



Digital Twin Applications for Fire Safety Testing, Commissioning and Risk Management in Saudi Smart Buildings

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Abstract: Digital twins are moving from descriptive building models toward continuously synchronised cyber-physical systems capable of testing, diagnosing, predicting and documenting safety performance. This review examines how that transition can support fire safety testing, commissioning and risk management in Saudi smart buildings. This review adopted a structured integrative approach to synthesise peer-reviewed research on digital twins, building information modelling, Internet of Things sensing, artificial intelligence, fire dynamics, evacuation, predictive maintenance, commissioning, and Saudi digital-construction readiness. The evidence indicates that the strongest near-term value lies not in a single 'fire twin' application but in a lifecycle assurance architecture that connects design intent, test evidence, live sensor states, functional cause-and-effect logic, maintenance history and emergency response models. Existing studies demonstrate credible capabilities in fire-scene reconstruction, intelligent fire-protection control, evacuation tracking, dynamic route guidance and predictive maintenance. Still, they remain fragmented across prototypes, individual systems and non-Saudi test environments. For Saudi Arabia, adoption therefore depends on interoperable data models, auditable commissioning rules, calibrated sensors under harsh environmental conditions, cybersecurity, workforce competence and governance that preserves an authoritative record from design through operation. The review proposes a fire-safety digital-twin assurance model and identifies research priorities for performance-based validation, continuous commissioning, uncertainty-aware risk analytics and regulatory acceptance. The resulting agenda positions the digital twin as an evidence infrastructure for safer, more transparent, and more resilient smart-building operation, rather than merely a visualisation platform.

Keywords: Digital Twin, Fire Safety, Commissioning, Smart Buildings, Saudi Arabia, BIM, Iot, Risk Management, Predictive Maintenance, Evacuation.

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1. INTRODUCTION

Saudi Arabia is delivering an unusually large portfolio of digitally enabled buildings, districts and infrastructure while simultaneously raising expectations for operational resilience, quality assurance and lifecycle performance. In this environment, fire safety cannot be treated as a static

compliance package completed at handover. Modern high-rise buildings, mixed-use complexes, transport-linked developments, hospitals, and large public venues depend on interconnected detection, alarm, smoke-control, suppression, access-control, vertical-transport, and building-management systems whose performance changes with configuration, occupancy,

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maintenance condition, and environmental exposure. The practical safety problem is therefore temporal: the building that passed a witnessed test at commissioning may not remain functionally equivalent months or years later.

Digital twin (DT) research offers a way to address that problem by linking a physical asset to a continuously updated digital counterpart. Built-environment reviews consistently distinguish a DT from conventional BIM by emphasising persistent data exchange, state synchronisation, analytics and decision support rather than a static geometric representation [8-21]. BIM remains essential because it provides spatial, asset, and system information, but a usable twin requires IoT data, semantic relationships, simulation models, and operational feedback [8-30]. This distinction is particularly important for fire safety, where a trustworthy representation must know not only where a detector, damper or pump is located, but also whether it is available, how it is configured, what upstream dependencies exist and how the system should respond to a specific initiating event.

Recent fire-focused studies demonstrate the technical feasibility of this direction. Digital-twin and semantic-web methods have been used to fuse BIM and sensing data for intelligent fire-protection control [1]. AI-enabled fire twins have reconstructed evolving fire conditions from sensor networks [2-4], computer vision has supported real-time evacuation tracking [3], and dynamic digital-twin frameworks have generated risk-sensitive evacuation guidance [5]. Related BIM-AR research has improved fire-equipment inspection and evacuation information delivery [6, 7]. However, the literature remains weighted toward prototype demonstrations and emergency response. Testing and commissioning are less developed, even though commissioning is the stage at which design intent, installed configuration, sequences of operation and observed performance are formally reconciled. Work on automated building-system commissioning shows that model-based engineering can shift verification earlier, reduce configuration error and support continuous operational assessment [22].

The Saudi context adds both urgency and constraints. Studies of BIM adoption and facility management in the Kingdom report organisational, skills, interoperability and governance barriers that can also impede DT deployment [26-29]. Recent Saudi research on AI-integrated DTs identifies perceived benefits alongside data, cost, competence and governance challenges [24,25]. Fire-safety digital twins must therefore be evaluated not as imported technology packages, but as socio-technical assurance systems that fit local project delivery,

authority requirements, environmental conditions and operational practices. This review focuses on that intersection: how DT capabilities can be applied across fire-safety testing, commissioning and risk management, and what must change for credible adoption in Saudi smart buildings.

