

Digital Twin-Based Predictive Modeling and Simulation for Critical Infrastructure Asset Management in Saudi Arabia

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Abstract- In Saudi Arabia critical infrastructure is growing and at the same time becoming more connected, equipped with a greater number of sensors, and operationally interdependent. Because of these features there arises an asset-management problem which cannot be properly solved by means of periodic inspections, isolated condition monitoring or static risk registers. This article critically looks at the way in which digital twin-based predictive modelling and simulation can assist with making decisions throughout the lifecycle of assets in the energy, water, transport, industrial and built-environment sectors. Evidence from between 2020 and 2025 is combined in a structured integrative review, with a focus on digital-twin architecture, data synchronisation, predictive maintenance, uncertainty-aware simulation, interoperability, cyber-physical trust and decision governance. The literature shows that value is not derived simply from visualisation but comes from keeping a continuously updated representation in which operational data constrain the models, the models forecast degradation, and simulations are used to test maintenance or recovery options before any actual intervention takes place. Hybrid approaches that combine physics-based models with machine learning seem especially appropriate for safety-critical assets since they are able to retain engineering meaning while making use of high-frequency data. Yet implementation is still limited by fragmented asset information, inconsistent semantics, a lack of validation across different operating conditions, exposure to cyberattacks, uncertainty regarding the transferability of models and poor integration with existing enterprise asset-management workflows. For Saudi Arabia a step-by-step approach is suggested in which data foundations, model fidelity, human supervision and interoperable governance all develop together. The review ends by stating that digital twins should be seen as decision infrastructure rather than as software replicas, and their performance should be measured in terms of the number of failures avoided, the improvement in maintenance timing, resilience, lifecycle cost and the quality of decisions that can be audited.

I. INTRODUCTION

The way in which critical infrastructure assets are managed is changing from a reliance on documents to a approach based on continuous decision-making supported by models. Nowadays, the electricity networks, water systems, transport structures, industrial facilities and public buildings produce operational data at a rate which goes beyond the capacity of traditional periodic assessments. Moreover, the reliability of these systems is becoming more interlinked: a power failure can disrupt pumping and communications, a road closure can delay emergency access, and deterioration in one part of an industrial subsystem can spread over the production and utility networks. Because of this, digital twins have come to be seen as a way of connecting the physical condition, live data, computational models and operational decisions in a lasting cyber-physical representation (Fuller et al., 2020; Jones et al., 2020). The idea of a digital twin is not limited to a three-dimensional model; in order to be useful, a twin must reflect the state and behaviour of a particular asset or system, have to be updated as new evidence becomes available, and have to be able to answer questions regarding what is currently happening, what might happen in the future and what intervention is preferable (Rasheed et al., 2020).

The fact that this distinction is important applies to infrastructure as well; although building information models, geographic information systems and supervisory-control platforms can each deal with part of an asset, they do not by themselves form a digital twin. Research carried out in the field of the built environment has demonstrated that the lifecycle value lies in the semantic continuity that exists between design information, operational measurements and decision-making processes rather than merely in

visual accuracy (Boje et al., 2020; Sacks et al., 2020). The same conclusion is reached by those focusing on maintenance: predictive value is obtained when condition data, knowledge of degradation and the maintenance history are linked to models that are used to estimate future states and to support the timing of interventions (Errandonea et al., 2020). Hence, the digital-twin problem is at the same time a modeling problem, a data-governance problem and an organizational decision problem.

Saudi Arabia offers a particularly significant context for this shift. The country's large-scale infrastructure projects, its rapidly expanding urban areas, its vast energy and industrial assets, and its various digital transformation initiatives provide both the scope and the motivation for adopting a more predictive form of asset management. Research into smart cities within the Kingdom stresses the importance of linking technological capability with good governance, citizen benefits, and sustainable urban management rather than viewing digitalisation as a standalone technology project (Alamoudi et al., 2023; Aldegheishem, 2023). For asset owners, this means that a digital twin should not be justified on the grounds of being new; instead, it should be justified by tangible reductions in unplanned downtime, by enabling the earlier detection of degradation, by improving plans for renewal, by allowing safer scenario testing, and by enabling faster restoration following a disruption.

