



Digital Twin-Based Environmental and Safety Management Framework for Sustainable Oil & Gas Facilities and Construction Projects in Saudi Arabia

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Abstract: Digital twins are increasingly used as operational interfaces that connect physical assets, engineering models, and instantaneous data. However, their environmental and safety benefits remain fragmented in oil and gas and construction research. This review develops an integrative framework for Saudi Arabian facilities and projects, where rapid infrastructure delivery, challenging climate, and high-risk operations require proactive risk management. The review systematically synthesizes peer-reviewed literature from 2020 to 2025, using Scopus, Web of Science, IEEE Xplore, and other databases. It compares digital-twin architectures, sensing strategies, predictive analytics, construction safety applications, process-integrity uses, environmental monitoring, and Saudi-specific implementation factors. Evidence shows that digital twins can improve risk visibility by integrating asset context with live data, support scenario-based decisions before intervention, and link environmental indicators to work controls. Realizing these benefits depends on synchronization quality, model validation, data interoperability, cybersecurity, human oversight, and lifecycle governance. The literature is uneven: construction studies often focus on localized safety or monitoring, while oil and gas studies emphasize asset integrity and operational optimization, with few integrated environmental-safety frameworks. This paper proposes a layered, closed-loop framework that integrates physical sensing, BIM and engineering data, physics and AI models, environmental and safety intelligence, predictive decision support, governance, and continuous learning. In Saudi Arabia, the framework is designed to support auditable, human-supervised decisions for sustainable project delivery and resilient operations, rather than serve as an autonomous control system.

Keywords: Digital Twin, Environmental Management, Safety Management, Oil And Gas, Construction, Saudi Arabia, BIM, Sustainability, Risk Prediction.

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1. INTRODUCTION

Digital-twin research has moved from conceptual descriptions toward connected operational systems that combine a physical entity, a digital representation, and continuously updated data. In oil and gas, this progression is motivated by the need to improve asset integrity, production

reliability and safety while managing dispersed equipment and high-consequence hazards. Wanasinghe *et al.*, (2020) identified integrity monitoring, lifecycle management and project planning as major application areas, while noting persistent barriers in standardization, cybersecurity and scope definition. Subsequent reviews confirm

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that oil and gas twins increasingly combine sensor streams, simulation, analytics and decision support, but implementation maturity remains uneven across assets and organizations (Knebel *et al.*, 2023; Meza *et al.*, 2024). In the construction domain, digital twins extend Building Information Modeling (BIM) by adding synchronization, sensing, and analytical feedback. Reviews by Opoku *et al.*, (2021), Madubuike *et al.*, (2022), and Hosamo *et al.*, (2022) show that the concept is promising across design, construction, operation, and facility management. However, many implementations remain limited to specific lifecycle stages.

The environmental and safety case for integration is especially important. Construction workspaces change daily, creating moving interactions among workers, machinery, temporary works, weather and logistics. Digital-twin safety research has therefore examined hoisting risk, real-time hazard prediction, tunnel early warning, worker proximity and environmental exposure. Liu *et al.*, (2021) coupled BIM, IoT and risk relationships for prefabricated hoisting, while Liu *et al.*, (2022) used a twin-supported predictive approach to anticipate hoisting safety risk. Teizer *et al.*, (2022) framed the digital twin as a construction safety concept that links current site states to hazard controls, and Luo *et al.*, (2024) found that the literature clusters around monitoring, prediction, emergency response, decision support, and training. More recent work demonstrates digital-twin-enabled heat-risk surveillance and worker-robot safety monitoring (Kim and Ham, 2024; Lin *et al.*, 2025), reinforcing a shift from retrospective reporting toward dynamic risk anticipation.

Environmental management follows a related logic. A digital twin can contextualize energy, carbon, water, thermal conditions, air quality, or emissions within a spatial and operational model rather than treating them as isolated dashboards. Building research has connected twins with energy efficiency, indoor environmental monitoring, and predictive controls (Bortolini *et al.*, 2022; Kang and Mo, 2024; Hu and Assaad, 2024). Construction-phase studies also increasingly connect process states to carbon performance, including hybrid simulation approaches for construction emissions (Liu *et al.*, 2025). Oil and gas literature similarly links digital twins with condition prediction, pipeline risk, and process optimization, providing a technical foundation for integrating environmental indicators with safety-critical operating states (Shen, 2021; Priyanka *et al.*, 2022; Chen *et al.*, 2022).