2. Aim of the Study

This review aims to develop a critical, evidence-based understanding of how digital twins can strengthen fire-safety testing, commissioning, and ongoing risk management in Saudi smart buildings. Rather than proposing a vendor-specific platform, the study interprets the literature through a lifecycle assurance lens. It asks how digital representations, live data and predictive models can improve verification of fire-safety functions, preserve traceable evidence after handover and support risk-informed decisions during operation and emergencies.

3. Research Objectives

Five objectives guide the review: (1) to synthesise recent evidence on digital-twin architectures and enabling technologies relevant to building fire safety; (2) to examine how DTs can support design verification, integrated testing, commissioning and continuous functional assurance; (3) to evaluate applications in operational risk detection, predictive maintenance, fire prediction and evacuation management; (4) to identify technical, organisational, governance and contextual barriers affecting implementation in Saudi Arabia; and (5) to formulate a research and implementation agenda linking DT capability with verifiable fire-safety outcomes across the building lifecycle.

4. Research Questions

The review addresses five questions. RQ1: Which DT capabilities are most relevant to fire-safety testing and commissioning? RQ2: How can live sensing, BIM, semantic models, and AI convert periodic verification into continuous assurance? RQ3: What evidence supports DT use for operational fire-risk management and emergency decision-making? RQ4: Which interoperability, data-quality, cybersecurity, competence and governance conditions are critical in Saudi smart buildings? RQ5: Which research gaps must be resolved before fire-safety DT outputs can be trusted as engineering or regulatory evidence?

5. REVIEW METHODOLOGY

A structured integrative review methodology was selected because the topic spans fire engineering, building services, digital construction, facility management, artificial intelligence and commissioning. The method combined systematic searching with interpretive

thematic synthesis. Searches were conceptually organised around Scopus, Web of Science Core Collection, ScienceDirect, IEEE Xplore, ASCE Library, SpringerLink and Emerald Insight, supplemented by publisher and Crossref records for bibliographic verification. Search strings combined three groups: digital-twin terms ("digital twin", "cyber-physical", "BIM-IoT", "semantic twin"); fire-safety terms ("fire protection", "fire detection", "fire evacuation", "smoke control", "firefighting", "fire safety equipment"); and lifecycle-assurance terms ("testing", "commissioning", "functional performance", "maintenance", "risk", "facility management"). Saudi-specific combinations added "Saudi Arabia", "smart building", "Vision 2030", "BIM adoption" and "facility management".

Peer-reviewed journal articles published from 2020 to 2025 were prioritised, with a limited number of earlier studies retained when they provided directly relevant enabling evidence, such as BIM-IoT integration [30]. Inclusion required a clear relationship to DT architecture, fire-safety functionality, commissioning, predictive maintenance, risk management, or Saudi built-environment digitalisation. Studies focused solely on manufacturing twins, non-building fire detection without lifecycle relevance, non-peer-reviewed promotional material, duplicated records, and papers lacking sufficient methodological or bibliographic transparency were excluded. As this is an integrative review rather than a registered systematic review, numerical search and screening totals are not reported; retrospective counts would imply a level of reproducibility that was not established.

Quality assessment considered peer-review status, methodological clarity, validation setting, fidelity between digital and physical states, treatment of uncertainty, interoperability, transferability to occupied buildings and relevance to the review questions. We weighted experimental or case-study evidence more heavily when the authors reported a physical test, an operational dataset, or an explicit validation process. Reviews mapped concepts and recurring barriers, while Saudi studies contextualised organisational and governance readiness. Bibliographic details and DOI strings for the final 30 references were checked against publisher pages or reliable DOI-indexed records before inclusion.

The synthesis used a framework approach. Evidence was coded into four lifecycle functions: virtual testing and pre-commissioning; integrated commissioning and handover; continuous operational assurance; and emergency/risk response. Cross-cutting themes included data architecture, model fidelity, human factors,

cybersecurity, governance and Saudi implementation conditions. This method supports comparison across technically different studies without treating heterogeneous prototypes as directly comparable experiments. Its main limitation is that qualitative integration cannot yield pooled effect sizes, and publication bias toward successful demonstrators may overstate maturity.