The research is however still scattered among the fields of manufacturing, construction, facility management, bridges, water systems and various new applications relating to critical infrastructure. Reviews point out inconsistent definitions, different degrees of synchronization and considerable variations in the way researchers define a digital twin (Semeraro et al., 2021; Hosamo et al., 2022). Furthermore, studies on asset management indicate that the social and organizational links between data owners, maintenance teams, engineers and decision makers are less well developed than those in the area of technical modelling (Arisekola and Madson, 2023). Such gaps have significant consequences in safety-critical situations since a highly accurate prediction which cannot be traced, trusted or turned into an approved work order has little operational value.

The review tackles this gap by combining evidence relating to predictive modelling and simulation with the particular needs of managing assets in critical infrastructure. It examines how a twin should be designed, which predictive methods are suitable, how simulation adds value beyond forecasting, what obstacles hinder the implementation over the asset's entire lifecycle, and how the results can be turned into a route for implementation in Saudi Arabia. Rather than focusing on any one software platform, the emphasis is placed on the quality of decision-making throughout the asset's lifecycle. Through integrating evidence from technical, operational and governance perspectives, the paper presents a coherent framework for progressing from descriptive digital representations to reliable predictive twins that can assist with maintenance, resilience and long-term capital planning.

II. AIM, OBJECTIVES AND RESEARCH QUESTIONS

This review aims to critically summarize the evidence that has been published between 2020 and 2025 regarding the use of digital twin-based predictive modelling and simulation for the management of critical-infrastructure assets, and to develop an implementation framework appropriate for Saudi Arabia. The analysis is guided by five objectives: (1) to describe the architectures and synchronization methods that ensure a operationally significant link between the physical assets and the virtual models; (2) to compare the physics-based, data-driven and hybrid methods regarding condition assessment, anomaly detection, remaining-life estimation and failure forecasting; (3) to look at the role of simulation in supporting maintenance planning, resilience analysis and lifecycle investment decisions in various infrastructure sectors; (4) to identify the interoperability, cybersecurity, data, validation and organizational barriers that hinder deployment; and (5) to establish a step-by-step research and implementation programme for Saudi Arabia based on specific, measurable outcomes in asset management.

The review is based on four questions: the first of these asks which capabilities of digital twins are essential for the purpose of predictive management of infrastructure assets. The second looks at how

predictive models and simulation should be combined in order to aid decision-making when there is uncertainty. The third question is about identifying the technical and governance obstacles that have the greatest impact on the trustworthy deployment with respect to important assets. The fourth question is how the international evidence can be turned into a scalable pathway for Saudi Arabia that brings digital investment into line with reliability, resilience, sustainability and lifecycle value.

III. REVIEW METHODOLOGY

A structured integrative review approach was chosen since the subject area involves engineering simulation, artificial intelligence, maintenance, information management relating to the built environment and the governance of critical infrastructure. The aim was not to carry out a bibliometric census or to provide artificial screening figures, but rather to put together a clear and conceptually consistent body of evidence that could address the four research questions. The searches were based on combinations of the terms 'digital twin' with 'predictive maintenance', 'predictive modelling', 'simulation', 'asset management', 'critical infrastructure', 'resilience', 'bridge', 'water', 'power', 'built environment', 'smart city' and 'Saudi Arabia'. The time frame for the evidence was limited to the period 2020–2025 in order to include the most recent advances in synchronization, artificial intelligence, uncertainty quantification and infrastructure deployment.

The search aimed to cover multidisciplinary engineering and computing indexes as well as major collections of peer-reviewed journals. In order to be included, an article had to be in English, have been published within the specified time frame, carry a persistent DOI, and be directly relevant to at least one of the analytical areas of the review—namely, digital-twin definition or architecture; infrastructure or facility asset management; predictive maintenance; model updating; simulation or uncertainty; interoperability; resilience; or human and governance integration. Studies were excluded if they dealt with digital transformation without making a contribution through twin-related modelling, if they focused merely on visualization without any relevance to lifecycle decision-making, if they were editorials or otherwise

not peer-reviewed, or if they presented evidence that had already been covered by a more substantial empirical or review-based source.

The assessment of quality was qualitative and tailored to the specific purpose. When looking at each potential source, account was taken of how clearly the physical asset or system was represented, how explicit the link between the digital and physical elements was, how transparent the data and model assumptions were, whether it had been validated using measured or operational evidence, how uncertainty or model limitations were addressed, and whether it was relevant to a specific asset-management decision. More importance was attached to work which showed a closed data-model-decision loop or included evidence obtained from operating assets. Although conceptual reviews continued to be important for establishing definitions and architecture, the claims made in them were not regarded as equivalent to field validation. This distinction is in line with the literature which indicates that the level of maturity of digital twins goes beyond simply having a virtual model (Aheleroff et al., 2021; Liu et al., 2023).

