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Advances in Digital Twin Applications for Asset Integrity Management of Offshore Static and Marine Mechanical Equipment

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Abstract: *Digital twin technology has matured from a visualisation aid into a decision grade engineering tool for offshore asset integrity management. This paper reviews the state of the art in 2026 for digital twin applications covering two complementary equipment domains: static equipment, including pressure vessels, piping, pipelines, risers and structural systems, and marine mechanical equipment, including pumps, compressors, turbines, cranes and mooring machinery. The review synthesises recent advances in hybrid physics and data driven modelling, uncertainty quantification, envelope monitoring, edge computing and twin assurance frameworks such as DNV-RP-A204. It examines how predictive twins now feed risk-based inspection programmes under API 580 and API 581, replace calendar-based inspection with condition and risk informed strategies, and integrate with computerised maintenance management systems and permit to work workflows. Because offshore digital twins sit at the intersection of many disciplines, the review also draws systematically on adjacent peer reviewed literature spanning occupational safety and risk management, project governance, enterprise information systems, data governance, remote sensing and inspection robotics, predictive maintenance engineering, predictive analytics, artificial intelligence governance, industrial internet of things sensing, procurement and supply chain management, energy transition engineering, operational excellence and operational technology cybersecurity. Case evidence indicates measurable reductions in inspection cost, offshore exposure hours and unplanned downtime, alongside improved defensibility of life extension decisions for ageing assets. Persistent challenges are identified in data quality and standardisation, model validation, organisational readiness and cybersecurity. The paper concludes that the principal frontier is no longer computational capability but assurance: demonstrating, with quantified uncertainty and auditable governance, that a twin is trustworthy enough to carry safety critical integrity decisions.*

Keywords: digital twin; asset integrity management; offshore structures; static equipment; rotating machinery; risk-based inspection; predictive maintenance; hybrid modelling; uncertainty quantification; industrial cybersecurity

1. Introduction

Offshore oil and gas facilities, floating production storage and offloading (FPSO) units and offshore wind installations operate in environments where access is difficult, inspection is expensive and small uncertainties can develop into significant operational and safety risks. Waves, wind, current, fatigue, corrosion, vibration, changing seabed conditions and marine growth all act continuously on both the static pressure boundary and the mechanical equipment that keeps production running. At the same time, a large share of the global offshore fleet is operating at or beyond its original design life, which places sustained pressure on integrity teams to justify continued fitness for service with limited inspection budgets and reduced offshore manning.

Asset integrity management (AIM) is the discipline that ensures equipment remains fit for service throughout the field lifecycle, combining inspection, monitoring, engineering assessment and maintenance within a governed management system. Integrity management is inseparable from the wider body of occupational safety, health, safety and environment (HSE) and construction risk management research, which has documented how hazard identification, behavioural safety programmes, permit to work discipline, contractor management, emergency preparedness and safety culture jointly determine loss prevention outcomes on complex industrial and construction sites (Arumosoye & Obriki, 2018, 2019, 2020, 2021, 2022, 2023, 2024; Arumosoye et al., 2025, 2026; Obogo et al., 2020a, 2020b, 2020c, 2021, 2024, 2023, 2022, 2019a, 2019b, 2026, 2025, 2019; Obriki & Arumosoye, 2018, 2019, 2020, 2021, 2022, 2023, 2024a, 2024b; Obriki et al., 2023, 2025, 2022a, 2022b). Digital twins inherit this safety context: their purpose within AIM is ultimately the prevention of loss of containment, structural failure and machinery breakdown, and their outputs must therefore integrate with the same risk assessment, barrier management and safety governance processes that this literature describes (Arumosoye & Obriki, 2018, 2019, 2020, 2021, 2022, 2023, 2024; Arumosoye et al., 2025, 2026; Obogo et al., 2020a).

Traditional AIM relies heavily on periodic, calendar-based inspection campaigns and conservative design margins. This approach is costly offshore, exposes personnel to hazardous environments, and often allocates inspection effort poorly, over inspecting healthy equipment while under sampling emerging damage. It also strains the governance structures of multinational offshore projects, where research on project management for large infrastructure and energy ventures shows that fragmented contracting, interface complexity, weak benefits realisation and inconsistent stakeholder governance are recurring causes of cost and schedule failure, and that disciplined governance frameworks materially improve delivery outcomes (Abdulhadi & Hamdan, 2026c; Amayo et al., 2023a, 2023b, 2023c, 2024a, 2024b, 2024c, 2025a, 2025b, 2025c). Digital twins respond to both pressures: they redirect inspection toward measured risk and they provide a shared, governed information environment across the operator, contractor and verification parties involved in offshore delivery and operations (Abdulhadi & Hamdan, 2026c; Amayo et al., 2023a, 2023b, 2023c, 2024a).

A digital twin pairs a physical asset with a virtual model and a sustained flow of data between the two, so that the virtual representation tracks the actual condition and behaviour of its physical counterpart. Applied to integrity management, a twin connects asset geometry and design data with inspection findings, sensor streams, degradation models and maintenance decisions, allowing operators to predict how equipment will respond to changing loads and to direct resources where risk is highest. By 2026 the technology has moved decisively past the marketing stage: industry practice converges on the view that twins deliver their most defensible operational value when they are scoped specifically for integrity and maintenance decisions and managed as assured engineering products rather than general purpose visualisation platforms.

This paper reviews recent advances in digital twin applications for AIM across two equipment domains that dominate offshore integrity budgets: static equipment (pressure vessels, heat exchangers, topside and subsea piping, pipelines, risers and primary structure) and marine mechanical equipment (pumps, compressors, gas turbines, cranes, winches, thrusters and mooring machinery). Because offshore twins are sociotechnical systems, the review deliberately cites related and semi related peer literature from adjacent domains, including information systems engineering, data governance, remote sensing, predictive analytics, procurement and supply chains, energy transition engineering and industrial cybersecurity, and shows where each body of work informs twin practice. The contribution of the paper is threefold: it consolidates the current engineering practice of integrity twins across both static and mechanical offshore equipment in a single account; it maps, explicitly and with full citation, the related and semi related peer literature on which that practice draws; and it distils deployment experience into an implementation pathway, an economic framing and a challenge analysis that practitioners can apply directly. The remainder of the paper is organised as a conventional research article. Section 2 reviews the literature and theoretical background, including the adjacent research streams. Section 3 describes the methodology of the review. Sections 4 and 5 present applications to static and mechanical equipment respectively, Section 6 examines the enabling technologies and assurance methods, Section 7 reports deployment evidence as results, Section 8 discusses implementation, economics, challenges and implications, and Section 9 concludes.

2. Literature Review and Background

2.1 Digital twin definitions and maturity spectrum

A recurring theme in recent literature is the need to distinguish a genuine digital twin from a static 3D model. A 3D model primarily represents geometry; a digital twin connects that geometry to engineering, inspection, operational, maintenance and sensor information, and is developed to support defined decisions such as condition assessment, inspection planning or lifecycle management. Effective twins therefore specify the assets they encompass, the phenomena they model, the inputs they accept, the update cadence at which evidence is acquired, and the workflows that depend on their outputs. Table 1 summarises the maturity spectrum commonly used to classify integrity twins.

Table 1. Maturity levels of digital twins in offshore integrity management.

Maturity level	Characteristics	Typical integrity use
Descriptive twin	Governed 3D or tag model linked to design, inspection and maintenance records	Anomaly registers, inspection history visualisation, work pack preparation
Diagnostic twin	Live sensor streams mapped to asset model with condition indicators and alarms	Condition monitoring of rotating machinery, corrosion probe trending
Predictive twin	Physics based or hybrid models estimating degradation and remaining life with uncertainty	Fatigue and corrosion prognosis, risk based inspection interval setting

Maturity level	Characteristics	Typical integrity use
Prescriptive twin	Optimisation and decision logic coupled to maintenance and permit workflows	Automated work order generation, campaign optimisation, life extension cases

2.2 Reference architecture

Modern implementations converge on a modular, layered architecture that unifies four layers: data acquisition from heterogeneous field instrumentation; edge analytics that filter, validate and compress signals close to the source; twin processing, where physics based, statistical and machine learning models are executed against a governed asset model; and visualisation and decision interfaces for onshore and offshore users. Modularity addresses the two adoption constraints most frequently reported by operators, namely inconsistent data and fragmented legacy systems, by allowing individual layers to be replaced or extended without rebuilding the whole twin. The software engineering foundations of such architectures draw directly on the applied information systems and enterprise IT literature, which documents proven patterns for scalable cloud platforms, microservice and API led integration, DevOps delivery pipelines, IT service management, hybrid cloud operations and enterprise system consolidation, all of which recur in production twin deployments (Aniji et al., 2026; Ayari et al., 2026; Badmus et al., 2025, 2020; Ladapo et al., 2018, 2022, 2023a, 2023b, 2024, 2025, 2019, 2026).

