Conceptual Framework for Process Safety and Operational Reliability in FPSO-based Energy Systems

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Abstract

This paper proposes a conceptual framework for process safety and operational reliability in floating production, storage, and offloading (FPSO) energy systems operating under harsh, data-sparse, and cost-constrained conditions. The framework integrates barrier-based safety thinking with reliability-centered maintenance and digital assurance to prevent loss of containment, mitigate escalation, and assure uptime across the asset lifecycle. A systems layer maps hydrocarbon, power, and utility networks, interfaces, and safety-critical elements to expose bow-tie hazards, safety functions, and dependencies. An observability layer fuses condition monitoring, process historians, and marine instrumentation with physics-informed digital twins to estimate unobserved states, detect weak signals, and quantify risk in real time. A decision layer combines risk-based inspection, reliability block diagrams, and Bayesian updating to prioritize interventions by consequence, likelihood, and uncertainty, enabling defensible ALARP demonstrations. An optimization-and-control layer orchestrates start-up, steady-state, and upset responses using model predictive control with constraint handling, supported by flare minimization, gas compression anti-surge, and power management strategies. A human-and-organization layer embeds just culture, competence management, and procedural discipline, aligning control room practices with safety cases and permit-to-work governance. Cyber-physical assurance closes the loop through verification and validation of models, safety instrumented system proof testing, cybersecurity hardening, and anomaly triage workflows. Implementation proceeds through four phases: (1) baseline risk and reliability modeling and data readiness; (2) pilot twin deployment on topsides subsystems (e.g., separators, compressors, cargo handling); (3) integrated optimization with alarm rationalization and barrier health dashboards; and (4) fleet scaling with continuous learning. Key performance indicators include barrier health, loss of containment frequency, safety system demand failure probability, mean time between failures, deferment, flare intensity, and recovery time from upsets. Illustrative use cases show earlier detection of incipient compressor surge, tighter flare compliance during turndown, and reduced SIMOPS conflict via dynamic risk visualization. The framework is standards-aware (ISO 31000, IEC 61511, ISO 14224, and IMO), technology-agnostic, and adaptable to brownfield retrofits, remote operations centers, and hybrid power integrations. By linking hazards, data, decisions, and controls within a governed, human-in-the-loop loop, the framework provides a practical pathway to demonstrably safer operations, higher reliability, and lower environmental footprint for FPSO-based energy systems at industrial scale.

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Keywords: FPSO, process safety, operational reliability, barrier management, digital twin, reliability-centered Maintenance, Model Predictive Control, Risk-Based Inspection, Bayesian Updating, ALARP, Flare Minimization, Compressor Anti-Surge, Cyber-Physical Security, IEC 61511, ISO 14224

1. Introduction

Floating production, storage, and offloading (FPSO) assets concentrate complex hydrocarbon processing, marine operations, and power generation on a single floating platform that must operate safely and reliably in remote, weather-exposed fields over multi-decade lifecycles. The risk profile is distinctive: high-pressure and high-temperature processing on a compact topsides.

layout; simultaneous marine and process hazards; cargo handling and offloading alongside continuing production; ageing infrastructure and brownfield modifications; and data sparsity or intermittency relative to onshore plants (Akinrinoye, *et al*. 2015, Bukhari, *et al*., 2019, Erigha, *et al*., 2019). Loss of containment, escalation through congested modules, impaired safety instrumented systems, compressor surge, flare non-compliance, turret and mooring integrity threats, and simultaneous operations during maintenance or offloading create tightly coupled failure pathways in which small degradations can propagate into major incidents or prolonged deferment.

The problem addressed in this work is that conventional safety and reliability programs on FPSOs are often fragmented barrier management is documented but weakly instrumented, reliability modeling is detached from live operating context, and optimization focuses on production or emissions in isolation from barrier health and marine constraints. This fragmentation hampers timely detection of weak signals, leads to reactive maintenance and alarm overloads, and obscures the trade-offs between throughput, regulatory compliance, and risk. The objective is to provide a coherent, auditable conceptual framework that links hazards, data, decisions, and controls in real time so that operators can prevent loss events, minimize deferment, and sustain safe production at the lowest lifecycle cost (Ajayi, *et al*., 2018, Bukhari, *et al*., 2018, Essien, *et al*., 2019).

The scope covers the FPSO as a system-of-systems: process and utility modules (separation, gas compression, dehydration, produced-water, flare), marine systems (hull, turret, mooring, ballast, cargo tanks), electrical generation and distribution, power management, cargo handling and offloading, and their control, safeguarding, and cybersecurity interfaces. It spans the asset lifecycle from commissioning through late-life operations, including brownfield tie-ins, turndown, and hybrid power integrations. The framework integrates barrier-based safety thinking with reliability-centered maintenance, risk-based inspection, and digital assurance (Ajayi, *et al*., 2019, Bukhari, *et al*., 2019, Oguntegbe, Farounbi & Okafor, 2019). It introduces an observability stack that fuses process historians, condition monitoring, and marine instrumentation into physics-informed digital twins for state and degradation estimation; a decision layer that combines Bayesian risk updating with optimization and model predictive control to orchestrate steady-state and upset responses; and human-organization elements that embed just culture, competence management, alarm rationalization, and permit-to-work discipline. Governance provides standards alignment (e.g., ISO 31000, IEC 61511, ISO 14224, IMO/Class), data quality metrics, model validation and cybersecurity controls to ensure traceable, safe deployment at scale.