The evidence chosen was thematically coded rather than statistically pooled since the infrastructure domains, the outcome measures and the types of model are diverse. The six synthesis themes employed were: digital-twin architecture and state synchronisation; predictive modelling and health estimation; simulation and uncertainty; domain-specific asset-management applications; interoperability, cybersecurity and human governance; and the circumstances of deployment in Saudi Arabia. Cross-case comparison was then carried out to identify recurring mechanisms and points of failure. For instance, the bridge study and the water-network study were compared not on the basis of common accuracy metrics but by looking at whether sensing had changed the virtual state, whether the model had produced a forward-looking assessment, and whether that assessment had led to changes in inspection, maintenance or resilience decisions.

The evidence base that has been finalised includes thirty peer-reviewed sources, each having a DOI and a publication date falling between 2020 and 2025. When choosing the sources, care was taken to ensure a

balance among the following areas: foundational digital-twin theory, predictive maintenance, built-environment information management, applications relating to bridges and water, critical-infrastructure resilience, interoperability, and research into smart cities in Saudi Arabia. This kind of distribution enables conceptual triangulation without considering it appropriate to treat evidence from one area of infrastructure as being generally applicable. Before carrying out the synthesis, the bibliographic metadata were verified and the claims were linked to the studies that were most directly relevant. In cases where empirical validation was still limited, the review makes a distinction between demonstrated mechanisms and proposed implementation principles and presents the recommendations for Saudi Arabia as hypotheses that need to be verified through local operational testing rather than as guarantees of performance.

IV. CONCEPTUAL FOUNDATIONS OF PREDICTIVE DIGITAL TWINS

A predictive digital twin may be defined as a computationally generated representation which, for a given asset or system, incorporates its identity, state, behaviour and uncertainty. It differs from a static digital model in four respects. The first of these is that the twin is specific to the asset: because of the accumulated loading, the repairs carried out, the exposure to the environment and the operational history, nominally identical assets will have different expected responses. Secondly, it is fed with data which cause the state or parameters to be updated. Thirdly, it includes models that are able to deduce an unobserved condition or future behaviour. Fourthly, it links its analytical results to decisions and then obtains feedback following action. Consistently, reviews of the field indicate that it is these connections—rather than the appearance of the model—that determine the level of maturity (Jones et al., 2020; Tao et al., 2022).

The modeling layer can be based on physics, derived from data, or a combination of both. Models based on physics incorporate conservation laws, structural mechanics, hydraulic behaviour, thermal processes or reliability relationships. The advantage of such models is that they are interpretable and can be used for extrapolation within the range of known physical

conditions, but they can be computationally costly to calibrate and the parameters involved may be uncertain. Data-driven models learn relationships from sensor and historical data and are able to identify complex patterns which are hard to specify analytically, yet their reliability decreases when the operating conditions differ from those in the training data. Hybrid models combine the advantages of the other approaches by incorporating physical constraints into the learning models, using the data to estimate the uncertain physical parameters, or by merging the separate predictions. Nowadays, research into digital twins is increasingly viewing hybridisation as a practical way of dealing with sparse failure data and the requirement for engineering explainability (Rasheed et al., 2020; Thelen et al., 2022).

Prediction and simulation carry out different roles. Prediction involves estimating a probable future state, for example the probability of a fault, the remaining useful life, the progression of corrosion or the risk of scour. Simulation, on the other hand, poses conditional questions such as what would happen if the loading changed, if a pump was isolated, if maintenance was delayed, if a bridge component was closed, or if a storm disrupted several networks? A fully developed twin therefore has to include both inference and experimentation. Since uncertainty quantification is essential, infrastructure decisions are almost never made on the basis of deterministic future scenarios. Measurement error, incomplete inspections, uncertain rates of deterioration and fluctuating demand all affect the results. Thelen et al. (2023) claim that uncertainty and optimization are not minor additions to digital twins; rather they are necessary in order to turn the model's outputs into defensible decisions.

In the field of asset management, the decision-making layer must convert model states into a priority list of actions. As shown in the predictive maintenance reviews, anomaly detection by itself is not enough unless the predictions are connected with inspection thresholds, maintenance windows, the availability of spares, workforce availability and the consequences of risk (Zhong et al., 2023). This results in a hierarchy of timeframes: from seconds to minutes for situational awareness, from days to months for maintenance scheduling, and over years for renewal and capital planning. A single digital representation can handle all

three levels only when the model's fidelity and the frequency of its updates are aligned with the specific

decision, rather than being maximized without consideration.