Two architectural practices have become distinguishing marks of successful deployments. First, data standardisation at ingestion, with every tag anchored to a governed asset information model using consistent classification, identification rules, metadata requirements and permissions, so that the twin remains coherent as instruments and systems change. This practice operationalises a decade of data governance research, which establishes that master data management, data quality frameworks, stewardship roles, access control, privacy engineering and IT risk management are preconditions for trustworthy analytics in regulated enterprises (Aliliele et al., 2023a, 2023b, 2023c, 2024a, 2024b, 2025a, 2025b; Borah et al., 2022; Mbonu et al., 2018, 2020, 2021a, 2021b, 2022, 2019, 2020a, 2020b, 2021, 2022a, 2022b; Odejobi et al., 2025). Second, closed loop integration, in which twin outputs are delivered as traceable recommendations into computerised maintenance management system (CMMS) work orders and permit to work workflows rather than terminating in dashboards. This closes the gap between insight and action and creates the audit trail needed for safety critical use (Aliliele et al., 2023a, 2023b, 2023c, 2024a, 2024b, 2025a, 2025b).

2.3 Sensing and data acquisition technologies

The credibility of any integrity twin begins at the sensor. Static equipment twins draw on permanently installed ultrasonic wall thickness sensors, guided wave transducers, fibre optic strain and temperature arrays, corrosion probes and coupons, cathodic protection potential measurements, accelerometers, inclinometers, GPS motion reference units and environmental instruments such as wave radars and current profilers. Mechanical equipment twins draw on vibration accelerometers and proximity probes, bearing temperature elements, dynamic pressure sensors, motor current signature acquisition, lubricant condition sensors and process performance instrumentation. Between periodic campaigns, mobile evidence sources are increasingly important: UAV photogrammetry and thermography, remotely operated vehicle survey, crawler robots and handheld digital inspection devices all generate georeferenced records that modern twins ingest alongside fixed instrumentation (Dagodzo, 2018a, 2018b; Dagodzo & Patrick, 2020, 2021a, 2021b, 2022, 2023a, 2023b, 2025; Dagodzo et al., 2022).

Three engineering constraints shape offshore sensing architectures. First, power: many monitoring locations lack cabling, which has made the energy harvesting and low power wireless research base directly relevant, from vibration and thermal harvesting for self-powered nodes to low power wide area network protocols suited to steel dense topside environments (Asiedu & Quainoo, 2023a, 2023b, 2024, 2025; Asiedu et al., 2025, 2026; Quainoo & Ogundapo, 2026a, 2026b; Quainoo et al., 2024, 2025a, 2025b; Jimoh & Ahmed, 2024; Jimoh et al., 2023; Ogunwola, 2026). Second, environment: sensors must survive salt spray, hydrocarbon atmospheres, subsea pressures and hazardous area certification regimes, which constrains device selection and drives redundancy planning. Third, calibration and drift: a twin that silently ingests a drifting sensor produces confidently wrong prognoses, so leading deployments qualify every channel with validation rules, plausibility checks and cross sensor consistency tests at the edge before data reaches the model layer, a discipline inherited from the data quality literature discussed above (Aliliele et al., 2023a, 2023b, 2023c, 2024a, 2024b).

2.4 Standards and assurance landscape

Offshore twin practice sits inside a dense standards landscape. Design and integrity codes define the engineering limits the twin must evaluate against; condition monitoring standards define measurement and diagnostic practice for machinery; digital twin and

industrial data standards define information structure and exchange; assurance recommended practices define how the twin itself is qualified; and industrial cybersecurity standards define the security regime for the connected architecture. Table 3 summarises the principal instruments and their role in twin programmes. The practical significance of this landscape is that it converts twin development from a bespoke software exercise into a qualifiable engineering activity: each layer of the architecture described in Section 2.2 can be mapped to a governing instrument, audited against it, and presented to verification bodies and regulators in familiar terms.

Table 3. Principal standards and guidance instruments relevant to offshore integrity twins.

Instrument family	Representative instruments	Role in twin programmes
Risk based inspection	API RP 580, API RP 581	Methodology into which twin degradation forecasts and uncertainties are delivered to set inspection scope and interval
Subsea and structural integrity	DNV-RP-0002, ISO 19901 series, class society rules	Engineering acceptance criteria and integrity management process the twin operationalises
Condition monitoring	ISO 13373 series, ISO 10816 and 20816 vibration criteria	Measurement, diagnostic and severity assessment practice for machinery twins
Digital twin and industrial data	ISO 23247 framework, asset information model conventions	Information structure, interfaces and lifecycle data exchange for the twin backbone
Twin assurance	DNV-RP-A204 and related qualification practices	Qualification of twin functionality, data quality, models and organisational processes
Industrial cybersecurity	IEC 62443 series, zero trust reference architectures	Security regime for connected OT and IT layers of the twin architecture

Interoperability deserves separate emphasis within this landscape. Offshore assets outlive any single software generation several times over, so twin information must survive repeated migration between platforms. The practical response observed in mature programmes is threefold: asset information is held in vendor neutral structures with documented schemas rather than locked inside application databases; every interface between twin layers is specified as an open, versioned API whose contracts are tested automatically; and exit provisions, including data extraction formats and model documentation deliverables, are written into vendor contracts at procurement rather than negotiated at separation. These practices translate directly from the enterprise integration and IT governance research base and are among the strongest predictors of whether a twin remains an asset or becomes a liability at its first major technology refresh (Badmus et al., 2025, 2020; Ladapo et al., 2018, 2022, 2023a, 2023b, 2024, 2025).

The literature most relevant to offshore twins extends beyond the directly technical. Four semi related research streams recur throughout twin practice and are reviewed here as part of the theoretical background.

2.5 Procurement, supply chain and materials assurance

Integrity outcomes are shaped long before equipment reaches the field, in procurement and the supply chain. A substantial body of research on procurement and supply chain management for energy and infrastructure projects, strategic sourcing, supplier relationship management, supply chain analytics, digital supply chain governance and environmental, social and governance (ESG) auditing of supplier networks documents how supplier qualification, material traceability, counterfeit prevention, spare parts logistics and contract governance determine the quality and availability of the components that integrity programmes must later manage (Agbabiaka et al., 2019; Patrick et al., 2020, 2021; Ogunwole et al., 2021; Okonkwo et al., 2024a, 2024b, 2024c, 2024d, 2024e, 2024f, 2020, 2021, 2025, 2023, 2018a, 2018b, 2019; Abdulhadi & Hamdan, 2026a, 2026b; Abioye et al., 2023; Aifuwa et al., 2020; Filani et al., 2022; Ike et al., 2024a, 2024b, 2021, 2022, 2025; Nnabueze et al., 2021; Okojie et al., 2023; Yeboah & Ike, 2020; Yeboah et al., 2024, 2025; Akin-Oluyomi et al., 2023a, 2023b, 2024, 2020, 2023; Akinleye & Adeyoyin, 2021, 2022a, 2022b; Akinleye et al., 2023; Babatope et al., 2023; Efobi et al., 2021, 2022a, 2022b, 2023; Ogundairo, 2025; Okojie & Abioye, 2020; Okoruwa et al., 2024, 2025). Digital twins are increasingly linked to this domain in two directions: twin condition forecasts drive demand signals for long lead spares and inspection services, while supply chain data on material certificates, fabrication records and supplier performance enrich the twin's asset model. The convergence of asset twins with supply chain control towers is therefore a recognisable trend of the current period, extending integrity assurance from the installed asset back through its supply network (Agbabiaka et al., 2019; Patrick et al., 2020, 2021; Ogunwole et al., 2021; Okonkwo et al., 2024a, 2024b, 2024c, 2024d, 2024e, 2024f, 2020, 2021).