The contributions are fourfold. First, a barrier-health-aware architecture that quantifies the performance of safety-critical elements and ties them directly to operating envelopes and production decisions. Second, a digital-twin approach that turns weak signals EGT spread, vibration sidebands, flare composition, power-quality anomalies into actionable estimates of degradation and near-term risk. Third, a coupled optimization-and-control strategy that balances flare minimization, anti-surge protection, emissions, and power management under uncertainty, with explicit treatment of SIMOPS and marine constraints. Fourth, a lifecycle feedback loop that reconciles predicted with realized benefits, refines risk and reliability models, and prioritizes inspections and maintenance by expected reduction in incident probability and deferment. Together these elements form a practical, standards-aware pathway to demonstrably safer operations and higher operational reliability in FPSO-based energy systems (Ajayi, *et al*., 2019, Bayeroju, *et al*., 2019, Sanusi, *et al*., 2019).

2. Methodology

The methodology for developing the Conceptual Framework for Process Safety and Operational Reliability in FPSO-based energy systems applies an integrated, multi-layered systems-engineering approach combining risk analytics, digital-twin modelling, predictive maintenance, and operational governance. The approach begins with comprehensive data acquisition across the FPSO’s process, marine, electrical, control, and cargo-handling subsystems. This includes real-time sensors, SCADA streams, laboratory analysis, marine motion data, safety-instrumented function logs, and maintenance histories. In alignment with data-quality principles highlighted across predictive analytics frameworks in Abass *et al*. (2019), Aduloju *et al*. (2021), and Filani *et al*. (2021), all raw inputs are subjected to structured quality checks, metadata tagging, anomaly screening, and harmonisation before processing.

The next step involves constructing a multi-domain risk knowledge base. Drawing from improved FMEA frameworks (Wang *et al*., 2021), zero-trust safety logic (Ajayi *et al*., 2019), and risk-automation architectures (Essien *et al*., 2020), the methodology integrates hazard identification, HAZOP deviations, bow-tie cause–consequence pathways, LOPA safeguards, and QRA event trees into a unified digital hazard model. This is supplemented with predictive risk models used in methane surveillance and leak-event forecasting (Fasasi *et al*., 2020–2021). Simulation-based uncertainty propagation (Aduwo & Nwachukwu, 2019) is used to estimate risk evolution under variable conditions such as sea states, process upsets, equipment degradation, and human-factor variability.

A hybrid digital-twin architecture is then built, combining physics-based models of separation trains, compression modules, gas treatment subsystems, turret motion, and power-generation units with data-driven anomaly detection techniques informed by deep-learning cybersecurity frameworks (Ayanbode *et al*., 2019). The digital twin supports degradation estimation, early-warning detection, barrier-health monitoring, and integrity forecasting for hull, moorings, piping, valves, compressors, and safety-instrumented systems. This is enhanced by real-time data engineering approaches from Lakehouse-DevOps integration models (Ajayi *et al*., 2020) to ensure continuous and reliable data flow.

Using outputs from the twin, the methodology applies risk-based inspection, reliability-centred maintenance, and RUL-based prioritisation. This draws on predictive maintenance concepts from HR-analytics models (Ajayi *et al*., 2019), supply-chain resilience frameworks (Alao *et al*., 2021), and facility-energy optimisation systems (Amini-Philips *et al*., 2021). Maintenance recommendations are optimised using resource-allocation logic from economic-policy analytics (Akinrinoye *et al*., 2019) and uncertainty-aware optimisation frameworks (Carrasco & Lima, 2017).

The next phase integrates advanced control strategies, including MPC with constraints for power management, compressor anti-surge control, flare minimisation, and marine stability handling. Control logic leverages AI-enhanced monitoring strategies from telecom and financial-operations optimisation frameworks (Seyi-Lande *et al*., 2018; Bankole *et al*., 2019). All analyses and decisions are visualised through an intelligent dashboard similar to integrated KPI-monitoring systems (Filani *et al*., 2020).

Finally, the methodology embeds a continuous-improvement loop that updates risk models, retrains anomaly-detection algorithms, and recalibrates maintenance strategies using new sensor data, inspection feedback, and incident-learning inputs. This reflects the adaptive governance characteristics of public-health surveillance frameworks (Atobatele *et al*., 2019) and systems-thinking energy-policy models (Giwah *et al*., 2020). The methodology thus integrates risk science, AI, operations research, and digital-engineering strategies into a cohesive framework capable of enhancing FPSO safety, reliability, and operational resilience.