6. Thematic Literature Review and Critical Analysis

6.1 From BIM Repositories to Fire-Safety Digital Twins

The central architectural issue is synchronisation. BIM can represent equipment, zones, routes and system topology, but real fire-safety assurance requires dynamic status, temporal history and relationships between physical observations and expected behaviour. Eneyew *et al.*, [8], emphasise BIM-IoT integration for smart-building twins, while Lu *et al.*, [9], and Moretti *et al.*, [10], show how heterogeneous building data can be federated to support operational decision-making. Semantic construction-twin research similarly argues that interoperability and machine-readable meaning are prerequisites for scalable automation [17]. These findings matter for fire systems because cause-and-effect verification depends on explicit relationships: a detector event should map to alarm annunciation, fan commands, damper positions, door releases, lift behaviour, and supervisory indications. A DT that only visualises sensor points does not provide this functional chain.

Jiang *et al.*, [1], move closer to that requirement by combining a fire-protection ontology, BIM information and IoT sensing within a DT data model. Their work demonstrates that semantic rules can support intelligent control, but the case relies on simulated fire conditions. The implication for commissioning is significant: the same semantic relationships used during an emergency can encode testable requirements before occupancy. Each requirement can link to an asset, trigger, expected response, acceptable tolerance, test record, and corrective action. This turns the twin into an evidence graph rather than a dashboard. Moretti *et al.*, [10], further explain why open, federated information structures matter; proprietary point naming or inconsistent asset identifiers would otherwise break continuity between design, commissioning, and operation.

6.2 Virtual Testing and Commissioning

Commissioning traditionally verifies that installed systems operate according to approved design intent and sequences. DTs can extend that process in three ways. First, virtual testing can evaluate sequences before physical tests and identify

incompatible control logic or missing interfaces. Second, live commissioning can compare observed sensor and actuator responses with expected states. Third, continuous commissioning can repeat selected tests analytically after handover by detecting drift or abnormal dependencies. Zech *et al.*, [22], demonstrate this broader principle for building control systems, using BIM-linked model-driven engineering to support preconfiguration, simulation-based evaluation and automated commissioning. Although their application is lighting rather than fire safety, the methodological transfer is strong because fire systems also depend on deterministic sequences, sensors, actuators and integration logic.

Predictive-maintenance studies provide a second commissioning bridge. Cheng *et al.*, [13], integrate BIM, IoT and machine learning to predict MEP condition, and Hosamo *et al.*, [12], develop a DT framework for automatic fault detection and diagnostics in air-handling units. Fire safety often relies on HVAC and smoke-control equipment whose degraded performance may not be obvious during routine visual inspection. A fire-safety twin could therefore use fan current, pressure, damper feedback, valve position, pump vibration and alarm history to identify latent impairment. The critical distinction is that predictive analytics should not replace witnessed acceptance tests; instead, it should prioritise testing, expose drift and preserve evidence of functional readiness between mandated inspections.

Table 1 synthesises how these capabilities map to the fire-safety lifecycle. The literature is strongest for sensing, visualisation, and prediction, but weaker for formal acceptance criteria and legally defensible commissioning records. That gap is consequential. A commissioning twin requires configuration control: the digital model, control logic and installed system must share verified identifiers and versions. Otherwise, a successful virtual test may validate an obsolete sequence rather than the actual building.

6.3 Operational Fire Prediction and Equipment Assurance

Fire-focused DT studies show rapidly improving predictive capability. Zhang *et al.*, [2], demonstrated an AI digital fire system combining IoT sensing and deep learning to reconstruct evolving fire information. Xie *et al.*, [4], extended this direction toward super-real-time fire forecasting and future hazard-region prediction. These studies are important because conventional fire alarm systems are primarily event detectors; they do not estimate how conditions may evolve. A DT can translate temperature, smoke and environmental measurements into forward-looking risk states,

allowing incident commanders or building operators to evaluate tenability, spread and intervention priorities.

Yet predictive accuracy in experiments does not automatically establish field reliability. Smart buildings introduce sensor fouling, communication loss, calibration drift, maintenance bypasses, changes in compartmentation and unrecorded fit-outs. The twin must therefore express uncertainty and data quality, not merely output a single predicted state. Predictive fire models should degrade gracefully when sensors fail and identify when conditions fall outside the training domain. Built-environment reviews repeatedly identify data quality, interoperability and implementation maturity as unresolved challenges [15-21]. For Saudi buildings, high ambient temperatures, dust exposure and large spatial scales further strengthen the case for sensor-health monitoring and redundant evidence pathways.