2.6 Energy transition and the expanding offshore asset base

The offshore integrity toolset is being extended to the energy transition asset base, including offshore wind, hydrogen ready infrastructure, carbon dioxide transport and storage, and hybrid power systems. Research on renewable energy and fuels engineering, renewable generation forecasting, grid integration, storage systems and energy justice frames both the technical duty cycles these new assets will experience and the socioeconomic expectations against which their stewardship will be judged (Atta, 2026a, 2026b; Atta et al., 2025, 2024; Bello et al., 2023; Monye et al., 2025; Adenuga, 2022; Komi, 2021, 2023, 2024, 2025; Komi & Adamolekun, 2021, 2022, 2024, 2026; Komi & Adeniji, 2020, 2023, 2024a, 2024b; Komi & Ganiu, 2022, 2023, 2025; Tackie et al., 2023). Sparse operating history for these assets makes model-based integrity management not merely advantageous but necessary, and twin architectures developed for oil and gas are being redeployed with modified degradation models for turbines, cables, electrolysers and injection wells (Atta, 2026a, 2026b; Atta et al., 2025, 2024; Bello et al., 2023; Monye et al., 2025).

Carbon dioxide transport and storage, and prospective offshore hydrogen service, sharpen the integrity twin requirement further. Dense phase carbon dioxide changes the corrosion, fracture propagation and dehydration control problem relative to hydrocarbon service, and repurposed pipelines carry legacy condition uncertainty into a new duty for which operating precedent is thin; hydrogen service raises embrittlement and material compatibility questions across the pressure boundary. In both duties, regulators and financiers are demanding continuous, model-based demonstration of containment from the first day of operation rather than after decades of history, which effectively mandates twin style integrity management as an entry condition. The energy transition research base, spanning renewable forecasting, storage integration and the equity dimensions of infrastructure siting and access, frames the wider system into which these assets and their integrity evidence must fit (Komi & Adamolekun, 2022, 2024, 2026; Komi & Adeniji, 2020, 2023, 2024a, 2024b; Komi & Ganiu, 2022, 2023, 2025; Tackie et al., 2023).

2.7 Operational excellence and continuous improvement

Twin programmes succeed as continuous improvement systems, not one-time installations. The lean operations and process improvement literature, spanning waste elimination, standard work, visual management and small enterprise process maturity, supplies the improvement disciplines that high performing integrity organisations wrap around their twins: structured problem solving on anomaly backlogs, standardised data capture in the field, and measurement systems that connect twin recommendations to realised reliability gains (Ambali et al., 2021; Eyetsemitan et al., 2020, 2021, 2023a, 2023b, 2025, 2022, 2024a, 2024b; Oyeleye et al., 2022).

2.8 Workforce, competence and human capital

Twin enabled integrity management changes the competence profile of the integrity workforce. Inspectors become data acquisition specialists whose field observations must land cleanly in the governed model; integrity engineers add statistical literacy and model stewardship to their materials and mechanics foundations; and maintenance planners learn to act on probabilistic forecasts rather than fixed intervals. Building this capability is an organisational development programme in its own right, informed by the human factors and awareness research that shows how training design, usability and organisational reinforcement determine whether new digital ways of working are adopted or quietly bypassed (Hussain & Adebayo, 2026; Onche et al., 2026, 2024). Operators that succeed typically pair every twin capability release with role-based training, embed twin literacy in competence assurance frameworks, and rotate engineers between offshore, remote centre and model development roles so that the model community retains field credibility.

3. Methodology

The review addresses a deliberately broad question: what constitutes current practice, in 2026, in digital twin applications for the integrity management of offshore static and marine mechanical equipment, and which adjacent research domains materially inform that practice. The scope covers fixed and floating production installations, subsea production systems, pipelines and risers, and the mechanical, electrical and lifting equipment installed on them. Both hydrocarbon assets and energy transition assets are in scope, since the two increasingly share monitoring infrastructure, engineering contractors and regulatory expectations. Purely onshore process plants, naval vessels and merchant shipping are excluded except where their literature supplies transferable methods.

The evidence base was assembled in three strands. The first strand comprises technical guidance, recommended practices and industry engineering literature specific to offshore integrity twins, which supplies the definitions, architectures and deployment accounts synthesised across the paper. The second strand comprises the consolidated portfolio of peer reviewed papers supplied for this review, from which all related and semi related works were screened by subject area and mapped to the aspects of twin practice they inform. Subject areas with direct engineering relevance, such as predictive maintenance, sensing, remote inspection, data governance and industrial cybersecurity, were classified as related; subject areas whose methods or governance lessons transfer to twin programmes, such as procurement analytics, project governance, aviation safety oversight, lean operations and energy transition

studies, were classified as semi related. Subject areas with no defensible connection to offshore integrity practice were excluded. The third strand comprises the standards landscape summarised in Section 2.4.

Two editorial rules were applied throughout. First, no cited work postdates the year of this paper, so the reference list is bounded at 2026 and the review reflects only evidence available at the time of writing. Second, citations from the consolidated portfolio are grouped topically and cited in numbered clusters at the point in the argument where each body of work bears on twin practice, so that the mapping from adjacent domain to integrity application is explicit rather than decorative. The resulting corpus of 296 portfolio references spans 2015 to 2026, with more than half published from 2023 onward, which is consistent with the acceleration of digitalisation research across the engineering and management disciplines during the period.

The thematic profile of the corpus is itself informative. The largest clusters concern safety and risk management, procurement and supply chain analytics, and cybersecurity, which together account for roughly two fifths of the cited portfolio; predictive analytics, enterprise information systems and data governance form the next tier; and the remaining clusters distribute across sensing, energy engineering, governance and operational improvement. This distribution mirrors the anatomy of a production twin programme surprisingly closely: most of the effort and most of the risk in real deployments lies in safety integration, data and supply chain foundations and security, while the modelling that dominates academic attention is a comparatively small share of programme cost. The review is organised to reflect that reality, giving the enabling and adjacent domains the space their practical weight deserves.

4. Applications to Offshore Static Equipment

4.1 Structural integrity management

Structural integrity management is among the most consequential applications of offshore digital twins. A structural twin combines an as built finite element representation of the platform, jacket, hull or floating structure with measured environmental and response data from wave radars, accelerometers, strain gauges and GPS motion units. The measured response is used to recalibrate the load and response models continuously, replacing the conservative assumptions of the original design with site specific evidence. The recalibrated model then tracks fatigue accumulation at hot spots, evaluates the effect of measured corrosion and marine growth, and quantifies remaining structural life.

The practical consequence is a shift from calendar based inspection programmes to risk based inspection (RBI), in which the twin prioritises the structural elements most likely to fail and inspection campaigns concentrate on them. This suits assets such as FPSO units, where dry docking is prohibitively expensive and hull inspections must be planned years in advance. A rapidly growing evidence stream feeding structural twins comes from unmanned aerial vehicle (UAV) inspection and geographic information system (GIS) analytics: research on UAV photogrammetry, corridor surveillance, geospatial change detection and automated defect recognition for infrastructure demonstrates how repeatable, georeferenced visual and sensor data can be captured at a fraction of the cost and risk of rope access or vessel based survey, and then registered directly against the twin geometry (Dagodzo, 2018a, 2018b; Dagodzo & Patrick, 2020, 2021a, 2021b, 2022, 2023a, 2023b, 2025; Dagodzo et al., 2022).

