi Arabia.