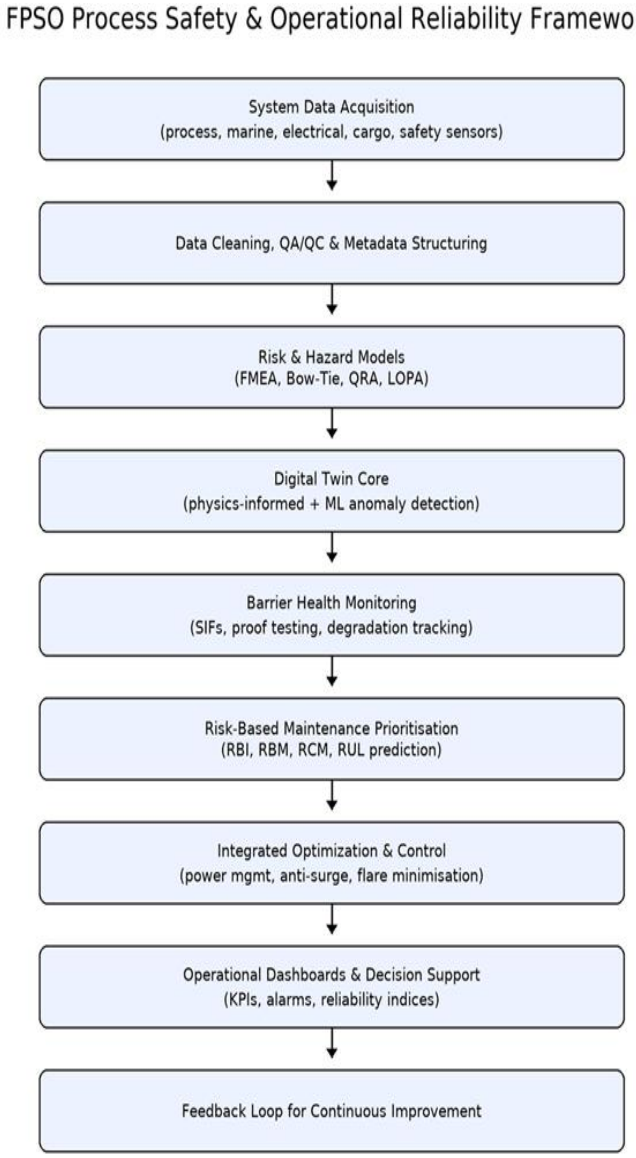

Fig 1: Flowchart of the study methodology

2.1 Background and Standards Landscape

Floating production, storage, and offloading assets operate at the intersection of offshore marine regulation and onshore-grade process safety expectations, and any credible framework for process safety and operational reliability must be grounded in the relevant standards while clarifying the vocabulary that organizes risk. Process safety refers to the disciplined management of hazards that can lead to major accidents loss of primary containment, fires, explosions, and toxic releases through the design, operation, and maintenance of engineered barriers and organizational controls. It is distinct from personal or occupational safety and is best understood as the integrity of the process over time (AdeniyiAjonbadi, *et al*., 2015, Didi, Abass & Balogun, 2019, Umoren, *et al*., 2019). Operational reliability complements this perspective by focusing on the ability of systems and components to perform their required functions under stated conditions for specified periods, capturing availability, maintainability, and degradation behavior. A central decision principle connecting these domains is ALARP "as low as reasonably practicable" which requires that risk be reduced until the incremental cost, time, or effort of further reduction would be grossly disproportionate to the benefit, provided that all good practice is first implemented. On an FPSO, ALARP translates to demonstrable barrier adequacy against credible scenarios, informed by quantitative risk analysis and tempered by operability, maintenance access, and marine constraints.

ISO 31000 provides the overarching methodology for risk management and underpins the governance layer of the framework. It defines risk as the effect of uncertainty on objectives and lays out principles, a process, and organizational arrangements for risk identification, analysis, evaluation, treatment, monitoring, and communication. In the FPSO context, ISO 31000 structures risk registers that bridge process and marine hazards, ensures consistent risk criteria, and requires feedback loops so that incident learnings, weak signals, and performance metrics recalibrate the risk picture. It does not prescribe techniques; rather, it harmonizes the use of HAZID, HAZOP, bow-tie analysis, layers of protection analysis, quantitative risk assessment, and consequence modeling so that decisions are made consistently across modules and lifecycle phases (Ajonbadi, Mojeed-Sanni & Otokiti, 2015, Evans-Uzosike & Okatta, 2019, Oguntegbe, Farounbi & Okafor, 2019).

IEC 61511 governs safety instrumented systems for the process industry sector and is indispensable for topsides safeguarding on FPSOs. It defines the safety lifecycle from hazard and risk assessment through allocation of safety functions, design and verification, operation, proof testing, and modification. Safety integrity levels (SILs) are assigned based on risk reduction targets, and architectural constraints, diagnostic coverage, and proof test intervals must be aligned to achieve the required average probability of failure on demand. The framework situates IEC 61511 within a wider barrier model: safety instrumented functions sit alongside relief and flare systems, passive fire protection, blast-rated structure, ignition control, and procedural safeguards. Digital assurance, model validation, and cyber-hardening are treated as enablers of lifecycle compliance rather than separate activities, with change management ensuring that modifications preserve the SIS safety case (Ajonbadi, Otokiti & Adebayo, 2016, Didi, Abass & Balogun, 20219). Figure 2 shows the processing technology flow diagram of floating production storage and offloading system (FPSO) oil and gas processing system presented by Wang, *et al*., 2021.