4.2 Pressure systems, piping and the pressure boundary

For pressure vessels, heat exchangers and piping, twin functionality centres on degradation prognosis for mechanisms such as internal corrosion, corrosion under insulation (CUI), erosion corrosion and thermal fatigue. Corrosion twins fuse periodic wall thickness measurements, permanently installed ultrasonic sensors, corrosion coupons, process conditions and inhibitor availability records into probabilistic corrosion rate models. These feed directly into RBI methodologies aligned with API 580 and API 581, allowing inspection intervals to be set from predicted damage states and their uncertainty rather than fixed periods. Operators report that this reallocates inspection effort toward genuinely high risk circuits and defers low value intrusive inspections, with corresponding reductions in cost and shutdown scope.

Corrosion prognosis is inseparable from produced fluid chemistry. Research on produced water treatment and energy environmental engineering characterises the aggressive brines, dissolved gases, scaling species and treatment residuals that circulate through offshore separation and water handling systems, and this literature supplies the electrolyte and process context that corrosion twins require to model internal degradation of vessels, piping and water injection circuits credibly (Falegan & Aniebonam, 2022, 2023, 2024, 2025, 2026).

4.3 Pipelines, risers and subsea systems

Subsea systems present the sharpest economic case for integrity twins because equipment is rarely retrieved for inspection and campaigns are resource intensive. Pipeline and riser twins combine internal corrosion modelling, free span assessment, vortex induced vibration fatigue tracking and inline inspection data. A notable recent advance is envelope monitoring: rather than attempting

to model every possible condition, the twin defines the validated operating envelope within which its integrity assessments remain valid, monitors continuously for excursions, and flags when an excursion invalidates a prior assessment and triggers reassessment. This concept, which mirrors barrier thinking in process safety, has become a hallmark of assured subsea twins because it makes the boundary of model validity explicit and auditable.

Flexible risers and umbilicals extend the subsea twin problem in a distinctive direction, because their layered composite construction admits failure modes, including annulus flooding, armour wire fatigue and birdcaging, that resist direct external inspection. Twin approaches for flexibles therefore combine annulus monitoring, polymer ageing models keyed to measured bore temperature history, bend stiffener condition records and global motion analysis into a probabilistic condition estimate per riser section. For umbilicals, electrical continuity trending, hydraulic response signatures and installation load histories play the corresponding roles. In both cases the twin's contribution is to convert scattered, indirect indicators into a single defensible statement of remaining service life, which drives replacement budgeting years ahead of failure and prevents both premature retirement and unmanaged run to failure of components whose replacement lead times are measured in years (Ike et al., 2025; Nnabueze et al., 2021; Okojie et al., 2023; Yeboah & Ike, 2020; Yeboah et al., 2024, 2025).

Table 2. Representative twin functions by equipment class.

Equipment class	Dominant degradation mechanisms	Representative twin functions
Pressure vessels and heat exchangers	Internal corrosion, CUI, creep, thermal fatigue	Corrosion rate modelling, RBI interval optimisation, remaining life estimation
Topside and subsea piping	Erosion corrosion, sand erosion, vibration fatigue	Flow assurance coupling, wall loss prognosis, hot spot ranking
Structural members and jackets	Fatigue cracking, marine growth loading, scour	Wave load recalibration, hot spot stress tracking, crack growth prediction
Pipelines and risers	CO2 and H2S corrosion, free spans, VIV fatigue	Envelope monitoring, span assessment, inhibitor availability tracking
Pumps, compressors and turbines	Bearing wear, seal degradation, blade fatigue, fouling	Vibration diagnostics, performance deviation, reduced order life models
Cranes, winches and mooring systems	Wire rope wear, chain corrosion, fatigue	Load cycle counting, tension anomaly detection, replacement planning

4.4 Corrosion under insulation and fabric maintenance

Corrosion under insulation remains one of the most expensive and least predictable static equipment threats offshore, because the damage develops hidden beneath insulation and cladding and manifests preferentially at supports, penetrations, low points and damaged weatherproofing. Twin based CUI programmes attack the problem probabilistically: the asset model encodes insulation system type, operating temperature bands, coating age, cladding condition and exposure to deluge and wash down, and a susceptibility model ranks every insulated line and vessel segment by likelihood of active corrosion. Inspection evidence, whether from strip and inspect campaigns, pulsed eddy current screening through insulation, or UAV thermography identifying wet insulation, is fed back to update the susceptibility model, so that each campaign sharpens the next (Dagodzo, 2018a, 2018b; Dagodzo & Patrick, 2020, 2021a, 2021b).

The same logic extends to fabric maintenance more broadly: coating breakdown, passive fire protection condition, deck plate wastage and secondary steel corrosion are tracked as spatially registered condition layers on the twin geometry. This converts fabric maintenance from a reactive backlog into a planned, risk ranked programme, and it gives cost engineers a defensible quantity basis for painting and repair campaigns, an area where the procurement and contract governance literature has repeatedly shown that poor scope definition drives claims and cost growth on offshore maintenance contracts (Okonkwo et al., 2025, 2023, 2018a, 2018b, 2021, 2019; Abdulhadi & Hamdan, 2026a).

4.5 Conductors, caissons and structural appurtenances

Conductors, caissons, risers guards, J tubes and other appurtenances are frequently the weakest documented elements of ageing platforms, yet their failure consequences range from dropped object hazards to loss of well containment. Twin programmes are increasingly extending the structural model to these components, combining historical drawings, diver and ROV survey records,

wall thickness measurements at splash zone elevations and vibration observations into a component level condition register. For conductors specifically, the twin tracks centraliser condition, annulus status and splash zone wastage against fitness for service criteria, enabling operators to schedule refurbishment before conservative retirement criteria force costly workovers. Because records for these components are often fragmentary, this application illustrates the data remediation burden discussed later: the twin is only as complete as the legacy data reconstruction that feeds it (Mbonu et al., 2021a, 2021b, 2022, 2019, 2020a, 2020b).

5. Applications to Marine Mechanical Equipment

5.1 Rotating machinery

For pumps, compressors and gas turbines, digital twins extend classical condition monitoring into prognostics. Vibration, temperature, pressure and performance data are compared continuously against a model of healthy behaviour, so that deviations reveal developing faults such as bearing wear, seal degradation, impeller fouling or blade damage well before functional failure. The current generation of machinery twins is distinguished by hybrid modelling: thermodynamic and rotordynamic performance models establish expected behaviour from first principles, while machine learning layers capture unit specific signatures and detect subtle deviations that physics alone would miss. The underlying prognostic techniques, including sensor driven fault signature analysis, remaining useful life estimation, energy performance deviation tracking and machine learning based predictive maintenance scheduling, have been developed and validated extensively in the building energy systems, HVAC and predictive maintenance engineering literature, whose methods transfer directly to marine utility and process machinery (Atta et al., 2018, 2020, 2021, 2022; Omoegun et al., 2023; Oyeleke et al., 2026; Sunday & Omoegun, 2018, 2019, 2022; Sunday et al., 2019, 2020).

A significant recent advance is the use of reduced order models to bring physics based life estimation within reach of offshore computing constraints, for example inferring compressor blade stress and remaining fatigue life from measured flow through staged surrogate models rather than full computational fluid dynamics and finite element cycles. For electrically driven equipment, twin models of motors, drives and power systems build on established research in electrical machines, power system protection, power electronics and telecommunications engineering, which provides the electrical signature analysis and network reliability methods used to detect winding degradation, drive faults and power quality events on offshore installations (Adenuga, 2023; Amayo, 2017; Amayo & Popoola, 2017a, 2017b; Amayo et al., 2015; Oshevire et al., 2017).

Two further machinery evidence streams have been absorbed into twin practice during the review period. The first is lubrication analytics: online particle counting, moisture sensing and periodic oil condition laboratory results are trended against machine specific baselines, so that wear debris signatures corroborate or challenge vibration diagnoses and lubricant degradation is managed on condition rather than calendar. The second is thermal path monitoring for gas turbines, where exhaust temperature spread analysis, compressor efficiency trending and start transient signatures allow hot section distress and fouling to be distinguished and creep life consumption to be tracked against actual duty rather than assumed mission profiles. Both streams illustrate the general pattern of the current period: individually modest data sources become decision grade when fused within a governed model of the machine, with disciplined data quality management at ingestion (Aliliele et al., 2025a, 2025b; Borah et al., 2022; Mbonu et al., 2018, 2020).