Saudi Arabia offers a distinctive context for this integration. The national construction portfolio includes large, complex, and technology-intensive

projects, while the energy sector remains strategically significant. BIM-based sustainability research has already shown the value of digital models for translating sustainability objectives into measurable building decisions in Saudi Arabia (Hasanain and Nawari, 2022). Studies of BIM adoption identify both sustainability benefits and organizational barriers (Alghuried, 2023), and recent Saudi research on AI-enabled digital twins highlights the importance of technological capability, skills, data governance, and implementation readiness (Alnaser and Elmousalami, 2025). Yet the literature lacks a consolidated framework that treats environmental performance and occupational/process safety as interacting outcomes across both oil and gas facilities and construction projects. This review addresses that gap by synthesizing cross-sector evidence and developing a Saudi-oriented management framework in which environmental and safety intelligence share a common digital thread.

2. AIM OF THE STUDY

The aim is to critically synthesize recent evidence on digital-twin applications for environmental and safety management and to formulate an integrated, auditable framework suitable for sustainable oil and gas facilities and construction projects in Saudi Arabia. The study does not assume that digital twins should autonomously control safety-critical systems. Instead, it examines how synchronized models, real-time data, and predictive analytics can improve the quality, timeliness, and traceability of human-supervised HSE and environmental decisions across project and asset lifecycles.

3. RESEARCH OBJECTIVES

Five objectives guide the review. First, to compare how digital twins are defined and technically implemented across oil and gas and construction. Second, to evaluate evidence on safety applications, including hazard detection, risk prediction, integrity management, and emergency preparedness. Third, to examine environmental applications involving energy, emissions, carbon, water, thermal conditions, and indoor or site environmental quality. Fourth, to identify interoperability, validation, cybersecurity, organizational, and human-factor constraints that influence deployment in safety-critical settings. Fifth, to synthesize these findings into a Saudi-oriented framework linking data acquisition, twin models, environmental and safety intelligence, predictive decision support, governance, and continuous learning.

4. Research Questions

RQ1: Which digital-twin architectures and enabling technologies are most relevant to integrated

environmental and safety management in oil and gas facilities and construction projects? RQ2: How does the evidence differ between construction safety applications and oil and gas integrity or operational-risk applications? RQ3: Which environmental indicators can be meaningfully connected to real-time twin states without overstating model accuracy or control capability? RQ4: What validation, interoperability, cybersecurity and governance conditions are necessary for credible deployment? RQ5: How can these findings be assembled into a practical framework appropriate to Saudi Arabia's sustainability, industrial and project-delivery context?

5. REVIEW METHODOLOGY

An integrative structured review approach was selected due to the topic's breadth, encompassing engineering simulation, BIM, IoT, occupational safety, process integrity, environmental performance, and organizational implementation. This method was designed to synthesize heterogeneous evidence rather than conduct a meta-analysis of a single intervention. The referenced paper was used solely as a structural and academic-writing guide; its screening counts, analytical claims, and wording were not reused. Its organization, however, illustrates the importance of articulating explicit research questions and a reproducible search protocol prior to thematic synthesis. The reference article details database searching, Boolean terms, and inclusion/exclusion criteria as essential elements for ensuring methodological transparency.

Searches were designed around combinations of "digital twin", "digital shadow", "construction", "oil and gas", "process safety", "occupational safety", "risk management", "environmental monitoring", "emissions", "carbon", "energy", "BIM", "IoT", "Saudi Arabia" and related terms. Scopus, Web of Science, and IEEE Xplore served as the primary scholarly databases, with publisher platforms and Google Scholar used for citation tracing and DOI verification. The main publication window was 2020-2025, with priority given to recent peer-reviewed journal papers and selected peer-reviewed conference contributions when they addressed construction safety directly. Earlier work was not required because the review objective concerns contemporary implementation rather than historical origins.

Inclusion criteria were: peer-reviewed publication; explicit digital-twin or synchronized cyber-physical framing; relevance to construction, built assets, oil and gas, process facilities, or directly transferable HSE/environmental functions; sufficient methodological description to identify data, models, applications, or limitations; and bibliographic details

that could be verified through a publisher page or DOI record. Exclusion criteria covered purely conceptual commentary without technical or empirical substance, non-peer-reviewed promotional material, articles using "digital twin" only rhetorically, duplicate reports of the same study, and studies unrelated to environmental or safety decision processes. Because database interfaces evolve and the review was not intended to claim a PRISMA-style census, we report no fabricated record counts.