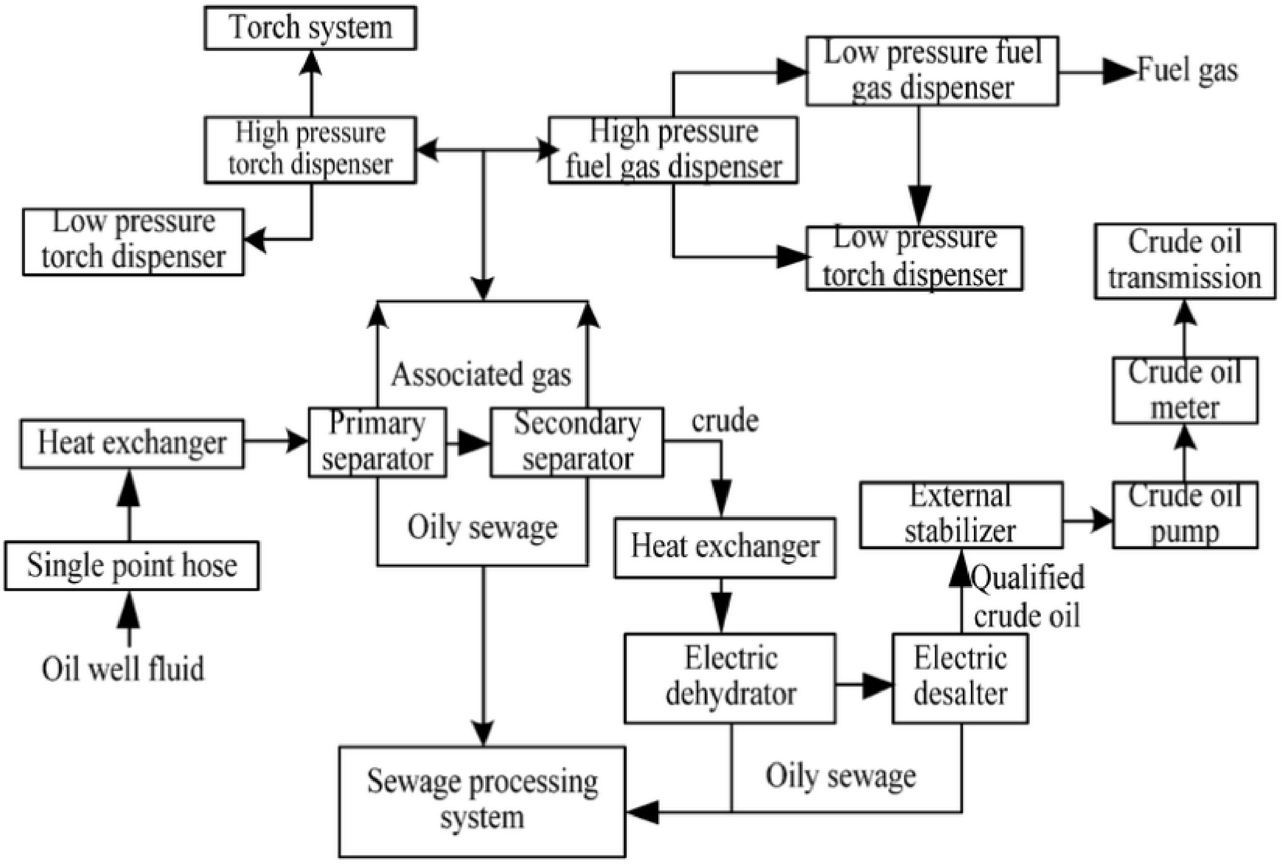

Fig 2: The processing technology flow diagram of floating production storage and offloading system (FPSO) oil and gas processing system (Wang, *et al*., 2021).

ISO 14224 standardizes the collection and exchange of reliability and maintenance data for equipment in the petroleum, natural gas, and petrochemical industries. For an FPSO, it provides taxonomies and data quality requirements to make failure statistics comparable across fleets and vendors, enabling reliability-centered maintenance, risk-based inspection, and RAM modeling. By adopting ISO 14224, the framework ensures that condition indicators and work histories flow into a structured dataset that supports Weibull analysis, proportional hazards modeling, and Bayesian updates of failure rates under actual duty cycles and environmental exposures. This standard is pivotal for converting digital twin estimates and inspection findings into actionable reliability improvements and credible expected value calculations for maintenance (Balogun, Abass & Didi, 2019, Otokiti, 2018, Oguntegbe, Farounbi & Okafor, 2019).

Marine regulation layers additional obligations. The International Maritime Organization's SOLAS convention governs fire protection, detection, and extinction; life-saving appliances; and safety of navigation. MARPOL imposes pollution prevention requirements, including volatile organic compound management and ballast water control. The ISM

Code mandates a safety management system with defined responsibilities, procedures for key operations, training, and continuous improvement through audits and corrective actions. Classification societies ABS, DNV, Lloyd's Register and others publish class rules covering hull structural integrity, mooring and turret systems, machinery, electrical, dynamic positioning (where applicable), and novel technology guidelines for floating production units (Ajonbadi, *et al.*, 2014, Didi, Balogun & Abass, 2019, Farounbi, *et al.*, 2019). These rules interact with flag state requirements and coastal state regulations, creating a multi-jurisdictional compliance field. The framework aligns barrier management and reliability activities with class notations and survey regimes so that proof testing, inspection, and software change control satisfy both process industry lifecycle standards and class/IMO expectations. Cybersecurity sits within this marine layer as well: IMO and IACS recommendations require cyber risk management to be integrated into the safety management system, while IEC 62443 and ISO/IEC 27001 provide technical and organizational controls for industrial automation and control systems that interface with process safeguarding. Figure 3 shows block diagram of FPSO process presented by Hosseinnia Davatgar, Paltrinieri & Bubbico, 2021.

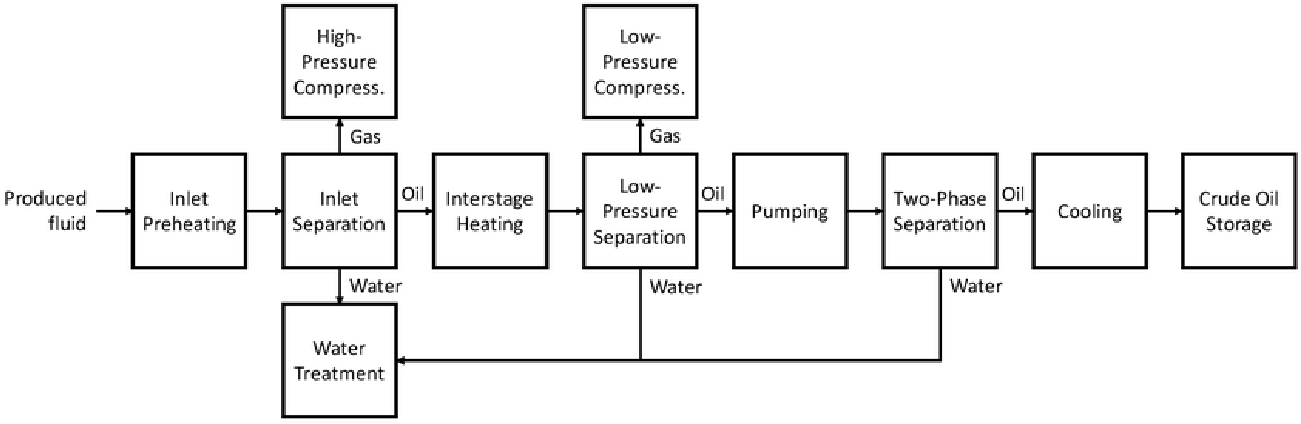

Fig 3: Block diagram of FPSO process (Hosseinnia Davatgar, Paltrinieri & Bubbico, 2021).