Figure 1. Reference architecture for a predictive digital twin supporting critical-infrastructure asset management.

V. EVIDENCE SYNTHESIS ACROSS CRITICAL INFRASTRUCTURE

The value of combining synchronized state estimation with forward-looking maintenance is shown by examples from energy infrastructure. Since power assets have a variety of possible failure modes, carry with them serious safety implications, and are closely interdependent with other services, digital twins are able to incorporate measurements relating to electrical, thermal and environmental conditions, to estimate the underlying condition of the assets, and to evaluate contingency or maintenance strategies before any physical action is taken. As the literature on critical infrastructure points out, these twins should also include representations of dependency and recovery, not just the condition of individual components (Lampropoulos et al., 2024). In the case of electric networks that face extreme events, digital-twin approaches can link power restoration with road access and the needs of essential facilities, showing how decisions regarding infrastructure recovery become problems of a systemic nature rather than ones

that can be treated in isolation from the rest of the system (Braik and Koliou, 2024).

The data patterns in the area of water infrastructure are different but the decision-making process is similar. Since hydraulic models are already based on strong physical principles, continuous evidence from smart meters, pressure sensors, pump telemetry and water-quality measurements can be used to update the current state of the system. It is therefore possible for a digital twin to examine scenarios involving leaks, changes in demand, contamination and outages while at the same time aiding in the optimisation of pump operations and maintenance. Pesantez et al. (2022) showed how a twin of a water system can look at the effects of an unusual demand shock, thus demonstrating the value of keeping a calibrated virtual system for questions that were not foreseen during the design phase. The wider implication for Saudi Arabia is important since water security, energy use and network reliability are closely linked; predictive models should not only measure the probability of failure but also the service and energy impacts.

Transportation structures offer some of the most clear-cut examples of condition-oriented twinning. Bridge twins integrate geometry, inspection, sensing and structural analysis in order to keep an up-to-date representation of deterioration. Laser scanning can enhance the accuracy of the geometric data and aid in detecting changes, while monitoring can update the parameters that influence capacity or the estimates of degradation (Hosamo and Hosamo, 2022). Research into railway bridges extends this approach to include resilience and adaptation to climate conditions, demonstrating that the twin can act as a repository for records of damage, interventions and environmental history throughout the structure's lifecycle (Kaewunruen et al., 2023). Further research on bridges using AIoT has shown how connected sensing can support maintenance communication and decision-making processes rather than just gathering data (Gao et al., 2023). A recent application involving a bridge made use of twin-based monitoring to detect scour early on, thus underscoring the practical value of linking predictions to a particular failure mechanism and to the inspection response (Sánchez-Haro et al., 2025).

The management of buildings and complex facilities extends the asset-management approach from individual components to systems of systems. Studies in the fields of construction and facility management indicate that digital twins are able to link BIM, operational data, occupancy information, energy systems and maintenance records, but semantic fragmentation remains a common problem (Opoku et al., 2021; Hosamo et al., 2022). Similarly, construction cyber-physical systems need to have clear connections between sensing, models and action; without such links a digital representation will continue to function only as an information repository and not as an operational twin (Akanmu et al., 2021). Accordingly, the body of literature on semantic construction twins places a focus on the machine-interpretable relationships between assets, observations and processes in order that analytics may be reused throughout the various stages of the lifecycle (Boje et al., 2020).

In all different areas, predictive maintenance is the most apparent short-term value proposition, but the evidence indicates that maintenance should be

considered as part of a single decision category within a more extensive asset-management system. Errandonea et al. (2020) pointed out the importance of integrating digital twins with maintenance processes and data flows, although subsequent reviews have shown that there are still difficulties concerning model validation and deployment. A twin may be used to estimate remaining life, but the economically best intervention will depend on the consequences of a failure, on access restrictions, on the need to coordinate shutdowns, on regulatory requirements and on the condition of other assets. That is the reason why portfolio-level asset management needs a common decision ontology: the health indicators must be good enough to allow for prioritisation even if the underlying physical models are different.