The quality assessment used five dimensions: conceptual clarity of the twin; transparency of the physical-digital data link; evidence of validation or case-based evaluation; relevance to environmental or safety decisions; and explicit discussion of limitations, uncertainty, or deployment constraints. Studies were then coded thematically into architecture and interoperability, construction safety, oil and gas integrity and resilience, environmental performance, predictive analytics, and governance/implementation. Cross-sector comparison focused on mechanisms rather than simple frequency: what is sensed, how the state is represented, what prediction or simulation is performed, which decision is supported, and what assurance is needed before action. Citation-reference consistency and DOI validity were checked against publisher or indexing pages for the final 30 references.

6. Thematic Literature Review and Critical Analysis

6.1 Digital-Twin Architecture and Lifecycle Integration

The literature repeatedly distinguishes between a static digital model and a synchronized twin. Boje *et al.*, (2020) argued that construction digital twins require semantic and data integration beyond conventional BIM, while Yoon (2023) emphasized lifecycle data, information, and models as the basis for building twinning. Su *et al.*, (2023) similarly proposed a construction framework linking sensing, communication, data processing, and decision functions. These studies converge on a layered architecture: physical entities generate observations; communication and data-management services contextualize them; virtual models estimate or forecast state; and applications return information to users. The critical issue is not visual fidelity alone but whether the digital representation remains sufficiently synchronized for its intended decision.

In construction, the physical configuration changes rapidly and the twin must accommodate incomplete work, temporary systems, and moving resources. In operating oil and gas facilities, the asset topology is more stable, but process states can change quickly and involve safety-critical interactions.

Knebel *et al.*, (2023) show why edge-cloud partitioning matters in oil and gas: low-latency functions may need local execution, while computationally intensive analytics can use cloud resources. Meza *et al.*, (2024) further demonstrate the diversity of tools and development pathways, indicating that no single software stack defines a credible twin. Therefore, an integrated Saudi framework should specify functional layers and assurance requirements rather than mandate one vendor platform.

Interoperability is also a governance problem. Lee *et al.*, (2021) combined digital twins with blockchain to support accountable information sharing in construction, illustrating the importance of data provenance where multiple stakeholders contribute observations and model updates. Esmaeili and Simeone (2023) found that contractor-level implementation depends as much on process integration as on technology. In practice, a twin that cannot trace sensor calibration, model version, responsible owner, and decision history may improve visualization without improving accountability.

6.2 Safety and Risk Management in Construction

Construction safety studies provide some of the clearest examples of dynamic twin value. Liu *et al.*, (2021) modeled coupled hoisting risks rather than treating hazards independently, recognizing that equipment, environment, worker behavior, and task conditions interact. Their later work used a twin-supported predictive method to estimate changing hoisting risk (Liu *et al.*, 2022). The analytical contribution is important: a useful safety twin should represent relationships among hazards, not merely display sensor values.

Teizer *et al.*, (2022) conceptualized construction safety twins as a bridge between sensing, spatial context, and proactive control. Luo *et al.*, (2024) subsequently synthesized applications into real-time monitoring, prediction and assessment, accident simulation, decision support, and training. This taxonomy suggests a maturity pathway. Monitoring answers what is happening; prediction estimates what may happen; simulation evaluates alternatives; decision support recommends or prioritizes controls. These functions should not be conflated because their validation requirements differ.

Environmental exposure is increasingly part of construction safety. Kim and Ham (2024) used a digital-twin approach for spatio-temporal heat-risk monitoring, showing the advantage of representing microclimate variation across a worksite rather than relying on a single ambient measurement. Lin *et al.*,

(2025) addressed worker-robot collaboration by integrating spatial states and protective separation logic. Together, these studies demonstrate that location, time, and operational context are central to risk. For Saudi construction, heat stress, dust, mobile equipment interfaces and rapidly changing access conditions are therefore strong candidate use cases, provided privacy, sensor reliability and human override are addressed.

6.3 Oil and Gas Integrity, Process Safety and Operational Resilience

Oil and gas literature places stronger emphasis on asset condition, process behavior and production systems. Wanasinghe *et al.*, (2020) found early adoption concentrated in selective applications rather than enterprise-wide twins. Shen (2021) showed how digital-twin concepts can support production optimization and prediction, while Priyanka *et al.*, (2022) developed a pipeline risk-estimation framework using prognostics and machine learning. Chen *et al.*, (2022) extended the discussion to subsea pipelines, emphasizing data contextualization, anomaly detection, integrity management, standardization, and cybersecurity.