Inspection technologies provide a complementary pathway. Chen *et al.*, [7], showed that BIM and augmented reality can improve access to fire-equipment information during inspection. At the same time, predictive-maintenance research suggests how historical and live condition data can support intervention planning [12,13]. Seghezzi *et al.*, [14], also illustrate the importance of occupancy-aware sensing in facility-management twins. A mature fire-safety DT should combine these ideas: asset identity, inspection evidence, live condition, maintenance history, environmental exposure and occupancy context. This integration supports risk-based maintenance rather than uniform calendar treatment, but any change to statutory inspection frequency would require regulatory validation rather than technological assumption.

6.4 Evacuation, Human Monitoring and Emergency Response

Evacuation is the most human-dependent DT application. Kanangkaew *et al.*, [6], integrate BIM and AR to provide real-time evacuation information; Ding *et al.*, [3], use computer vision and a DT interface to track evacuees; and Tan *et al.*, [5], propose a fire-resilience DT that selects routes using current hazard information and occupant consequences. These studies show a progression from static route display to situation-aware guidance. The value is especially clear in large or complex Saudi developments where occupants may be unfamiliar with layouts and where routes can become unsafe as smoke spreads.

However, dynamic guidance creates new failure modes. If localisation is wrong, network latency is excessive, or the hazard model is uncertain, the system may recommend a route that conflicts

with physical signage or emergency procedures. Privacy is also material when CCTV or device tracking is used. Accordingly, an operational twin should distinguish advisory analytics from safety-critical control and should include fallback modes that remain intelligible when digital services fail. Human factors must be tested under stress, not inferred from interface usability in normal conditions. Emergency twins should also support responders with building geometry, fire-system status and hazard forecasts without overwhelming them with low-confidence data.

6.5 Saudi Implementation Conditions

Saudi studies on BIM and digital-twin adoption consistently indicate that technical potential alone is insufficient. Hasanain and Nawari [26], show how BIM can support locally relevant performance frameworks; Alghamdi *et al.*, [27], examine BIM within Gulf sustainability practice; Hassanain *et al.*, [28], identify challenges in using BIM

for Saudi facility management; and Iqbal *et al.* [29] analyse drivers of BIM adoption in the Kingdom. More recent Saudi DT studies report expected gains in quality, risk and project performance but also highlight data, cost, skills and governance concerns [24, 25].

For fire safety, these findings suggest a staged implementation model. The priority is a trustworthy asset and system information baseline at handover. The second is integration of critical fire-safety points with the building-management and fire-alarm ecosystems. The third is rule-based continuous assurance using verified cause-and-effect logic. Predictive AI should follow only when sufficient high-quality operational data and validation protocols exist. This sequence prevents building sophisticated analytics on unreliable identifiers, incomplete as-built data, or poorly maintained sensors. It also aligns DT investment with visible assurance outcomes rather than technology novelty.

Table 1: Digital-twin functions across the fire-safety assurance lifecycle

Lifecycle stage	Digital-twin function	Primary evidence/data	Fire-safety value	Key assurance concern
Design and pre-commissioning	Virtual sequence testing; rule checking; scenario simulation	BIM, cause-and-effect logic, system topology, fire/smoke models	Detect interface and logic defects before site testing	Model must match approved design and intended sequence
Integrated commissioning	Compare expected and observed system responses	Live point data, test scripts, actuator feedback, timestamps	Traceable verification of end-to-end functions	Configuration/version control; calibrated instrumentation
Operation	Continuous condition monitoring and anomaly detection	Sensor health, alarms, trends, maintenance history	Earlier identification of latent impairment and drift	Normal proxy data cannot substitute for mandatory functional tests
Emergency response	Fire-state estimation, responder information, evacuation analytics	IoT, CCTV/localization, BIM geometry, AI/physics models	Situation awareness and adaptive decision support	Latency, uncertainty, privacy and fail-safe behavior
Post-event learning	Replay, root-cause analysis and risk-model update	Event logs, commands, maintenance and incident records	Improved procedures, testing priorities and resilience	Evidence integrity and change governance

7. DISCUSSION

The literature supports a reframing of fire-safety DTs from visualisation tools to lifecycle assurance infrastructures. Figure 1 represents this synthesis. The physical building provides sensed states and test responses; the information layer maintains BIM geometry, asset identity, semantics and histories; analytical models compare expected and observed performance; and assurance outputs

feed commissioning, maintenance and emergency decisions. The closed loop is important because a safety-relevant change in either world must update the other. A replaced damper, revised smoke-control sequence, or altered compartment boundary cannot remain only in maintenance paperwork.