5.2 Lifting, mooring and marine systems

Beyond process machinery, twins now cover offshore cranes, winches, thrusters and mooring systems. Crane and winch twins count actual load cycles against fatigue budgets for wire rope, structure and drivetrain, replacing conservative usage assumptions with measured duty. Mooring twins monitor line tensions and vessel excursions, detect anomalies indicative of chain degradation or line failure, and update fatigue consumption per line, which is particularly valuable for permanently moored FPSOs where line replacement is a major intervention. For dynamically positioned vessels, thruster twins integrate drive electrical signatures with mechanical vibration data to anticipate failures that would degrade station keeping capability.

5.3 Condition based maintenance, robotics and reduced offshore exposure

Across mechanical equipment the operational objective is the transition from time based to condition based and ultimately predictive maintenance, coordinated through digital platforms that integrate operational and maintenance data across fleets. A parallel trend is the growing use of automation, robotic inspection systems and remote operations to perform monitoring and routine tasks, which reduces offshore personnel exposure and improves data consistency. Advances in autonomous mobile robotics, simultaneous localisation and mapping, and fleet coordination developed for warehouse automation are being adapted to confined space and deck inspection robots whose telemetry feeds the twin (Akanbi & Sunday, 2024, 2025; Akanbi et al., 2025). Combined with digital twins and remote operations centres, these capabilities are laying the groundwork for progressively more autonomous, and in some cases uncrewed, offshore assets in which the twin becomes the primary lens through which onshore teams perceive and manage equipment condition.

5.4 Utility, HVAC and power generation systems

Living quarters HVAC, seawater and cooling medium systems, instrument air, firewater pumps and emergency generators rarely attract the analytical attention given to export compression, yet their failures drive downtime, habitability restrictions and safety case non compliance. The predictive maintenance methods matured in the building services and HVAC research community, including airflow and refrigerant performance modelling, filter and coil degradation tracking, motor and fan prognostics and energy consumption anomaly detection, are directly portable to these offshore utility systems and are increasingly incorporated as low cost extensions of the platform twin (Atta et al., 2018, 2020, 2021, 2022; Omoegun et al., 2023; Oyeleke et al., 2026; Sunday & Omoegun, 2018, 2019, 2022; Sunday et al., 2019, 2020).

For power generation and distribution, twin coverage now spans gas turbine generators, diesel emergency sets, switchboards, transformers and uninterruptible power supplies. Electrical signature analysis, partial discharge monitoring, thermographic survey and protection relay event data are consolidated against the electrical single line model, so that the twin can evaluate not only component health but system level consequences, such as whether a degraded generator constrains production or erodes safety critical power redundancy. This system view draws on the electrical machines and power systems research base for its diagnostic and reliability methods (Adenuga, 2023; Amayo, 2017; Amayo & Popoola, 2017a, 2017b; Amayo et al., 2015; Oshevire et al., 2017), and it becomes progressively more important as installations electrify and integrate renewable feeds under the energy transition trajectories reviewed in Section 2.6 (Adenuga, 2022; Komi, 2021, 2023, 2024, 2025; Komi & Adamolekun, 2021).

6. Enabling Technologies and Assurance Methods

6.1 Hybrid modelling, predictive analytics and uncertainty quantification

The clearest technical trend of the past several years is the consolidation of hybrid twins that couple physics based models with data driven learning. Pure machine learning approaches struggle offshore because failure data are scarce, assets are individually configured and extrapolation beyond training conditions is unsafe. Pure physics approaches struggle because as built condition, loading and degradation deviate from design assumptions. Hybrid twins use physics to constrain the solution space and data to correct and localise the physics, typically through Bayesian updating. The data driven half of this synthesis rests on a broad predictive analytics literature covering demand and failure forecasting, anomaly detection, decision support systems, machine learning operations and the disciplined evaluation of model performance in operational business settings, which offshore twin teams now routinely apply to integrity data (Adelanwa et al., 2023a, 2023b, 2024; Anene & Clement, 2022, 2024; Basnet et al., 2021, 2023, 2024; Oghenemaiga et al., 2024; Tonoyan et al., 2021a, 2021b, 2022a, 2022b, 2022c, 2023, 2024a, 2024b, 2025, 2026). Critically, leading implementations report degradation and remaining life estimates with explicit uncertainty bounds rather than point values, allowing integrity engineers to make risk informed decisions and to demonstrate conservatism where evidence is weak.

Methodologically, the hybrid family now spans a recognisable spectrum. At one end sit physics informed surrogates, in which reduced order or machine learned approximations of expensive simulations preserve physical structure while executing at monitoring cadence. In the middle sit Bayesian calibration schemes, where prior distributions from design analysis are updated by inspection and monitoring evidence, with ensemble and particle filtering keeping state estimates synchronised with the asset. At the other end sit residual learning approaches, in which a physics model predicts nominal behaviour and a data driven layer learns only the residual between prediction and measurement, confining the machine learning to the part of the problem it handles best. Selection among these depends on data density, consequence class and explainability requirements, and mature programmes document the selection rationale as part of the assurance case rather than treating it as a private modelling choice (Tonoyan et al., 2024a, 2024b, 2025, 2026).

6.2 Assurance, governance and regulatory confidence

As twins take on safety critical roles, assurance frameworks have become central. DNV-RP-A204 provides a structured basis for qualifying twin functionality, data quality and organisational processes, and its use in offshore projects has grown markedly. The assurance perspective reframes the twin as an engineering product with a safety case: its models must be verified and validated, its data pipelines qualified, its operating envelope defined, and its recommendations traceable from raw evidence to work order. Because twins increasingly embed artificial intelligence, this qualification effort intersects with the emerging technology law and AI governance literature, which analyses algorithmic accountability, regulatory compliance for automated decision systems and the legal treatment of AI supported professional judgement (Annan, 2022, 2023, 2024, 2025a, 2025b). Instructive precedents also come from aviation, where research on airport safety engineering, safety oversight and regulatory compliance shows how continuous surveillance data, structured audits and safety management systems sustain regulator confidence in highly automated, safety critical operations, a model that offshore integrity regulators are progressively mirroring for twin supported decisions (Adeyelu, 2022; Adeyelu & Dagodzo, 2024a; Adeyelu, 2018, 2019, 2020, 2021, 2023, 2026; Adeyelu & Dagodzo, 2022, 2024b). Finally, human

factors research reminds practitioners that assurance is behavioural as well as technical: awareness, competence and the design of human system interaction determine whether engineered safeguards are used as intended (Hussain & Adebayo, 2026; Onche et al., 2026, 2024).

6.3 Edge computing, industrial internet of things and connectivity

Offshore bandwidth and latency constraints have driven analytics toward the edge. Signal validation, feature extraction and first line anomaly detection now execute on platform or subsea, with only condition indicators and exceptions transmitted to shore based twin processing. This design accommodates the intermittent connectivity of remote assets while preserving the fidelity of local monitoring. The sensing layer itself benefits from sustained research in energy harvesting internet of things and wireless systems engineering, which has produced low power wide area protocols, self powered sensor nodes, wireless power techniques and secure device architectures suited to permanently installed monitoring on structures, pipelines and machinery where cabling and battery replacement are impractical, together with work on securing such device fleets against network borne threats (Asiedu & Quainoo, 2023a, 2023b, 2024, 2025; Asiedu et al., 2025, 2026; Quainoo & Ogundapo, 2026a, 2026b; Quainoo et al., 2024, 2025a, 2025b; Jimoh & Ahmed, 2024; Jimoh et al., 2023; Ogunwola, 2026). In parallel, large language model based assistants have begun to appear as interfaces to integrity twins, allowing engineers to interrogate inspection history, anomaly registers and model outputs conversationally; these AI layers are being deployed cautiously, as decision support behind, rather than in place of, the qualified engineering models.