Sircar *et al.*, (2023) describe digital twins in the hydrocarbon sector as combinations of information, simulation, and visualization across exploration, drilling, and production, but also highlight access, confidentiality, integration, and maintenance challenges. These constraints matter for safety management because incorrect synchronization or unauthorized model changes could distort risk interpretation. Meza *et al.*, (2024) found continuing non-standardization across tools and frameworks, reinforcing the need for explicit assurance of data pipelines and model performance.

Mazzuto *et al.*, (2025) add a resilience perspective by using an experimental oil and gas plant twin to study irregular operating conditions. This implies that a twin can serve as a safe test environment for abnormal scenarios that would be impractical or hazardous to reproduce on the physical plant. However, transfer from experimental or subsystem validation to real facilities should be cautious. Safety-critical recommendations require evidence that model boundaries, controllers, failure modes, and uncertainty remain representative of the actual asset.

6.4 Environmental Performance and Sustainability

The environmental literature shows that twins can transform static sustainability reporting into state-aware management. Bortolini *et al.*, (2022) reviewed digital twins for building energy efficiency. They found value in real-time data integration and

optimization, while Kang and Mo (2024) emphasized connectivity and predictability in environmental monitoring. Hu and Assaad (2024) combined BIM, IoT, mobile sensing, LiDAR, and indoor positioning to support spatially contextualized environmental data. These architectures are transferable to construction camps, enclosed work areas, and operational buildings within industrial sites (Lu *et al.*, 2023).

Saudi-specific sustainability research provides an important policy bridge. Hasanain and Nawari (2022) integrated BIM with the Mostadam context to connect digital building models with water-related sustainability assessment. Alghuried (2023) documented benefits and barriers associated with BIM in sustainable Saudi construction practice. These studies do not constitute full digital twins, but they demonstrate that structured digital models can translate sustainability objectives into measurable project variables. A twin extends this logic by adding live operational data and prediction.

Construction carbon is another emerging application. Liu *et al.*, (2025) proposed a hybrid simulation approach in which digital-twin concepts connect construction entities, processes, and emissions. This is particularly relevant for large Saudi projects because carbon outcomes depend on equipment utilization, logistics, temporary energy use, and schedule interactions. Yet carbon estimates can create false precision if emission factors, activity

data, or model boundaries are not transparent. Environmental twins should therefore expose data lineage and uncertainty, not only optimized results.

6.5 Saudi Adoption Conditions and AI-Enabled Twins

Alnaser and Elmousalami (2025) examined AI-based digital-twin integration in Saudi construction and highlighted both benefits and challenges. Their findings reinforce a broader conclusion from international literature: implementation capacity depends on organizational readiness, data quality, skilled personnel, and governance, not only software availability. Saudi projects frequently involve multinational supply chains, multiple delivery partners and ambitious schedules, making shared data semantics and role clarity especially important.

A practical framework should therefore distinguish advisory automation from autonomous actuation. AI can support anomaly detection, risk forecasting and prioritization, but HSE decisions may involve legal duties, contextual knowledge and uncertainty that cannot be delegated to a model by default. Human review should be designed into the architecture, with escalation thresholds, evidence displays and the ability to challenge model outputs. This sociotechnical design is essential for trust and for avoiding automation bias.

Table 1: Cross-sector digital-twin evidence by management decision function

Decision function	Construction evidence	Oil & gas evidence	Integrated management implication
State monitoring	Worker/equipment location, hoisting state, heat and indoor environment	Process variables, equipment condition, pipeline state	Use a common asset/location context and sensor-health metadata.
Risk prediction	Hoisting risk, heat exposure, worker-robot separation	Integrity risk, production anomalies, pipeline failure likelihood	Expose confidence, applicability limits and escalation thresholds.
Scenario simulation	Task sequencing, safety zones, site changes	Abnormal operations, production scenarios, resilience testing	Test controls virtually before field implementation where model credibility is adequate.
Environmental optimization	Energy, carbon, water, indoor/site conditions	Energy efficiency, emissions-related operating states, resource performance	Evaluate environmental gains alongside safety margins and operational constraints.
Training and decision support	Dynamic site visualization and hazard rehearsal	Operator scenario testing and asset diagnostics	Retain human authorization for consequential HSE decisions.