This interpretation clarifies the relationship between testing, commissioning and risk

management. Testing generates observations about component or system behaviour. Commissioning determines whether those observations satisfy specified functional requirements and whether interfaces operate coherently. Risk management uses both the verified configuration and subsequent operational evidence to judge current exposure and prioritise action. A DT adds value when it preserves traceability across those activities. Without requirement-to-asset-to-test linkage, digitalisation may accelerate data collection but not strengthen assurance.

The evidence also suggests that continuous commissioning is the most strategically important but least mature fire-safety application. Fire systems are periodically tested because many faults are dormant until demand. A DT could monitor proxy indicators between tests and automatically flag deviations from commissioned baselines. Smoke-control fans, pressure differentials, fire-pump readiness, power-transfer states and communication pathways are suitable candidates. Yet such monitoring must be carefully bounded: a normal sensor value does not prove full system performance, and inferred readiness must not be presented as equivalent to a code-required functional test. The engineering objective is earlier detection of impairment and better-targeted verification, not replacement of independent assurance.

Saudi smart buildings create a strong business case for this approach because projects are large, system-rich and increasingly operated through digital platforms. At the same time, governance must be designed from the outset. Ownership of the fire-safety information model, approval of control-logic changes, cybersecurity access, retention of commissioning evidence and responsibility for model validation require explicit allocation. Figure 2 therefore places configuration management and assurance governance around the technical feedback loop. This aligns with broader Saudi evidence that human, organisational, and governance factors condition the value of AI-enhanced twins [24-29].

A further implication concerns regulatory evidence. Current DT studies demonstrate technical capability, but few show how authorities could accept a twin's prediction or automated test result. Regulatory use requires transparent algorithms, calibrated sensors, version-controlled rules, reproducible test procedures and auditable exceptions. Black-box risk scores are poorly suited to life-safety decisions unless their uncertainty and failure boundaries are explicit. The most credible near-term pathway is therefore decision support: use the twin to organise evidence, detect anomalies and

prioritise human review while retaining formally defined acceptance responsibilities.

A commissioning-oriented twin also changes the unit of evidence. Conventional integrated systems testing often records whether a prescribed sequence passed at a particular time. A DT can preserve the conditions that produced that result: initiating device, software revision, alarm logic, fan command, damper state, pressure response, door condition, standby-power status and elapsed response time. This richer evidence chain is valuable because fire-protection systems fail through interfaces as often as through isolated component defects. A passed detector test does not demonstrate that smoke control, elevator recall, access release and supervisory signalling will interact correctly under every relevant scenario. The twin can therefore serve as a scenario library in which approved cause-and-effect matrices become machine-readable test requirements. Virtual execution can expose impossible states, missing dependencies or contradictory commands before witnessed tests, while field observations can then confirm whether the installed building behaves as the verified model predicts. This concept extends the automation logic demonstrated for general building commissioning [22], into a life-safety context where independent witnessing and conservative acceptance criteria remain indispensable.

The evidence also supports more disciplined risk management. Rather than assigning risk from static inspection status, a DT can combine consequence models with time-dependent indicators of protection availability. An impaired fire pump, disabled detector zone, unreliable network segment or overdue damper test changes the protection architecture. It should therefore change the building risk picture until the impairment is closed. Digital-twin research on construction safety similarly emphasises the value of integrating dynamic site information with risk assessment. However, operational fire safety requires stronger configuration control and validation because recommendations may influence life-safety actions [23]. The useful output is not an opaque numerical score. It is an explainable risk state showing which barriers are degraded, what evidence supports that judgement, which scenarios are affected, what compensating measures apply and when the condition must be reassessed. Such transparency is crucial when facility managers, specialist contractors, insurers and authorities need a common basis for escalation.

A further implication concerns model validity. Fire-safety twins inevitably combine measurements, engineering rules and simulations

with unequal uncertainty. Sensor drift can distort temperature or pressure trends; occupancy estimates can be incomplete; as-built BIM may lag physical modifications; and AI predictions may be accurate only within the scenarios represented in training data. Consequently, every safety-relevant inference should carry provenance and an indication of confidence. A twin should be able to distinguish measured facts from inferred states, design assumptions from verified as-built conditions, and advisory predictions from commands that are permitted to influence equipment. This separation creates an assurance boundary around analytics. High-consequence automated actions should require stronger validation, redundancy and fail-safe logic than low-consequence visualisation. The architectural value of the twin therefore lies partly in making uncertainty visible rather than hiding it behind a realistic three-dimensional interface.