Prior frameworks offer building blocks but often fall short of the integration needed for FPSO realities. The bow-tie method has become the lingua franca for barrier-based risk visualization, connecting initiating events to consequences through preventive and mitigative controls and enabling barrier performance standards. However, on many assets the bow-tie is static a poster on the wall rather than instrumented with live barrier health indicators, proof-test results, impairment registers, and alarm system performance (Seyi-Lande, Oziri & Arowogbadamu, 2018). Reliability-centered maintenance defines functions, functional failures, failure modes, and consequences, and prescribes tasks to manage the risk at least cost, but it can be decoupled from real-time operating context and not updated with actual failure and duty data. Risk-based inspection prioritizes inspection resources by risk rather than fixed intervals, yet its models may ignore process variability and changing corrosion drivers during turndown or high-water-cut operation. Quantitative risk assessment provides scenario frequencies and consequence contours for layout and emergency response, but it is often used as a project deliverable rather than a living decision tool. The Center for Chemical Process Safety's Risk-Based Process Safety framework adds pillars such as process safety culture, competency, and metrics, but translating these into offshore practice requires explicit alignment with class/IMO and SIMOPS constraints. What is missing is a digital nervous system that ties barrier health and reliability models to the actual operating state, escalating risk when protection layers are degraded or when process conditions approach limits, and showing the economic and safety consequences of alternative actions in a transparent, ALARP-consistent way (Akinbola & Otokiti, 2012, Dako, *et al.*, 2019, Oziri, Seyi-Lande & Arowogbadamu, 2019).

Definitions provide the glue. Process safety performance is evidenced through leading and lagging indicators: testing compliance, safety critical element impairments, safety demand failures, and tiered loss-of-containment metrics consistent with API RP 754 or similar guidance. Operational reliability is measured via mean time between failures, mean time to repair, forced outage factor, deferment, and readiness measures for critical functions such as emergency shutdown, firewater, and cargo offloading. ALARP judgments require an auditable comparison of options, demonstrating that good practice has been met (e.g., SIL targets achieved, fire/blast structural design margins satisfied, alarm system rationalized per IEC 62682) and that further risk reduction measures have been considered and rejected only when disproportionate. On an FPSO, "reasonably practicable" must be judged against constraints such as crane access, weather windows, marine traffic, and turret rotation limits, which affect implementability and risk during the work (Akinrinoye, *et al.* 2019, Didi, Abass & Balogun, 2019, Otokiti & Akorede, 2018). Figure 4 shows schematic diagram of an offshore LNG FPSO presented by Hwang, Roh & Lee, 2012.

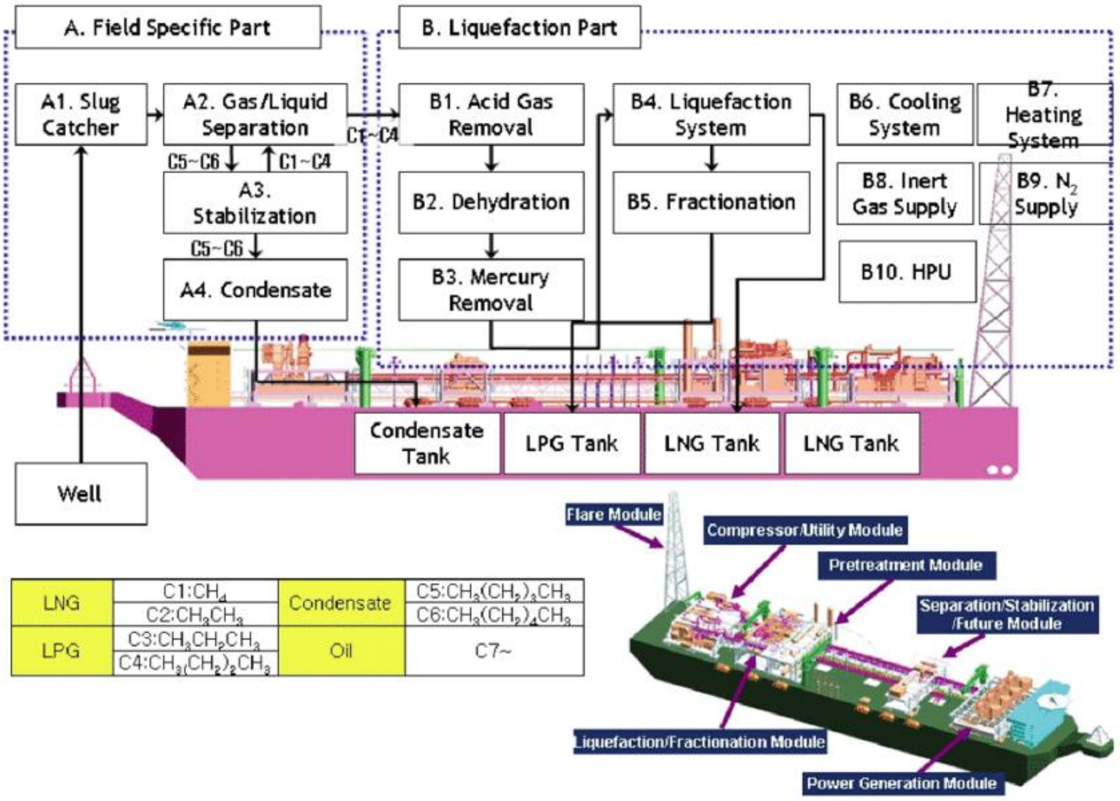

Fig 4: Schematic diagram of an offshore LNG FPSO (Hwang, Roh & Lee, 2012).