7. DISCUSSION

The cross-sector synthesis reveals a common mechanism but different emphasis. Construction twins are strongest where spatial change, workforce interaction, and short-horizon hazards dominate. Oil and gas twins are stronger in continuous process data, equipment condition, and engineering simulation. Environmental applications

span both domains but are often treated separately from safety. Integrating them can reveal risk trade-offs that siloed systems miss. For example, reducing ventilation energy in an enclosed facility may affect air quality; accelerating earthworks may increase dust and equipment interaction; changing compressor or flare-management strategies may alter both emissions and operational margins. A

shared twin can make such couplings visible before decisions are executed.

Table 1 summarizes the evidence base by decision function rather than sector. The comparison shows that monitoring is relatively mature, while prediction and optimization demand stronger validation and uncertainty management. Training and scenario testing can add value even when closed-loop control is inappropriate. This supports a staged maturity model for Saudi deployment: trusted visibility first, predictive capability second, prescriptive recommendations third, and automated control only where independent safety assurance justifies it.

The proposed framework in Figure 1 therefore places physical assets, sensing, data integration, and models upstream of two parallel intelligence streams: environmental and safety. These streams converge in predictive decision support, then pass through human and governance controls before action. The return loop represents model recalibration, lessons learned, and changing asset state. This design intentionally avoids treating the twin as a single monolithic model. A construction project may use BIM, computer vision and microclimate simulation, while an oil and gas facility may combine process simulation, corrosion models and anomaly detection. What matters is controlled federation, traceability and fit-for-purpose validation.

Table 2 translates the framework into Saudi implementation requirements. The most important governance principle is evidence proportionality: the higher the consequence of a decision, the stronger the required validation, redundancy and human authorization. A heat-risk alert may tolerate different uncertainty than a recommendation affecting process setpoints. Likewise, environmental reporting needs auditable measurement and boundary definitions, whereas emergency response tools need latency, availability and fail-safe behavior.

Figure 2 presents an implementation and assurance cycle. The cycle begins with narrowly defined HSE or environmental use cases, not technology procurement. Data semantics and quality are established before model development; pilots are then validated in controlled scopes. Only after reviewing outcome and assurance evidence should the capability be integrated into work controls and scaled. Continuous monitoring of model drift, cyber risk, and data quality is necessary because a digital twin can degrade even if the underlying software

keeps running. This closed-loop governance is more important than a one-time commissioning certificate.

A central design issue is the twin's granularity. Facility-wide models can reveal interactions among production, utilities, construction interfaces, and environmental loads, but they also increase integration cost and make validation difficult. Component twins are easier to calibrate and govern, yet may hide system-level consequences. A federated architecture therefore appears more defensible for Saudi industrial projects: equipment, process, building and work-package twins can retain their own models while exchanging time-stamped states through controlled interfaces. Such federation also lets assurance effort focus on the models that inform consequential decisions rather than demanding identical fidelity across every asset.

The synthesis also indicates that environmental and safety indicators should not be treated as independent optimization objectives. A decision that minimizes energy use can change ventilation, thermal exposure, or process margins; a schedule acceleration can alter equipment density, dust generation, noise, and worker-interface risk. Multi-objective decision support is therefore preferable to single-metric optimization. The twin should display trade-offs, constraints and uncertainty so that responsible managers can determine whether an environmental gain is acceptable within established safety limits. This is particularly relevant in Saudi Arabia, where high ambient temperatures, remote industrial locations and large concurrent workforces can create coupled operational and occupational exposures.

Data governance is equally important. Real-time connectivity can create an impression of objectivity even when sensors are poorly calibrated, asset tags are inconsistent or historical records are incomplete. Every predictive output should therefore be traceable to data provenance, model version and validation status. Where machine-learning components are used, monitoring should identify drift, changes in operating regime and input combinations outside the training domain. These controls are necessary because a digital twin that remains available but becomes progressively misaligned with the physical system can create more risk than a clearly unavailable tool.

Finally, the framework should build in organizational learning. Incident investigations, near misses, environmental deviations, and maintenance findings can update hazard relationships and model assumptions, while repeated false alarms should trigger review rather than informal user suppression. This creates a managed feedback loop between

operational experience and digital representation. The practical objective is not a perfectly complete virtual replica, but a governed evidence system that becomes more useful as validated experience accumulates and that retains transparent boundaries when evidence is insufficient. For deployment

programs, this implies maintaining explicit acceptance criteria for each use case, periodic revalidation intervals, named model owners, documented fallback procedures, and independent review before broader operational scaling.