For Saudi smart buildings, staged implementation is preferable to technology-first deployment. Owners can begin with authoritative asset identifiers, validated BIM handover, digital cause-and-effect logic and structured commissioning evidence. The next stage can connect reliable fire-alarm, smoke-control and building-management points for continuous status checking. Predictive analytics, evacuation intelligence and automated risk prioritisation should follow only after data quality, cybersecurity, competency and change-control processes are demonstrably mature. This sequence aligns investment with assurance value and reduces the risk of creating a visually sophisticated twin with incomplete underlying records. It also lets project teams define measurable acceptance gates:

synchronisation latency, the percentage of safety assets with verified identifiers, the proportion of integrated test scenarios represented digitally, unresolved configuration deviations, sensor-health coverage, and the time required to reconstruct an impairment history. These measures make DT maturity auditable and connect digital transformation to fire-safety performance rather than to software procurement alone. The resulting assurance process should be governed by explicit ownership of data, models, test rules, software versions and safety decisions. Each interface should have an accountable maintainer, a defined verification frequency and a documented response when data quality falls below its accepted threshold. This governance prevents the twin from becoming an unofficial parallel record that diverges from approved fire strategies, maintenance systems or authority documentation. It also provides a practical basis for periodic independent audit, because reviewers can trace a reported condition back to the evidence and configuration that produced it. In complex portfolios, standardised naming and test templates can additionally support benchmarking without assuming that different buildings have identical hazards or protection strategies. Standardisation therefore enables comparability of evidence, not uniformity of engineering judgement. This additional control keeps the assurance record clear and usable for independent review throughout future building operations and planned system changes, under documented governance requirements and defined safety responsibilities for all relevant stakeholders during routine operation, maintenance, testing, and emergency preparedness activities across the complete building service life.

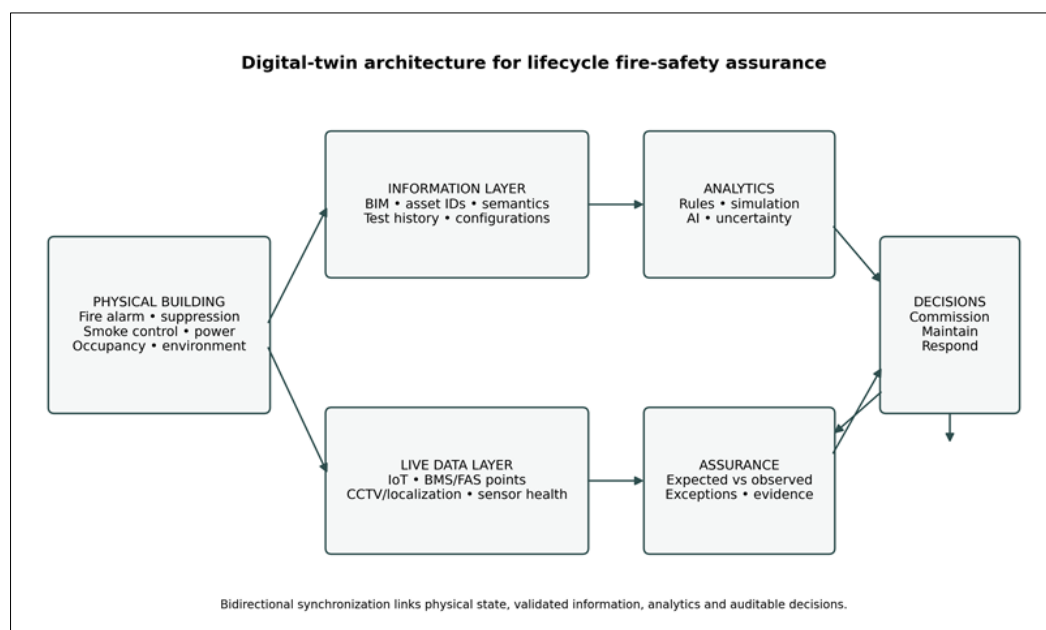


Figure 1: Digital-twin architecture for lifecycle fire-safety assurance.