The background also includes the evolution of digital assurance and cyber-physical integration. Historically, process safety and reliability were paper-centric; now, digital twins and condition monitoring promise continuous assurance, but they introduce new failure modes. The standards landscape has responded by emphasizing lifecycle and management-of-change rigor: IEC 61511 demands proof testing and functional safety assessments; ISO 31000 calls for monitoring and review; ISM requires internal audits; class societies have digital model assurance guidelines and software-in-the-loop testing expectations. Incorporating IEC 62443 hardening and secure development practices into safeguarding and power management systems reduces the risk that cyber events defeat layers of protection. The framework adopts these expectations, treating data quality, model validation, and cybersecurity as safety enablers rather than IT hygiene (Seyi-Lande, Oziri & Arowogbadamu, 2019).

Finally, the FPSO context demands explicit treatment of simultaneous operations and integrated power/flare management. Standards and guidance on SIMOPS require hazard identification and permitting for co-located work and marine evolution; flare management must comply with environmental permits and class rules while safeguarding anti-surge and overpressure protection. Prior optimization efforts in upstream facilities often target production alone; here, the framework situates optimization within barrier and reliability constraints, showing, for example, how flare minimization interacts with compression anti-surge logic and how power management choices influence firewater pump availability and black-start capability. By rooting decisions in ISO 31000 risk governance, implementing SIS lifecycle discipline per IEC 61511, structuring reliability data under ISO 14224, and aligning with IMO/Class obligations, the framework turns a dense regulatory environment into a coherent operating model. The result is a standards-aware backbone where definitions are operationalized, prior methods are connected and instrumented, and ALARP becomes an enduring, data-backed practice rather than a one-time justification.

2.2 System Architecture and Interfaces

A credible architecture for process safety and operational reliability on an FPSO begins with a system-of-systems view that recognizes five tightly coupled domains process, marine, electrical, control/safeguarding, and cargo and then specifies explicit interfaces, dependencies, and safety-critical elements with measurable performance standards. The process domain encompasses hydrocarbon and utility systems from wellstream ingress to export: inlet facilities, separation trains, gas compression and dehydration, produced-water treatment, stabilisation, metering, and flare and relief networks, as well as support utilities such as instrument air, nitrogen, cooling medium, fuel gas, and heating (Abass, Balogun & Didi, 2019, Ogunsola, Oshomegie & Ibrahim, 2019, Seyi-Lande, Arowogbadamu & Oziri, 2018). These modules must operate within compact, congested topsides where elevation, blast partitions, and drainage define escalation pathways. The marine domain covers hull structure, turret and bearing systems, moorings and anchors, ballast and bilge, thrusters and maneuvering (or dynamic positioning where applicable), and classification-driven structural integrity management. Electrical covers power generation (gas turbines/diesel), switchboards and transformers, power management, variable-speed drives, UPS and battery systems, emergency generation, and black-start capability. Control and safeguarding include the distributed control system for normal operation, the safety instrumented system for emergency shutdown and high-integrity protection, fire and gas detection with automatic deluge and ventilation shutdowns, and the data/communications backbone that ties alarm management, historian, and cybersecurity together. Cargo embraces crude storage tanks, inert gas and tank venting, VOC management, cargo pumps and stripping, offloading reels and hoses or loading arms, pigging interfaces, tandem or side-by-side offloading control, and mooring winches and hawser release systems.

Interfaces are where incidents are made or prevented. Process–marine coupling is profound: turret rotation, vessel motions, heel and trim change line pressures and liquid levels, altering separator performance, gas carry-under risks, and flare backpressure. Mooring stiffness and weather windows constrain offloading timing; if tanks approach high-high levels during prolonged shut-in or offloading delays, process pressure protection and cargo overfill protection systems become the last line of defense. Swivel stacks and flexible risers bridge subsea and topsides; their pressure integrity and leak detection performance bound allowable process operating envelopes (Ayanbode, *et al.*, 2019, Onalaja, *et al.*, 2019). Process–electrical dependencies determine whether compressors, injection pumps, and export systems remain stable during load rejections and motor starts; in turn, the fuel gas supply quality and pressure set the stability of prime movers and emissions compliance. Electrical–control interfaces must guarantee deterministic trip propagation: a generator differential trip must shed load, reconfigure tie breakers, maintain essential buses via UPS, and signal the safety instrumented system to drive the plant to a defined safe state. Control–cargo coupling covers emergency shutdown hierarchy across FPSO and shuttle tanker, vapor balance control during offloading, inert gas quality assurance, and interlocks that prevent pump-on with closed valves or over-vacuuming of cargo tanks. Marine–control coupling ensures that watertight doors, HVAC fire dampers, and ventilation shutdowns coordinate with fire zones and deluge, while ballast control sustains trim and deck drainage assumptions used in fire and explosion consequence modeling.

Dependencies should be codified in interface control documents and realized in logic and hardware that respect failure modes. A simple example is anti-surge and flare interaction: when a compressor approaches surge, the antisurge valve must open quickly to a relief path sized to protect the train without over-pressurizing downstream equipment or violating flare tip radiation and noise limits; the flare system must accept the load without flameout or flashback. Another is power management and firewater: load shedding must not isolate firewater pumps unintentionally; essential service buses should be fed from diverse sources with automatic transfer that meets response-time standards for deluge actuation and sprinklers (Amini-Philips, Ibrahim & Eyinade, 2021, Okare, *et al.*, 2021). Cargo offloading provides additional coupling: ESD-1 (process) and ESD-2 (transfer) trip levels must be agreed with the offtake tanker so that a confirmed gas detection above threshold triggers pump trip, valve closure, hawser release logic, and emergency towing arrangement readiness in the right order and within specified latencies.