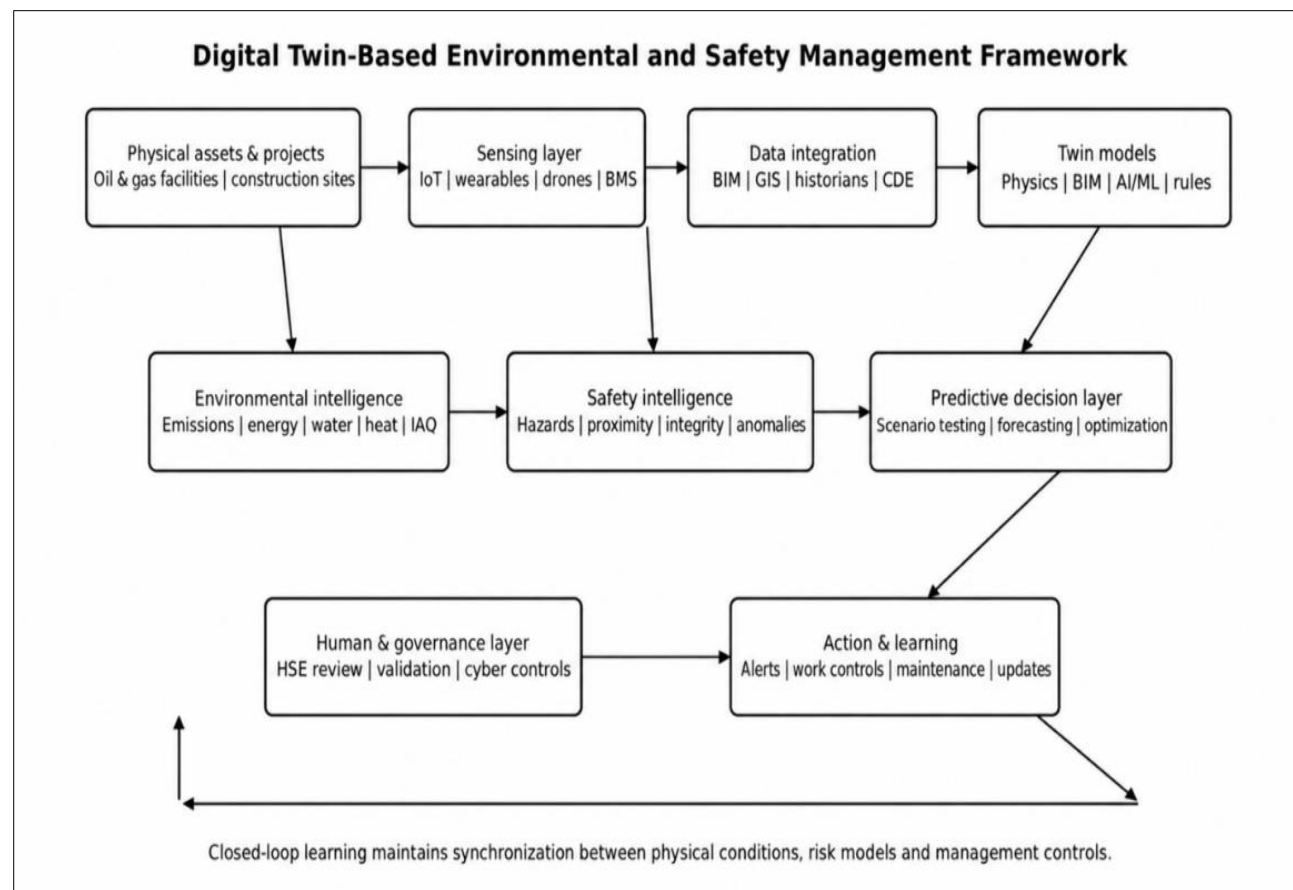


Figure 1: Proposed integrated digital twin-based environmental and safety management framework

Table 2: Saudi implementation and assurance requirements for the proposed framework

Framework layer	Saudi implementation requirement	Assurance question
Sensing and connectivity	Rugged sensors; heat/dust resilience; edge capability where latency matters	Are measurements calibrated, available and time-synchronized?
Data integration	Common asset identifiers linking BIM/GIS, historians, HSE and environmental records	Can each value and model input be traced to an authoritative source?
Twin models	Fit-for-purpose physics, BIM, statistical or hybrid models	Has the model been validated for the intended operating envelope?
Environmental intelligence	Transparent boundaries for energy, carbon, water, air quality and emissions	Are factors, baselines and uncertainty documented?
Safety intelligence	Hazard rules, integrity models, exposure thresholds and spatial logic	Are false-negative consequences and fallback controls addressed?
Governance and action	Role-based access, cybersecurity, human review and change control	Who may modify models, approve thresholds and authorize action?