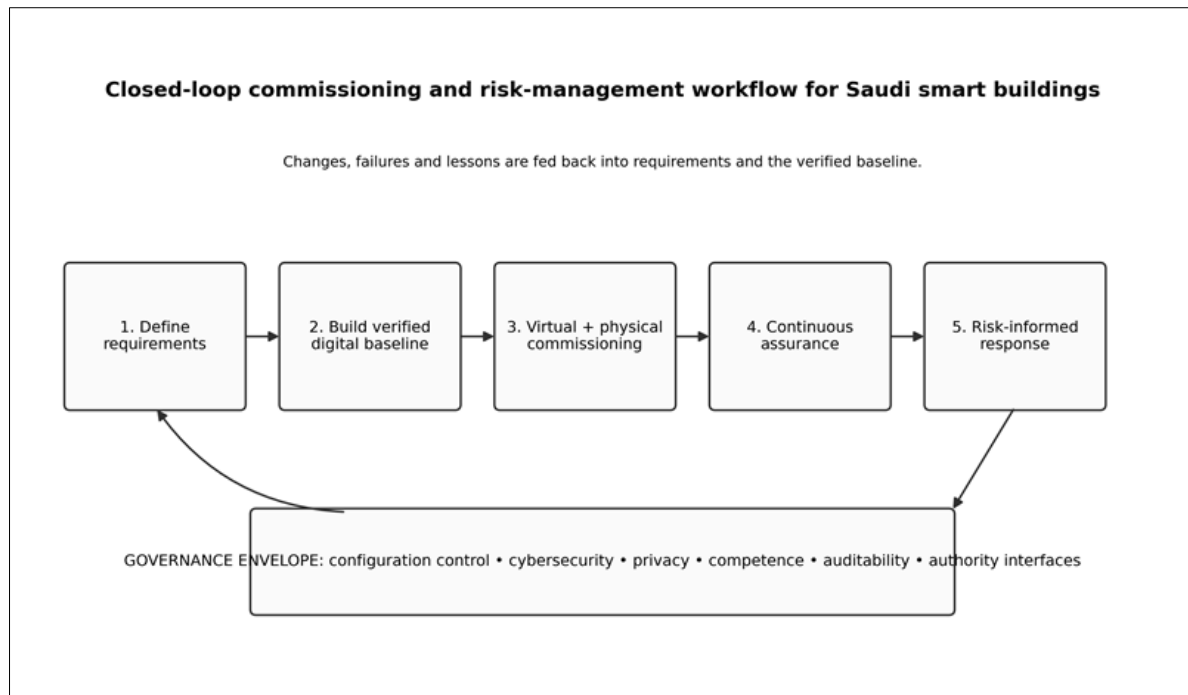


Figure 2: Closed-loop commissioning and risk-management workflow for Saudi smart buildings

8. Research Gaps and Future Research

Five gaps merit priority. First, commissioning research should move from generic building controls to fire-specific integrated systems. Controlled studies should test whether DT-based pre-commissioning can detect logic errors in cause-and-effect matrices, smoke-control sequences, fire-pump dependencies and emergency power transfers before on-site testing. Second, continuous-assurance research needs validated degradation models that connect sensor trends with meaningful fire-safety impairment rather than equipment efficiency alone. Third, uncertainty must become a first-class DT variable. Future systems should display confidence, sensor health, missing data and model validity alongside predicted fire or evacuation states.

Fourth, Saudi field validation is limited. Research should use occupied local buildings and representative environmental conditions to evaluate sensor reliability, network resilience, maintenance workflows and operator behaviour. Comparative pilots across building types would reveal which DT functions deliver the highest safety value per unit of implementation effort. Fifth, governance and regulatory research should define evidence standards for digitally witnessed tests, automated logs and AI-supported risk decisions. This includes cybersecurity requirements, change-control procedures, minimum data retention, independent validation and interfaces with inspection authorities. Such research should be co-designed with fire engineers, commissioning specialists, facility operators, technology providers and regulators

rather than conducted solely as software development.

Future research should also examine interoperability through open schemas and semantic models, building on federated and ontology-based approaches [1-17]. The goal is not a universal monolithic model, but durable relationships between requirements, assets, events, tests and risk controls. Benchmark datasets for fire-safety DTs would improve reproducibility, while privacy-preserving occupant monitoring would strengthen evacuation applications. Finally, economic studies should compare lifecycle cost with measurable reductions in retesting, downtime, false alarms, undetected impairments and emergency decision time. Safety value should be demonstrated through auditable performance indicators rather than generalised claims of digital transformation.