Safety-critical elements (SCEs) are the engineered and procedural barriers whose performance must be demonstrably adequate. For process containment and pressure protection, these include risers and piping with verified isolation, emergency shutdown valves at module boundaries and on risers with proven closing times and tightness criteria, blowdown valves and segments sized for credible fire and process upsets, pressure safety valves with certified set points and capacity, and the flare and vent systems including knockout drums, seal drums, pilots, ignition, and tip with specified availability and pilot flame monitoring (Filani, Nwokocha & Babatunde, 2019, Kamau, 2018). For ignition control and escalation prevention, SCEs include hazardous area electrical integrity, ventilation and HVAC shutdown with certified fire dampers, passive fire protection thickness and coverage, fire and gas detectors with coverage maps and voting logic, deluge and foam systems with nozzle density and hydraulic performance standards, and portable and fixed monitors. Marine SCEs include the turret bearings and chafe chains with monitoring of wear and lubrication, mooring lines with tension monitoring and redundancy designed for environmental loading envelopes, hull structural scantlings with corrosion protection and inspection regimes, ballast and bilge with cross-flooding and segregation to maintain stability under damage scenarios, and lifesaving appliances with capacity and readiness standards. Electrical SCEs cover emergency generators with start reliability and load acceptance tests, UPS autonomy for essential control and safeguarding, switchgear arc-flash containment, and earthing and bonding integrity across process and marine interfaces (Eyinade, Ezeilo & Ogundeji, 2020, Fasasi, *et al.*, 2020). Cargo SCEs include overfill prevention with independent high-level alarms, gauging systems with redundancy, inert gas or nitrogen generators with oxygen content and dewpoint targets, P/V valves and flame arrestors with flow capacity, hose or loading arm integrity with emergency release couplings, and tandem-offloading emergency shutdown and hawser quick release with response-time standards.

Performance standards translate “adequate” into measurable terms. Each SCE should have a defined function, performance requirement (capacity, set point, response time, availability, demand failure probability), assurance tasks (inspection, test, maintenance), and verification criteria. For example, an ESD valve may require closure to specified leak-tightness within a set number of seconds against full differential pressure with ≥ 99% availability and a proof-test interval that maintains average probability of failure on demand within the allocated SIL. A deluge system may require a density in $l/min/m^2$ achieved within seconds of confirmed detection, with nozzle blockage criteria and pump start reliability verified monthly (Pamela, *et al.*, 2020, Patrick & Samuel, 2020). The flare system may require a pilot availability above a target with auto-ignition probability on demand, a tip radiation contour under wind conditions, and liquid handling capacity that covers maximum credible blowdown while retaining flame stability. Mooring may require line tension monitoring with alarms at threshold load fractions and inspection frequencies tied to fatigue life consumption. Cargo overfill protection may require independent high-high alarms with proof testing at intervals that preserve the target risk of overflow during transfer.

To turn standards into operations, the architecture binds SCE performance to real-time operating envelopes. If two gas detectors are impaired in a module, the allowed hydrocarbon inventory or operating pressure in that module narrows; if deluge pump availability drops below standard, hot work or SIMOPS in adjacent areas is deferred; if mooring line tension rises due to weather, offloading is suspended and separator levels and export rates are adjusted to avoid approaching tank high-high. This dynamic barrier-aware operation requires that the control system ingest barrier health states and apply logic that enforces safe envelopes without relying on operator memory alone. It also requires that impairment registers, isolation certificates, and permit-to-work status are digitally reconciled with control permissions so that bypasses and inhibits are visible and governed (Nwachukwu, Chima & Okolo, 2021, Tewogbade & Bankole, 2021).

Interfaces depend not only on logic but on data and communications integrity. Time synchronization across process control, SIS, F&G, marine automation, and cargo transfer is essential so that event sequencing and trip analysis are accurate. Network segmentation and deterministic gateways preserve the independence of safety layers while allowing the minimum required data exchange; for example, the SIS should accept an “ofloading ESD-2” signal via hardened links but not depend on non-safety networks for core trip logic. Diagnostic coverage and heartbeat supervision between peer systems detect silent failures of interface paths, and simulated proof tests verify end-to-end action within response-time standards (Bankole, *et al*., 2020, Dako, *et al*., 2020).

Finally, architecture must anticipate degraded and emergency modes. Black-start pathways define the order and interlocks for energizing essential buses, restoring cooling and ventilation, and reintroducing process inventory while preventing flammable mixtures. Fire scenarios define how deluge, ventilation shutdown, blowdown, and ESD partition the plant and how cargo and marine systems react, including hawser release and emergency towing engagement. Loss of station-keeping scenarios define how turret lock, swivel disconnection designs (if fitted), and riser emergency release systems behave, and which process states are permissible during controlled drift-off or disconnection. Each of these modes ties back to performance standards for the SCEs involved and to interface latencies and dependencies across the five domains (Atobatele, Hungbo & Adeyemi, 2019, Hungbo & Adeyemi, 2019).

Taken together, this system-of-systems architecture and its explicit interfaces create a platform where safety and reliability are properties of the whole, not just of parts. By specifying how process, marine, electrical, control, and cargo systems see and constrain one another and by defining safety-critical elements with unambiguous performance standards, verification, and live integration into operating envelopes the FPSO gains a coherent nervous system. That nervous system senses barrier health in context, adapts operations when protection is impaired, and orchestrates responses across domains so that credible hazards are contained and uptime is preserved within demonstrable, standards-aligned risk tolerances (Egemba, *et al*., 2020).

2.3 Hazard Identification and Barrier Management

Hazard identification on an FPSO begins long before first oil and continues throughout the asset’s life, because process, marine, electrical, and cargo operations evolve under changing reservoirs, turndown conditions, brownfield tie-ins, and weather. The initial sweep is a HAZID to surface credible threats across the system-of-systems: high-pressure gas and condensate in compact modules; rotating equipment with surge potential; hot surfaces and ignition sources in classified areas; flare system overload or flame instability; cargo overfill and vapor releases during offloading; turret, mooring, and swivel failures that alter loads and leak paths; and impaired evacuation or firewater during severe weather (Amuta, *et al*., 2020, Ezeanochie, Akomolafe & Adeyemi, 2022, Filani, Olajide & Osho, 2020). Outputs are structured as scenarios with initiating causes, immediate consequences, safeguards, and information gaps. These feed targeted HAZOPs at node level separator trains, compression and dehydration, produced-water, fuel gas conditioning, power generation, cargo handling using guidewords to challenge deviations (more/less flow, higher/lower pressure, reverse flow, off-spec composition, external events) and to test whether instrumentation, alarms, interlocks, and procedures prevent drift toward loss of containment or unstable operation.