Interoperability is a key enabler. Since infrastructure organisations usually have a number of different supervisory systems, maintenance databases, document repositories, GIS platforms and sensor environments that are specific to various vendors, a digital twin which relies on manually reformatting each of the data sources cannot be kept in sync on a large scale. As research into digital-twin maturity has shown, interoperability should be considered a basic architectural feature rather than something that is added in at a later stage (Klar et al., 2024). Semantic models, stable asset identifiers, time synchronization, provenance and machine-readable interfaces enable various analytical services to use the same authoritative asset context. Furthermore, a service-oriented architecture can separate reusable twin capabilities from individual applications, thus reducing the tendency to set up isolated pilot projects (Aheleroff et al., 2021).

Data quality and model validity are just as important since errors can be transmitted by synchronization in just as efficient a way as can accurate information. Forecasts that appear to be very precise can still be misleading because of sensor drift, missing timestamps, inconsistent units, undocumented changes during maintenance, and incomplete failure labels. As a result, digital-twin modelling places a strong emphasis on verification, validation and the updating of models as continuous activities rather than as tests carried out before deployment (Tao et al., 2022; Liu et al., 2023). With regard to critical

infrastructure, confidence in a model should depend on the current operating conditions. A model which has been validated under normal loading conditions should not be automatically relied on during an extreme heat event, a flood, an unusual demand pattern or a major reconfiguration of the network. Practical digital twins must include mechanisms for detecting when data move outside the validated ranges and for reducing decision-making authority in such cases.

The idea that human involvement is a temporary constraint to be eliminated is wrong. When making decisions about infrastructure there is a responsibility for safety, the presence of informal knowledge, the need to meet regulatory requirements and the requirement to balance different service goals. Agrawal et al. (2023) point out the importance of determining where people should be in digital-twin systems, a matter that becomes all the more significant as predictive recommendations become more autonomous. Operators need explanations that link a recommendation to observable evidence, engineering assumptions and possible consequences. Maintenance engineers should have the possibility of questioning a model when actual field conditions go against it. Management should have auditable records showing who approved an action and for what reason. It therefore follows that explainability should be based on the decision role rather than being seen as merely an artificial-intelligence visualisation feature.

Resilience goes beyond maintenance optimization and involves managing disruption. According to research

into urban resilience, there is a cycle in which the virtual environment takes in changing conditions, assesses various scenarios and guides action, while the results from the physical world feed into the following decision cycle (Wang et al., 2024). This concept of a closed loop is particularly appropriate for Saudi critical infrastructure since such high-value assets could be affected by heat, dust, flash flooding, rapid increases in demand and complex construction interfaces. The twin adopted from a resilience perspective therefore needs to include degraded modes and recovery procedures, not just normal operation. Scenario libraries should be developed for plausible disruptions and then be updated with real-time information when an event takes place.

Table 1 brings together the consistent evidence from the various infrastructure areas. The comparison indicates that the fundamental architecture can be reused, although the predictive targets and the kind of evidence that is acceptable vary. In the case of a bridge, changes on a millimetre scale might be decisive; for a water network, pressure transients and demand balance are the main factors; for a power network, state estimation and protection constraints are important. The conclusion is that the Saudi asset owners should standardise the interfaces, the governance structures and the meaning of decisions, while at the same time permitting domain-specific physical and predictive models. It would be unproductive to standardise the models themselves; rather, the more feasible aim should be to standardise how evidence, uncertainty and decisions are communicated.

Table 1. Evidence synthesis across critical-infrastructure domains

Domain	Typical twin inputs	Predictive simulation tasks /	Asset-management value	Principal evidence gap
Energy grids & substations	SCADA, electrical state, thermal and environmental sensing, protection events	Fault risk, health estimation, contingency and restoration simulation	Reduced outage exposure, maintenance prioritization, faster restoration	Cross-vendor semantics, cyber trust and multi-site validation

Domain	Typical twin inputs	Predictive simulation tasks /	Asset-management value	Principal evidence gap
Water networks	Pressure, flow, pump status, demand, quality data, hydraulic models	Leak and anomaly detection, demand forecasting, isolation and outage scenarios	Lower losses, energy optimization, service continuity	Data completeness, calibration under changing demand, coupled energy-water analysis
Bridges & transport structures	Geometry, inspection, strain/vibration, environment, traffic/load history	Deterioration, scour and damage prediction; closure or intervention scenarios	Risk-based inspection, earlier intervention, resilience planning	Long-term ground truth and transfer across structure types
Industrial / oil & gas assets	Process history, vibration, temperature, pressure, integrity inspection, work orders	Failure forecasting, degradation modeling, shutdown and maintenance simulation	Avoided downtime, safer intervention, coordinated turnaround planning	Rare failures, proprietary data, model drift across operating regimes
Buildings & smart facilities	BIM/GIS, meters, occupancy, HVAC, maintenance history, environmental data	Energy and equipment prediction, occupancy scenarios, facility maintenance	Lifecycle efficiency, comfort, maintenance integration	Semantic fragmentation and weak integration with enterprise workflows