9. Practical, Managerial and Policy Implications

For practitioners, the immediate priority is to specify the DT as part of the fire-safety assurance plan, not as a post-handover visualisation add-on. Information requirements should define asset identifiers, system dependencies, required sensor points, test evidence, cause-and-effect logic and update responsibilities before procurement. Commissioning teams can then structure test scripts to capture observed states against expected responses and retain them in the twin. Facility managers should use the commissioned baseline to establish anomaly thresholds and maintenance

priorities, with clear escalation rules when digital evidence is incomplete.

For managers and owners, procurement should evaluate interoperability, exportability and lifecycle support alongside software features. The business case should focus on avoided rework, faster fault localisation, better evidence retrieval and reduced duration of impaired states. Competence plans are equally important: fire engineers, controls specialists, BIM managers, cybersecurity teams and FM staff must share a common information-governance process. Vendor lock-in is a material safety risk if critical histories or logic cannot be transferred when platforms change.

For Saudi policymakers and authorities, a phased assurance framework is preferable to

immediate reliance on AI predictions. Initial guidance could standardise digital handover requirements and machine-readable fire-system information; subsequent phases could define acceptance conditions for automated test evidence and continuous monitoring. Cybersecurity and privacy controls should be embedded because fire systems and evacuation data are safety-sensitive. Public-sector pilots could establish reference architectures, validation datasets and performance criteria applicable to giga-projects and conventional buildings alike. Table 2 summarises these implementation priorities.

Table 2: Priority implementation actions for Saudi fire-safety digital twins

Saudi implementation priority	Immediate action	Performance indicator	Policy/management implication
Authoritative digital handover	Define machine-readable fire-safety asset and system information requirements	Percentage of critical assets with verified identifiers and links	Make data quality a contractual acceptance criterion
Integrated commissioning evidence	Capture test triggers, responses, tolerances and exceptions in the twin	Critical cause-and-effect tests traceable to approved requirements	Standardize digital commissioning records without removing independent witnessing
Interoperability	Adopt open interfaces, semantic mappings and stable naming conventions	Successful exchange across BIM, FAS, BMS, CMMS and analytics	Avoid platform-specific lock-in for life-safety records
Sensor and model assurance	Calibrate critical sensors; monitor health and uncertainty	Known confidence/health state for safety-relevant data streams	Define validation intervals suitable for local environmental exposure
Cybersecurity and privacy	Segment networks, control privileges and protect occupant data	Audited access; tested fallback operation; incident logging	Treat DT connectivity as part of fire-safety risk governance
Competence and governance	Assign accountable owners for model, logic and change approval	Named roles; documented approval workflow; training completion	Integrate fire engineering, controls, BIM, FM and cybersecurity responsibilities

10. Limitations

This review has four limitations. First, the integrative design supports cross-disciplinary synthesis but does not provide meta-analytic effect estimates. Second, the evidence base contains many prototypes, simulations and university case studies, so transfer to complex occupied buildings remains uncertain. Third, direct Saudi fire-safety DT research is limited; Saudi implications are therefore inferred by combining fire-DT evidence with local studies of BIM, facility management and AI-integrated DT adoption. Fourth, fast-moving technology means architecture and product capabilities may evolve

faster than peer-reviewed validation. These limitations reinforce the need for transparent local pilots rather than weaken the central conclusion that lifecycle data continuity is the key research and implementation problem.

11. CONCLUSION

Digital twins can materially strengthen fire safety in Saudi smart buildings when designed as assurance systems that connect requirements, physical assets, live states, test evidence, and risk decisions. The literature already demonstrates

important components: semantic integration of fire-protection data, AI-based fire reconstruction and forecasting, predictive maintenance, evacuation tracking and dynamic guidance [1-13]. Broader built-environment research supplies the information architecture and interoperability foundations [8-30], while commissioning research shows how model-based verification can bridge design and operation [22]. Saudi studies confirm that governance, competence, data quality and organisational readiness will shape adoption as strongly as technical capability [24-29].

The most defensible near-term application is therefore not autonomous fire-safety control. Still, a verified digital thread that improves commissioning traceability, detects post-handover drift and provides decision support during risk management and emergencies. Predictive AI should be layered onto that foundation only after sensor health, configuration control and validation are demonstrably reliable. For Saudi Arabia, this creates a practical pathway from BIM-enabled project delivery to continuous fire-safety assurance: establish trustworthy as-built information, link it to operational evidence, automate bounded verification, and progressively validate predictive functions. Research that follows this sequence can move digital twins from compelling demonstrations to auditable safety infrastructure suitable for high-consequence smart buildings.

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