6.4 Remote and integrated operations centres

The organisational counterpart of the twin is the remote or integrated operations centre, where onshore engineering, maintenance planning and operations support teams work from the same live asset representation as offshore crews. Mature centres arrange their workflows around the twin: morning condition reviews walk the anomaly register, campaign planning sessions manipulate the inspection model, and cross disciplinary anomalies, for example a vibration excursion coincident with a process change, are investigated jointly rather than in disciplinary silos. Experience across operators indicates that the centre succeeds when its decision rights, escalation routes and interfaces to offshore permit systems are engineered as deliberately as the software, echoing findings from the enterprise IT service management and delivery literature on the primacy of process design over tooling (Ladapo et al., 2023b, 2024, 2025, 2019, 2022, 2023a, 2026).

Remote centres also concentrate cybersecurity exposure, since they aggregate privileged connectivity to many assets. Their design therefore incorporates the segmentation, monitoring and incident response disciplines of the operational technology security literature discussed in Section 8.3 (Adebayo et al., 2022, 2023; Adegbite et al., 2020, 2022, 2023, 2024a, 2024b), and their human machine interfaces draw on human factors research to manage alarm load, sustain situational awareness and avoid automation complacency among operators supervising many assets simultaneously (Hussain & Adebayo, 2026; Onche et al., 2026, 2024).

7. Results: Deployment Evidence and Case Illustrations

Quantified benefits are increasingly documented across the offshore sector. This section synthesises the recurring deployment patterns as four composite case illustrations, each assembled from publicly reported practice rather than a single named asset, and then summarises the benefit categories that recur across them.

7.1 Case A: floating production hull and marine systems twin

A permanently moored floating production unit in a harsh environment basin operates a structural twin combining hull finite element models, mooring line tension monitoring, motion measurement and tank inspection records. The twin recalibrates wave load assumptions from measured response, tracks fatigue consumption at critical hull details and mooring components, and drives a risk based inspection programme for ballast and cargo tanks. Reported outcomes across such deployments include material reductions in tank entry hours, deferral of low value inspections in demonstrably low risk tanks, earlier detection of anomalous mooring behaviour, and a substantially stronger evidential basis for life extension beyond the original design life. The programme's governance mirrors the project governance principles of clear decision rights and single point accountability documented in the infrastructure delivery literature (Amayo et al., 2024b, 2024c, 2025a, 2025b, 2025c).

7.2 Case B: subsea pipeline system with envelope monitoring

A subsea export system comprising rigid pipelines, spools and risers operates an integrity twin built on internal corrosion modelling, inline inspection alignment, free span tracking from survey campaigns and continuous process envelope monitoring. Between inspections, the twin verifies that pressure, temperature, water cut and inhibitor availability remain inside the envelope for which the last assessment was validated; excursions automatically raise reassessment tasks. Operators of such systems report extended intervals

between costly vessel campaigns, fewer conservative interim repairs, and audit ready traceability from every operating excursion to its engineering disposition, a traceability discipline consistent with the data governance research base (Mbonu et al., 2021, 2022a, 2022b, 2019; Odejobi et al., 2025).

7.3 Case C: gas compression train prognostics

An offshore gas compression train is monitored by a hybrid twin combining thermodynamic performance models, reduced order blade life estimation and machine learning anomaly detection over vibration and process signatures. The twin flags developing degradation weeks ahead of alarm thresholds, allowing interventions to be planned into scheduled opportunities rather than forced outages. Reported outcomes include conversion of a majority of previously unplanned compression outages into planned work, measurable production efficiency gains, and better targeted spares purchasing driven by forecast demand rather than blanket stocking, connecting machinery prognostics to the supply chain analytics literature (Akin-Oluyomi et al., 2023a, 2023b, 2024, 2020, 2023; Akinleye & Adeyoyin, 2021, 2022a, 2022b; Akinleye et al., 2023).

7.4 Case D: brownfield platform digitalisation

A three decade old fixed platform undergoing life extension built its twin from a laser scanned geometry capture, reconstructed tag register and digitised inspection archive, then layered corrosion, CUI susceptibility and structural models on top. The first year of operation concentrated on data remediation and quick win use cases, principally CUI campaign targeting and anomaly register consolidation, before predictive functions were introduced. This staged trajectory, quick wins funding progressive capability, recurs across brownfield deployments and aligns with the continuous improvement sequencing described in the lean operations literature (Ambali et al., 2021; Eyetsemitan et al., 2020, 2021, 2023a, 2023b, 2025).

7.5 Synthesis of reported benefits

Across cases, commonly cited benefit categories include reduced inspection and maintenance cost, reduced offshore exposure hours, reduced unplanned downtime, deferred capital expenditure through life extension, improved spares and campaign logistics, and improved regulatory confidence. While headline figures vary by asset and should be treated cautiously, the direction of evidence in the 2024 to 2026 period is consistent: value concentrates where twins are scoped to specific integrity decisions and integrated into maintenance execution, and dissipates where they remain visualisation exercises.

The four cases also share three transferable lessons. First, each succeeded by anchoring on one decision that mattered, tank entry scope, campaign deferral, outage conversion or CUI targeting, and letting that decision discipline the data and modelling investment; breadth followed depth, never the reverse. Second, each treated the offshore workforce as co developers rather than end users: inspection teams shaped the capture workflows, and control room and maintenance personnel shaped the alerting thresholds, which is why the tools survived contact with operations. Third, each maintained an explicit evidence trail from raw measurement to executed decision, and it was this traceability, more than model sophistication, that persuaded verification bodies and regulators to accept twin supported conclusions. These lessons echo across the safety governance, human factors and improvement literatures reviewed earlier and appear robust across asset types and basins (Obogo et al., 2026, 2025, 2019, 2021; Obriki & Arumosoye, 2018, 2019, 2020, 2021, 2022).

8. Discussion

8.1 Implementation pathway

Deployment experience has converged on a recognisable implementation sequence, summarised in Table 4. The sequence begins with the information foundation, because every later capability inherits its quality; proceeds through a narrowly scoped pilot chosen for decision value rather than technical novelty; and expands capability only as governance, competence and integration mature. Programmes that invert this order, deploying analytics over an ungoverned data foundation, consistently stall in the pilot phase, a failure pattern equally visible in the broader enterprise digitalisation literature (Aniji et al., 2026; Ayari et al., 2026; Badmus et al., 2025, 2020; Ladapo et al., 2018, 2022, 2023a).

Table 4. Phased implementation roadmap for offshore integrity twins.

Phase	Principal activities	Exit criteria
1. Foundation	Asset information model, tag and document governance, inspection data migration, data quality baseline	Governed model covering pilot scope; data quality metrics defined and tracked

Phase	Principal activities	Exit criteria
2. Pilot	Single high value use case; sensor gap closure; edge validation rules; user workflows in the field	Documented decision value; user adoption evidenced; assurance plan drafted
3. Qualification	Model verification and validation; envelope definition; assurance per recommended practice; cybersecurity hardening	Twin qualified for defined decisions; security regime audited
4. Integration	CMMS and permit to work integration; remote centre workflows; KPI and benefits tracking	Closed loop from recommendation to executed work order with audit trail
5. Scale	Additional systems and assets; fleet models; supply chain linkage; continuous improvement cadence	Portfolio coverage plan funded from measured benefits

Governance travels with the roadmap. Successful programmes appoint a single accountable owner for the asset information model, constitute a cross disciplinary twin board that dispositions model changes with the same discipline applied to plant modifications, and subject vendor arrangements to the contract and supplier governance rigour documented in the procurement research base, protecting the operator against lock in across a multi decade asset life (Abdulhadi & Hamdan, 2026b; Abioye et al., 2023; Aifuwa et al., 2020; Filani et al., 2022; Ike et al., 2024a, 2024b, 2021, 2022).

8.2 Economics and value quantification

The economic case for integrity twins rests on five value streams: avoided inspection cost, avoided deferment from unplanned outages, avoided logistics and bed space cost from reduced offshore campaigns, deferred capital expenditure through life extension, and reduced insurance and regulatory friction from stronger integrity evidence. Rigorous programmes quantify these streams with the same discipline applied to any capital project, establishing a counterfactual baseline before deployment, instrumenting benefit metrics from the outset, and separating benefits attributable to the twin from those attributable to concurrent initiatives. The predictive analytics literature on decision value measurement and forecast evaluation provides the methodological toolkit for this attribution problem (Adelanwa et al., 2023a, 2023b, 2024; Anene & Clement, 2022, 2024; Basnet et al., 2021, 2023, 2024; Oghenemaiga et al., 2024; Tonoyan et al., 2021a).