VI. SAUDI ARABIA IMPLEMENTATION FRAMEWORK

The approach to implementing in Saudi Arabia should start with making decisions about business-critical assets rather than with a nationwide digital twin. The development of smart cities in the Kingdom shows a great deal of digital ambition, but the research also highlights governance, participation and institutional coordination as factors that determine sustainable results (Alamoudi et al., 2023; Aldegheishem, 2023). This is also true of infrastructure. A pilot project is worthwhile if it involves a repeated high-consequence decision, has accessible data, and can be assessed against an existing maintenance or reliability baseline. Examples of appropriate initial applications are the condition of transformers, rotating equipment, pipeline integrity, the deterioration of bridges, pump performance and the cooling or energy systems in large facilities.

The initial stage of maturity is the establishment of a reliable asset-data foundation. The asset identifiers

have to be matched together across engineering documents, GIS records, SCADA systems, computerized maintenance management systems and the inspection records. Time series data should include quality flags, use common units and have traceable calibration. Maintenance events need to be connected with the relevant condition history so that a model can tell the difference between genuine recovery and a sensor interruption. Although this stage is usually less obvious than three-dimensional modelling it provides greater long-term benefit. If it is omitted, subsequent machine-learning models end up with structural ambiguity and portfolio scaling becomes costly.

The next stage involves the development of models that are specific to decision-making. In cases where the underlying behaviour is well understood and it is important to be able to interpret safety aspects, physics-based models should be used. Data-driven models are most appropriate when extensive operational histories show nonlinear patterns that cannot be modelled explicitly. A hybrid approach should be chosen when failure data are limited but the

physical constraints are known. Model performance must be reported in terms of uncertainty, the consequences of false alarms, and its calibration over different operating conditions, not just in terms of overall accuracy. When it comes to maintenance, the question to be answered is whether the model gives enough lead time and confidence to alter an intervention without increasing operational risk.

In the third stage, simulation is combined with the workflow. After the digital twin is able to assess the current state of health, it should evaluate various options: delaying maintenance, altering the loading, isolating the equipment, speeding up inspections, replacing a component, or rerouting the service. Each of these scenarios must highlight the assumptions involved and the consequences in terms that asset managers are familiar with, for example regarding service availability, safety risk, cost, emissions, recovery time and resource demand. It is in this respect that digital twins differ from condition-monitoring dashboards. The twin does not just issue an alarm; instead, it provides a controlled environment in which different courses of action can be compared before deciding to assign people, carry out shutdowns or spend capital.

The fourth stage involves portfolio federation, whereby the individual twins should not be combined into a single, unified model. Rather, common asset identities, interfaces, spatial references and decision semantics should enable various twins to share only the information needed to answer system-level questions. For instance, a power twin can pass on information about the expected duration of an outage to a water twin; a road-access model can place constraints on the sequence of repairs; and a facility twin can report its critical load requirements. This kind of federation promotes resilience without increasing model complexity, but it also gives rise to a governance need: organisations must decide which system is responsible for each fact, how uncertainty is

to be passed on, and how cyber access is to be restricted.

Cybersecurity needs to develop in parallel with increasing connectivity, since the greater amount of data flowing between operational technology, cloud analytics and enterprise systems leads to a larger attack surface. It follows that a reliable architecture should make use of the principle of least privilege, implement network segmentation, provide for authenticated interfaces, ensure secure methods of updating, carry out logging and monitor for anomalies. Special care should be given to model integrity since manipulated sensor data or modified parameters could lead to maintenance priorities being distorted without causing an obvious failure in the control system. The digital twins of critical infrastructure should keep records of the provenance of the data, the versions of the models and the recommendations so that analysts will be able to reconstruct the evidence that was available when a decision was made.

In the end, governance must define human authority and ensure that high-consequence actions are still subject to qualified engineering approval even if prediction has been automated. The interface should convey uncertainty, causal evidence and alternative scenarios instead of providing a single opaque score. Performance governance should monitor whether the recommendations had a positive effect on outcomes, such as preventing failures, reducing unplanned downtime, lowering maintenance lead time, improving inspection efficiency, decreasing energy use, reducing lifecycle cost and shortening recovery time. Table 2 turns these principles into priorities for implementation in Saudi Arabia. The main idea is that a successful national ecosystem will develop from a network of interoperable, outcome-verified twins, not from aiming to have the greatest number of digital models.