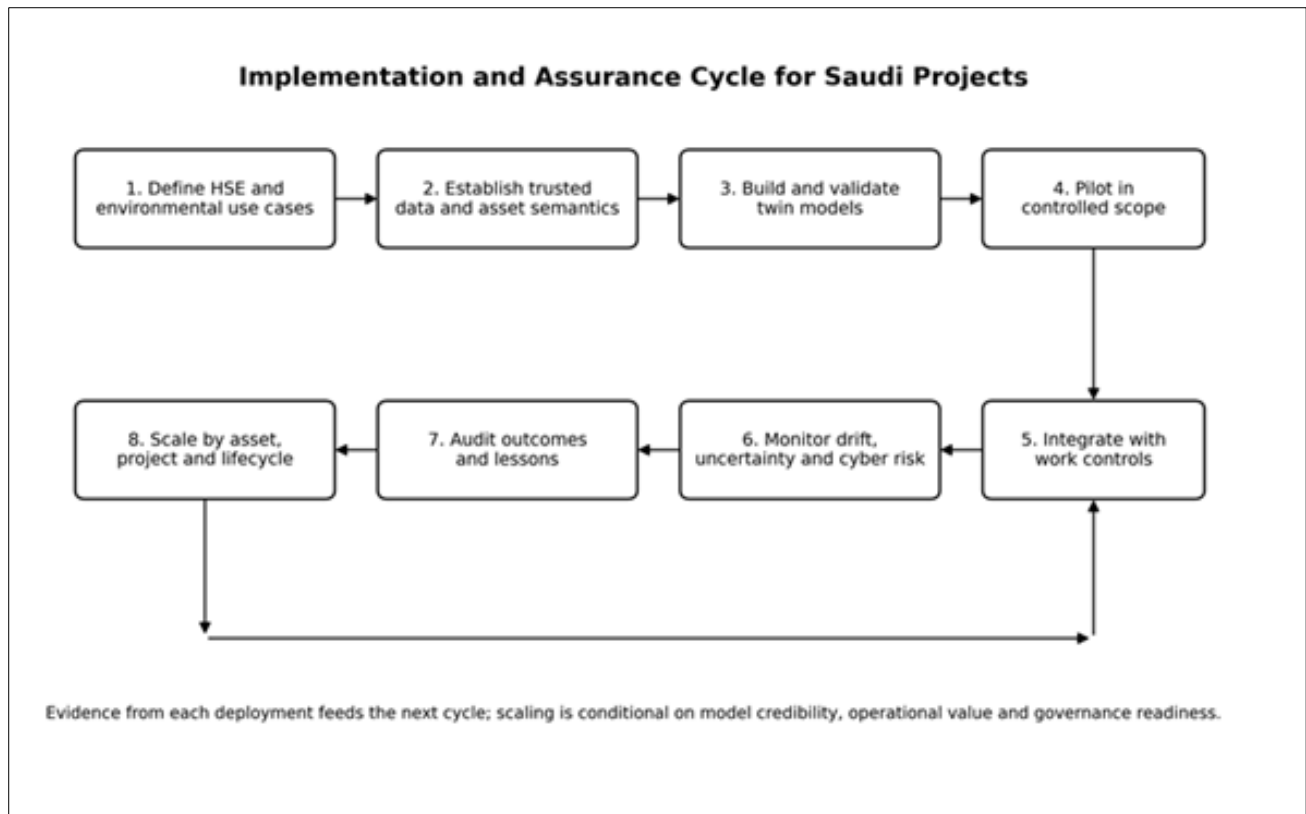


Figure 2: Staged implementation and assurance cycle for scaling digital-twin capabilities in Saudi projects and facilities

8. Research Gaps and Future Research

Five gaps deserve priority. First, integrated environmental-safety twins remain rare. Future studies should test how emissions, energy, heat, air quality, and operational hazards interact in shared decision models rather than parallel dashboards. Second, real-world validation is limited. Longer Saudi case studies are needed across construction phases and operating facilities to measure false alarms, missed events, decision latency, maintenance burden, and user response, not only model accuracy.

Third, uncertainty representation is underdeveloped. Predictive twins should communicate confidence, sensor health, and model applicability domains so that users can distinguish reliable forecasts from extrapolation. Fourth, interoperability research should move from generic standards discussion to executable mappings among BIM, GIS, process historians, maintenance systems, HSE records, and environmental data. Fifth, human factors need deeper study. Research should examine how operators, safety officers, environmental specialists and project managers interpret twin outputs, when they override recommendations, and how interface design affects automation bias.