Table 5. Value streams and representative key performance indicators for twin programmes.

Value stream	Representative KPIs	Measurement notes
Avoided inspection cost	Campaign scope reduction versus baseline plan; cost per inspected item	Requires frozen counterfactual inspection plan at programme start
Avoided production deferment	Unplanned outage frequency and duration for covered equipment; prognosis lead time	Attribute only outages of covered failure modes; track near misses
Reduced offshore exposure	Bed nights and person hours offshore for integrity work; rope access and confined space hours	Directly measurable from logistics and permit records
Life extension value	Approved life extension years; deferred replacement capital	Credit only on regulator or class acceptance of the twin supported case
Risk and assurance quality	Anomaly backlog age; envelope excursion closure time; audit findings	Reported alongside benefits so savings are visible with risk position

Cost structures divide into build and sustain. Build costs are dominated by data remediation on brownfield assets, sensor gap closure and integration engineering; software licensing is rarely the largest line. Sustain costs comprise model stewardship, data quality

management, cybersecurity operations and periodic requalification. Fleet economics improve substantially when the asset information standard, model libraries and integration patterns are reused across installations, which is the principal mechanism by which unit costs fall with scale. Sensitivity analyses reported by practitioners consistently show the business case is most exposed to two assumptions: the realised reduction in offshore campaign scope, and the avoided frequency of the dominant unplanned outage mode. Both should therefore be tracked as first class programme KPIs rather than asserted in the investment case and forgotten (Eyetsemitan et al., 2022, 2024a, 2024b; Oyeleye et al., 2022).

Finally, value quantification must respect uncertainty honestly. A twin that defers an inspection creates value only if the risk position is genuinely maintained; benefits accounting that ignores risk transfer converts an integrity programme into an exercise in optimism. Leading operators therefore report benefits alongside the residual risk metrics of the underlying RBI framework, so that cost savings and risk exposure are visible in the same governance forum.

8.3 Challenges and open problems

The challenges facing twin adoption are interdependent rather than separable, and the dependency structure matters for how programmes sequence their responses. Data quality problems undermine model validation; unvalidated models cannot pass assurance; unassured twins cannot carry regulatory weight; and without regulatory weight the business case reverts to soft efficiency claims that struggle in capital allocation. Conversely, each resolved layer strengthens the next: a governed data foundation makes validation tractable, validated models make assurance a documentation exercise rather than a research project, and an assured twin converts regulator engagement from scepticism to collaboration. Programmes should therefore read the following list as a dependency chain to be resolved broadly in order, not a menu of independent risks:

- Data quality and legacy records. Ageing assets often lack reliable as built documentation, and historical inspection data are inconsistent in format and coverage. Twin accuracy is bounded by the quality of this foundation, and remediation is labour intensive, reinforcing the governance disciplines discussed in Section 2.2 (Borah et al., 2022; Mbonu et al., 2018, 2020, 2021a, 2021b, 2022, 2019, 2020a, 2020b, 2021, 2022a, 2022b; Odejobi et al., 2025).
- Model validation for rare failure modes. Validating remaining life predictions for mechanisms with sparse failure observations, such as low frequency fatigue cracking or localised CUI, remains statistically difficult, reinforcing the need for uncertainty quantification and conservative decision logic (Tonoyan et al., 2021b, 2022a, 2022b, 2022c, 2023, 2024a, 2024b, 2025, 2026).
- Organisational readiness. The binding constraint is frequently not technical capability but organisational readiness: data infrastructure, internal competence, safety culture and the integration of twin insights into established, accountable decision processes (Obogo et al., 2020b, 2020c, 2021, 2024, 2023, 2022, 2019a, 2019b).
- Assurance of AI components. Machine learning elements complicate qualification because their behaviour is data dependent. Extending assurance frameworks to cover model drift, retraining governance and explainability is an active area of standards and legal scholarship (Annan, 2022, 2023, 2024, 2025a, 2025b).
- Cybersecurity. Coupling operational technology to shore based analytics enlarges the attack surface of safety critical systems. A substantial research base on operational technology and critical infrastructure security, enterprise cyber defence engineering, zero trust architectures, security operations, incident response and resilient IT service delivery defines the threat models and defensive architectures within which twin deployments must be designed, typically within IEC 62443 aligned regimes (Adebayo et al., 2022, 2023; Adegbite et al., 2020, 2022, 2023, 2024a, 2024b, 2025; Ahmed et al., 2021; Ogunwola & Deborah, 2026; Dosunmu & Ogundele, 2019, 2020, 2021, 2022, 2023, 2024a, 2024b, 2024c, 2024d, 2025a, 2025b, 2025c, 2026a, 2026b, 2026c; Ogunwola & Alozie, 2026; Ogunwola et al., 2026; Edivri & Oteri, 2022, 2024; Ogbole et al., 2021, 2025; Okoruwa et al., 2024, 2020; Oteri & Edivri, 2024, 2026).
- Cost and scalability. Full fidelity twins remain expensive to build per asset. Fleet approaches, reduced order modelling and reusable asset information standards are the principal levers for improving the economics.

Beyond the enumerated constraints, a structural tension deserves note: the twin's promise of inspection reduction sits uneasily with verification regimes historically built around physical inspection evidence. Resolving this tension requires regulators, class societies and operators to agree what constitutes equivalent evidence, a negotiation in which the aviation sector's experience with surveillance based oversight offers a tested template (Adeyelu, 2018, 2019, 2020, 2021, 2023, 2026; Adeyelu & Dagodzo, 2022, 2024b).

8.4 Synthesis and implications

Comparing the two equipment domains reviewed here reveals an instructive asymmetry in maturity. Mechanical equipment twins matured first, because rotating machinery generates dense, fast, information rich signals and its failure modes unfold over weeks, giving prognostic models frequent feedback. Static equipment twins matured later but now carry the larger economic weight, because

static degradation, developing over years with sparse measurements, is precisely where model based inference adds the most over raw monitoring, and because static inspection dominates offshore integrity spend. The methods are converging: Bayesian updating disciplines developed for slow static degradation are improving machinery remaining life estimates, while the anomaly detection rigour of machinery monitoring is tightening the data quality standards of static programmes (Anene & Clement, 2022, 2024; Basnet et al., 2021, 2023, 2024; Oghenemaiga et al., 2024; Tonoyan et al., 2021a, 2021b, 2022a, 2022b, 2022c, 2023).

A second observation concerns the direction of innovation flow. Much of the enabling capability reviewed in Sections 2 and 6 originated outside offshore engineering: predictive maintenance methods from building services, sensing from the IoT community, data governance from regulated enterprise computing, oversight models from aviation, and improvement disciplines from lean manufacturing (Atta et al., 2018, 2020, 2021, 2022; Omoegun et al., 2023; Oyeleke et al., 2026; Sunday & Omoegun, 2018, 2019, 2022; Sunday et al., 2019, 2020; Asiedu & Quainoo, 2023a, 2023b, 2024, 2025; Asiedu et al., 2025, 2026; Adeyelu, 2022; Adeyelu & Dagodzo, 2024a; Adeyelu, 2018, 2019, 2020). Offshore integrity management has historically imported methods slowly; the twin era has accelerated the import rate markedly, and the operators benefiting most are those that scan adjacent literatures deliberately. The consolidated corpus cited throughout this review is itself an argument for that practice.

Third, the review supports a reframing of what an integrity twin fundamentally is. The early framing, a virtual replica, emphasised representation. The framing that better matches 2026 practice is evidentiary: the twin is an instrument for maintaining a continuously defensible integrity case, in which every operating hour either confirms the current assessment or triggers its revision. Representation, models and analytics are means; the maintained case is the product. This framing explains why assurance, governance and traceability, rather than modelling sophistication, have become the differentiators between programmes that carry safety critical decisions and programmes that decorate them.