Table 2. Saudi Arabia implementation priorities and measurable outcomes

Priority	Implementation action	Representative metric	Near-term evidence need
Asset-data foundation	Reconcile asset IDs, timestamps, units, maintenance and inspection history	Completeness, latency, sensor quality, traceable provenance	Quantify how data-quality improvement changes prediction and maintenance decisions
Decision-specific models	Combine physics, statistics and ML according to failure mechanism and data availability	Lead time, calibration, false-alarm burden, confidence coverage	Validate across seasons, load regimes and abnormal conditions
Interoperability	Use stable interfaces, semantic mappings and authoritative asset context	Percentage of sources integrated without manual transformation	Demonstrate reuse across vendors and multiple asset classes
Cyber and model trust	Segment networks, authenticate interfaces, version models, record provenance	Security events, model-integrity checks, audit completeness	Test resilience to corrupted or adversarial data
Human governance	Define decision rights, override rules and explanation requirements	Acceptance rate, override quality, decision time, auditability	Measure operator understanding and safe use of uncertainty
Portfolio federation	Exchange summarized state, risk and service dependencies between proven twins	Avoided outage impact, recovery time, portfolio lifecycle value	Multi-infrastructure pilots and economically grounded benefit cases

VII. DISCUSSION AND FUTURE RESEARCH

The available literature shows that the way infrastructure digital twins are assessed has changed. The important question isn't whether an organisation has a twin, but whether the twin leads to a significant decision based on evidence that is more up-to-date, more integrated or more predictive than that of the earlier process. This viewpoint puts an end to many of the ongoing ambiguities in the field. Geometry of a high fidelity is useful where the geometry has an effect on performance; high-frequency synchronisation is useful when decisions need to be made at that frequency; and artificial intelligence is useful when it enhances inference within operational constraints. In no case is any one of these a general requirement for maturity. Maturity consists in the way in which the physical representation, data latency, model fidelity, uncertainty and decision horizon match one another.

Another conclusion is that hybrid intelligence will probably be the main approach in relation to safety-critical infrastructure. While purely data-driven prediction can work well within familiar operating conditions, it is susceptible to having a small number of failure cases and to changes in distribution. On the other hand, pure physical models retain interpretability but might fail to account for unmodelled degradation or variations in operation. A more reliable method of achieving prediction is to combine physical prior knowledge with learned residuals, use Bayesian updating or rely on ensemble evidence, especially since the models are provided with confidence intervals. In the field of modelling, there is an increasing tendency to treat uncertainty quantification as a necessary part of optimisation rather than as an aside that is merely academic (Thelen et al., 2022; Thelen et al., 2023).

With regard to organizational structure there is a third point to consider. Digital-twin initiatives typically lie

between the departments of engineering, operations, information technology, cybersecurity and asset management. Since one group is in charge of the visualisation, another holds ownership of the sensor data and a third is responsible for approving maintenance, value may be lost at the interfaces. Again and again, studies of construction, facilities and asset networks point to information fragmentation and a lack of organizational integration as obstacles (Sacks et al., 2020; Arisekola and Madson, 2023). Saudi programmes should therefore create for each high-value twin cross-functional product ownership, together with clear responsibility for data quality, model validation, cyber controls, decision integration and benefits realization.

Research in the future should focus on four areas. Firstly, multi-hazard and cross-infrastructure twins must be developed in order to show cascading disruption and recovery. Secondly, validation methods should examine transferability across different sites,

seasons and abnormal regimes rather than merely giving retrospective accuracy. Thirdly, there is a need for standard methods of expressing model confidence, provenance and the consequences of decisions in order to enable federation without requiring identical domain models. Fourthly, economic evaluations should link predictive performance to maintenance costs, the amount of service loss avoided, resilience and the extension of asset life. As has been argued in recent infrastructure reviews, there should be stronger connections between digital-twin capabilities and measurable management outcomes (Qiu et al., 2025). Figure 2 presents the proposed closed-loop decision cycle.

These priorities together result in a research programme based on evidence which links predictive performance with practical decisions regarding trustworthy and economically defensible infrastructure.