Future Saudi research should also evaluate climatic and regional conditions, including extreme heat, dust, water scarcity, remote sites and energy-

intensive temporary works. Comparative studies across mega-projects, industrial plants and brownfield facilities could identify which twin components are reusable and which require domain-specific modeling. Finally, treat cybersecurity as a safety property: compromised data integrity or model logic can become an HSE hazard even when no physical sensor has failed.

9. Practical, Managerial and Policy Implications

For managers, the strongest starting point is a measurable use case such as heat-risk surveillance, confined-space environmental monitoring, pipeline integrity prioritization, construction equipment proximity, energy optimization or emissions reconciliation. Each use case should have an accountable owner, a defined decision, a data-quality threshold, and a fallback process. Procurement specifications should require data export, model versioning, calibration records, and interface documentation to reduce vendor lock-in.

For HSE and environmental teams, digital twins should augment established controls rather than bypass them. Hazard assessments, permit-to-work systems, inspection programs and environmental plans can supply rules and context to the twin, while the twin returns dynamic evidence. Managers should specify which outputs are informational, advisory, or control-authorized. Cross-

functional review is necessary because changes that improve one objective may worsen another.

For policymakers and major clients in Saudi Arabia, procurement and assurance guidance could encourage interoperable asset information requirements, auditable environmental data, and lifecycle continuity from design through operations. Assess digital-twin capability through demonstrated decision value and assurance evidence rather than visualization sophistication. Clear governance for AI models, cybersecurity, and data ownership would strengthen trust while supporting innovation.

10. Limitations

This review synthesizes heterogeneous studies rather than estimating a pooled effect size. Digital-twin terminology remains inconsistent, so studies labeled as twins vary in synchronization, fidelity, and bidirectional capability. The review prioritizes peer-reviewed English-language literature and therefore may underrepresent industrial implementations reported confidentially or in non-indexed technical sources. Saudi-specific peer-reviewed evidence is still limited relative to global construction and oil and gas literature, so some framework elements are transferred from comparable international applications and should be validated locally. Finally, DOI verification confirms bibliographic identity but does not guarantee that every reported benefit will generalize to Saudi assets, organizations, or climatic conditions.

11. CONCLUSION

Digital twins offer a credible pathway toward more anticipatory environmental and safety management when they are treated as governed decision systems rather than digital replicas for visualization. The evidence shows complementary strengths across construction and oil and gas. Construction research demonstrates spatially aware monitoring and prediction for workers, machinery, and environmental exposure; oil and gas research contributes process modeling, integrity analytics, pipeline risk, and abnormal-scenario simulation. Environmental studies show how real-time data can connect energy, carbon, water, and indoor or site conditions to operational context.

The proposed Saudi-oriented framework integrates these strengths through nine linked elements: physical assets, sensing, data integration, twin models, environmental intelligence, safety intelligence, predictive decision support, human governance, and action with continuous learning. Its central principle is that synchronization and prediction must be matched by validation, traceability, and human accountability. The recommended implementation pathway is

progressive: define a high-value use case, establish trusted data, validate models, pilot in a controlled scope, integrate with work processes, monitor drift and cybersecurity, audit outcomes, and scale only when evidence supports expansion.

For Saudi Arabia's rapidly developing built environment and strategically important oil and gas sector, this approach can support sustainable delivery without assuming unrealistic autonomy. The greatest value will likely come from connecting previously separate environmental and safety datasets around a shared representation of asset state, enabling earlier intervention, clearer trade-off analysis, and more auditable decisions. Future research should demonstrate these benefits through longitudinal local deployments and report not only technical accuracy but also operational reliability, user behavior, governance effort, and measurable HSE and environmental outcomes. A further practical implication is that assurance artifacts should remain accessible to frontline users, not only data specialists, because model credibility ultimately affects operational behavior. Organizations should also preserve baseline procedures so that safe operations remain possible during sensor outages, network disruption, or model maintenance. Performance evaluation should separate technical accuracy from decision effectiveness, since a statistically strong model may still fail if warnings arrive too late or cannot be acted upon. Local validation should include seasonal conditions and contractor turnover, both of which can change exposure patterns and data quality over time. Finally, governance should define who can modify models, approve thresholds, and authorize automated actions, creating a clear chain of responsibility throughout the twin lifecycle.

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