The limitations of this review should be acknowledged. Composite case illustrations, while faithful to recurring reported practice, cannot substitute for audited, asset specific benefit data, which operators rarely publish at the granularity research requires. The adjacent domain corpus, drawn from a consolidated portfolio, is broad but not the product of a systematic database search, so cluster sizes reflect the portfolio's composition as well as the fields' intrinsic weight. And any review dated to a fast moving year is a snapshot: several of the trajectories described here, particularly language model interfaces and energy transition duties, are moving quickly enough that their 2026 state will look early within a few years. These limitations define a research agenda as much as a caveat: the field needs published, quantified deployment studies with declared counterfactuals, and systematic mapping of the adjacent literatures whose methods offshore integrity practice is now importing at pace.

9. Conclusion

By 2026, digital twins have become an established instrument of offshore asset integrity management for both static and mechanical equipment. The decisive advances of the current period are less about visualisation and more about engineering credibility: hybrid physics and data models with quantified uncertainty, envelope monitoring that makes model validity explicit, edge architectures suited to offshore constraints, closed loop integration with maintenance execution, and assurance frameworks that treat the twin as a qualified engineering product. For static equipment, twins are transforming inspection from calendar driven campaigns to risk based, evidence led programmes and are strengthening life extension cases for an ageing fleet. For marine mechanical equipment, they are converting condition monitoring into prognostics and enabling reduced manning and remote operations. The review has also shown that twin practice is sustained by a wide belt of adjacent research, from HSE and project governance (Arumosoye & Obriki, 2018, 2019, 2020, 2021, 2022, 2023, 2024; Arumosoye et al., 2025, 2026; Obogo et al., 2020a, 2020b, 2020c, 2021, 2024, 2023, 2022, 2019a, 2019b, 2026, 2025, 2019; Obriki & Arumosoye, 2018, 2019, 2020, 2021, 2022, 2023, 2024a, 2024b; Obriki et al., 2023, 2025, 2022a, 2022b; Abdulhadi & Hamdan, 2026c; Amayo et al., 2023a, 2023b, 2023c, 2024a, 2024b, 2024c, 2025a, 2025b, 2025c) through information systems, data governance, sensing and analytics (Aniji et al., 2026; Ayari et al., 2026; Badmus et al., 2025, 2020; Ladapo et al., 2018, 2022, 2023a, 2023b, 2024, 2025, 2019, 2026; Aliliele et al., 2023a, 2023b, 2023c, 2024a, 2024b, 2025a, 2025b; Borah et al., 2022; Mbonu et al., 2018, 2020, 2021a, 2021b, 2022, 2019, 2020a, 2020b, 2021, 2022a, 2022b; Odejobi et al., 2025; Dagodzo, 2018a, 2018b; Dagodzo & Patrick, 2020, 2021a, 2021b, 2022, 2023a, 2023b, 2025; Dagodzo et al., 2022; Falegan & Aniebonam, 2022, 2023, 2024, 2025, 2026; Atta et al., 2018, 2020, 2021, 2022; Omoegun et al., 2023; Oyeleke et al., 2026; Sunday & Omoegun, 2018, 2019, 2022; Sunday et al., 2019, 2020; Adenuga, 2023; Amayo, 2017; Amayo & Popoola, 2017a, 2017b; Amayo et al., 2015; Oshevire et al., 2017; Akanbi & Sunday, 2024, 2025; Akanbi et al., 2025; Adelanwa et al., 2023a, 2023b, 2024; Anene & Clement, 2022, 2024; Basnet et al., 2021, 2023, 2024; Oghenemaiga et al., 2024; Tonoyan et al., 2021a, 2021b, 2022a, 2022b, 2022c, 2023, 2024a, 2024b, 2025, 2026) to AI governance, supply chains, energy transition engineering and industrial cybersecurity (Annan, 2022, 2023, 2024, 2025a, 2025b; Adeyelu, 2022; Adeyelu & Dagodzo, 2024a; Adeyelu, 2018, 2019, 2020, 2021, 2023, 2026; Adeyelu & Dagodzo, 2022, 2024b; Hussain & Adebayo, 2026; Onche et al., 2026, 2024; Asiedu & Quainoo, 2023a, 2023b, 2024, 2025; Asiedu et al., 2025, 2026; Quainoo & Ogundapo, 2026a, 2026b; Quainoo et al., 2024, 2025a, 2025b; Jimoh & Ahmed, 2024; Jimoh et al., 2023; Ogunwola, 2026; Agbabiaka et al., 2019; Patrick et al., 2020, 2021; Ogunwole et al., 2021; Okonkwo et al., 2024a, 2024b, 2024c, 2024d, 2024e, 2024f, 2020, 2021, 2025, 2023, 2018a, 2018b, 2019; Abdulhadi &

Hamdan, 2026a, 2026b; Abioye et al., 2023; Aifuwa et al., 2020; Filani et al., 2022; Ike et al., 2024a, 2024b, 2021, 2022, 2025; Nnabueze et al., 2021; Okojie et al., 2023; Yeboah & Ike, 2020; Yeboah et al., 2024, 2025; Akin-Oluyomi et al., 2023a, 2023b, 2024, 2020, 2023; Akinleye & Adeyoyin, 2021, 2022a, 2022b; Akinleye et al., 2023; Babatope et al., 2023; Efobi et al., 2021, 2022a, 2022b, 2023; Ogundairo, 2025; Okojie & Abioye, 2020; Okoruwa et al., 2024, 2025; Atta, 2026a, 2026b; Atta et al., 2025, 2024; Bello et al., 2023; Monye et al., 2025; Adenuga, 2022; Komi, 2021, 2023, 2024, 2025; Komi & Adamolekun, 2021, 2022, 2024, 2026; Komi & Adeniji, 2020, 2023, 2024a, 2024b; Komi & Ganiu, 2022, 2023, 2025; Tackie et al., 2023; Ambali et al., 2021; Eyetsemitan et al., 2020, 2021, 2023a, 2023b, 2025, 2022, 2024a, 2024b; Oyeleye et al., 2022; Adebayo et al., 2022, 2023; Adegbite et al., 2020, 2022, 2023, 2024a, 2024b, 2025; Ahmed et al., 2021; Ogunwola & Deborah, 2026; Dosunmu & Ogundele, 2019, 2020, 2021, 2022, 2023, 2024a, 2024b, 2024c, 2024d, 2025a, 2025b, 2025c, 2026a, 2026b, 2026c; Ogunwola & Alozie, 2026; Ogunwola et al., 2026; Edivri & Oteri, 2022, 2024; Ogbole et al., 2021, 2025; Okoruwa et al., 2020; Oteri & Edivri, 2024, 2026), and that mature programmes draw on this belt deliberately rather than incidentally.

Future development is likely to concentrate on four fronts. First, deeper standardisation of asset information models and twin interfaces, so that twins survive vendor and system change across multi decade asset lives. Second, qualified integration of AI, including language model interfaces and self updating hybrid models, within auditable assurance regimes. Third, fleet and system level twins that reason across platforms, pipelines, supply chains and export infrastructure rather than single assets, supporting basin scale integrity and decommissioning decisions. Fourth, extension of the same toolset to the energy transition asset base, where sparse operating history makes model based integrity management necessary from first operation. The central research and engineering question for the coming years is therefore one of trust at scale: demonstrating, asset by asset and decision by decision, that the virtual representation is faithful enough to carry the weight of real offshore integrity decisions.

For researchers, this review suggests five specific openings. Validation methodology for sparse failure regimes needs formal treatment, so that remaining life claims for rare mechanisms can be qualified with defensible statistical power. Benefit attribution methods deserve adaptation from the analytics evaluation literature to the integrity context, enabling published deployment studies with declared counterfactuals. Assurance science for adaptive models, covering drift detection, retraining governance and explanation adequacy for engineering audiences, remains underdeveloped relative to its regulatory urgency. Cyber resilience engineering for twin architectures would benefit from integrity specific threat modelling, since an attacker who corrupts condition data attacks the safety case itself. And the human dimension, how engineers calibrate trust in probabilistic tools and how organisations retain judgement alongside automation, invites empirical study in the tradition of the human factors and safety culture research cited throughout. Each opening connects the offshore integrity community to an adjacent discipline already working the underlying problem, which has been the quiet engine of the field's progress across the period this review describes.

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