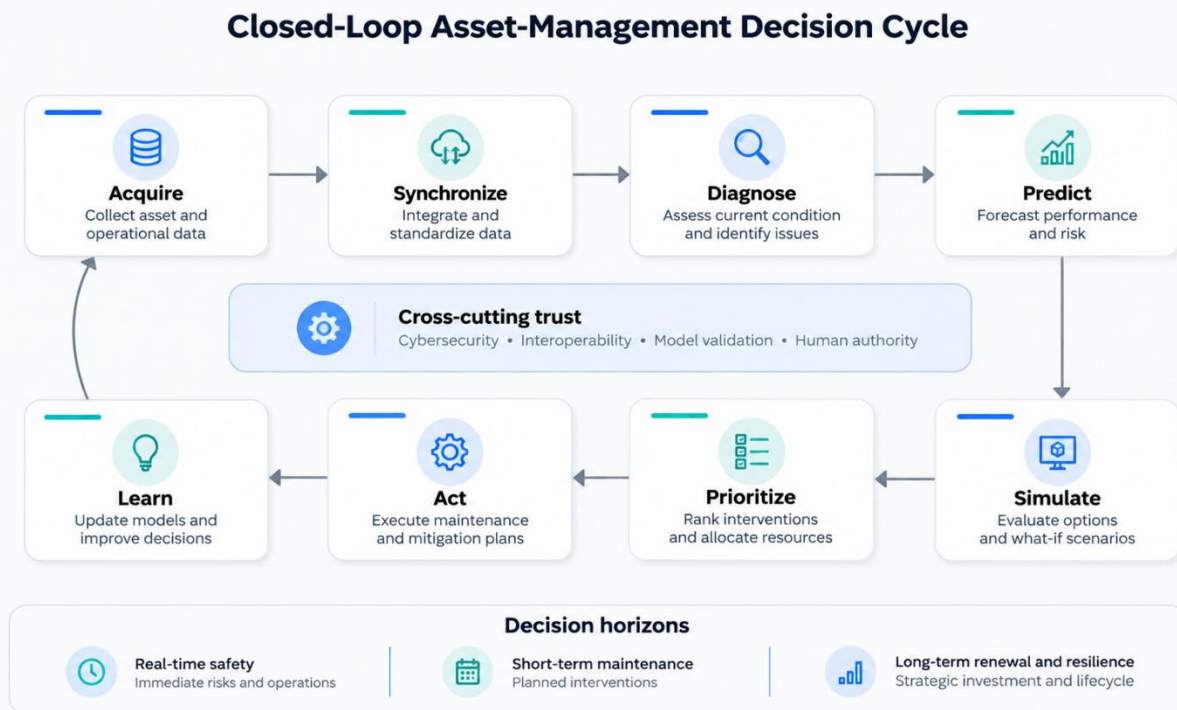


Figure 2. Closed-loop asset-management lifecycle showing predictive, simulation and governance feedback across decision horizons.

VIII. LIMITATIONS

The review has some limitations. Since it focuses on peer-reviewed research published between 2020 and 2025, it does not include every earlier fundamental contribution, any proprietary industrial applications, or the quickly changing implementations that have been reported outside of journals. The variety among the different infrastructure areas makes it impossible to statistically combine the results of the models, and a great many of the published studies are still in the pilot stage rather than having been subjected to long-term operational assessments. Moreover, the amount of peer-reviewed evidence specific to Saudi Arabia is less than that found in the international literature, which means that the proposed implementation framework represents an analytically based transfer of the underlying mechanisms rather than a statement that all the international results will directly apply. These limitations underline the importance of carrying out transparent local validation before proceeding with operational scaling.

IX. CONCLUSION

Using digital twin-based predictive modelling and simulation, effective management of critical-infrastructure assets can be achieved if the technology is applied as a closed decision system rather than simply as a visual representation. It has been demonstrated that the key capabilities required are trustworthy state synchronisation, validated predictive models, scenario simulation, communication of uncertainty, interoperable information, cyber-secure exchange and human-governed action. While physics-based, data-driven and hybrid models each have their place, hybrid methods provide a particularly useful compromise between engineering interpretability and adaptive learning. For Saudi Arabia, the most realistic course of action is a step-by-step one: first ensure asset-data integrity, then develop twins that are specific to decision-making purposes, connect the predictions with simulation and maintenance procedures, and finally federate the proven twins when making portfolio and resilience decisions. Success should be judged by reliability, the avoidance of failure, the timing of maintenance, service continuity, lifecycle cost and recovery performance. In this way, digital twins move from being mere technology

demonstrations to becoming a lasting analytical infrastructure that contributes to the safety, resilience and sustainability of the nation's assets.

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