Bow-tie analysis links the HAZID/HAZOP universe into visual risk stories, with initiating events on the left, consequences on the right, and barriers preventive and mitigative arrayed between. For a compression train, “anti-surge valve fails close” or “rapid inlet slugging” might be initiating events; on the preventive side sit surge detection logic, fast-acting recycle valves, adequate flare capacity, and operator procedures; on the mitigative side lie PSD/ESD actions, blowdown segmentation, fire and gas detection with deluge, and emergency response. For cargo overfill, initiating events include level measurement failure or communication loss with the offtake tanker; preventive barriers are independent high-high alarms, transfer interlocks, and inert gas quality controls; mitigative barriers include automatic ESD-2, emergency release couplings, hawser quick release, and spill response (Giwah, *et al*., 2020, Ibrahim, Amini-Philips & Eyinade, 2020). The power of the bow-tie is its discipline: each barrier must have a named owner, a performance standard (function, capacity, response time, availability), and a proof or assurance task. Degraded barriers are recorded in an impairment register with compensating measures, and the overall residual risk must still sit “as low as reasonably practicable.”

Escalation controls are the connective tissue between barriers, designed to stop small failures from becoming major accidents in confined, congested topsides. Layout-derived passive fire protection on critical steel, blast-resistant partitions, drainage gradients and scuppers to remove flammable liquids from hot areas, ventilation shutdown and fire dampers to prevent smoke and gas spread, and ignition control through certified electrical equipment form the physical backbone (Pamela, *et al*., 2021). Dynamic escalation controls include alarm rationalization to avoid flooding operators during upsets; permissives that prevent starts into unsafe states; and cause-and-effect logic that coordinates ESD, blowdown, deluge, HVAC shutdown, and power management within defined latencies. Marine escalation controls ballast adjustments to preserve deck drainage assumptions, turret locking limits, and weather-based SIMOPS holds ensure process assumptions remain valid as the vessel moves. For flare and relief, escalation controls ensure that anti-surge recycle and blowdown do not exceed tip radiation, noise, or stability limits, with staged blowdown, pilot monitoring, and auto-reignition to avoid flameout.

Safety instrumented functions are the high-integrity automation heart of preventive and mitigative barriers. Each SIF is allocated based on risk reduction targets derived from LOPA or equivalent analysis, with architectural constraints, diagnostics, and proof testing aligned to achieve the required average probability of failure on demand. Typical preventive SIFs include low suction pressure trips to prevent surge, high discharge temperature trips to protect compressors, and high pressure trips with fast-closing ESD valves to prevent vessel rupture (Alao, Nwokocha & Filani, 2021, Elebe, Imediegwu & Filani, 2021). Mitigative SIFs include high-high pressure blowdown, fire detection-initiated ESD and deluge, and gas detection-initiated ventilation shutdown. Independence from the basic process control system is preserved via separate safety PLCs, segregated I/O, and hardened communications for critical cross-system signals such as tanker ESD-2. Time-stamped cause-and-effect matrices specify required action sequences and latencies so that, for example, a confirmed gas detection initiates ventilation shutdown and ESD before ignition sources are isolated and deluge starts, all within performance limits validated during commissioning.

Proof testing is the assurance mechanism that sustains SIF integrity over long intervals and harsh environments. Intervals are set to maintain PFDavg within allocation, considering diagnostic coverage and spurious trip tolerances. Testing is risk-based and staged to avoid excessive simultaneous impairment: partial stroke testing of ESD valves between full functional tests; bypass permits with time-bound compensatory measures; simulation or injected-signal tests for sensors where process interruption is unacceptable; and end-to-end integrated tests that verify logic, actuation, and field device response times, not just component function (Akinlade, Filani & Nwachukwu, 2021, Kufile, *et al*., 2021). Fire and gas systems require coverage-based validation: test plans use detector siting models and environmental conditions to demonstrate that target gas cloud sizes and fire heat release rates are detected within time and voting constraints, and that deluge achieves density and coverage. Test results are captured in structured records tied to the barrier's performance standard, and failures trigger root-cause analysis and updates to maintenance, spares, and design if systematic.

Barrier health metrics convert assurance activity into leading indicators that drive decisions. Each safety-critical element has availability tracked over rolling windows; impairments and bypasses are counted and aged; overdue proof tests are flagged; latent failures discovered on demand are recorded against demand counts to compute observed PFD; and alarm performance is measured as standing alarms, chattering, and time-to-response. For fire and gas, metrics include detector uptime, false alarm rates, coverage deviations due to scaffold/temporary equipment, and deluge nozzle blockage. For flare and blowdown, pilot availability, auto-ignition success rate, and observed tip stability during large releases are trended (Atobatele, Hungbo & Adeyemi, 2019, Hungbo & Adeyemi, 2019). These metrics are contextualized: if two gas detectors in a module are out of service, the operating envelope narrows (inventory or pressure limits), SIMOPS are restricted, and work priorities shift to restoration. If blowdown segment capacity is reduced due to a temporarily isolated valve, hot work permits in the segment are blocked. Barrier health thus becomes a live input to operations, not a quarterly report.

Linking hazards to business trade-offs is essential. The framework integrates barrier metrics with optimization and planning so that, for example, flare minimization strategies respect current pilot reliability and tip stability margins; anti-surge controller aggressiveness is increased if recycle valve proof testing shows healthy response times, but constrained if latencies degrade; offloading proceeds only when cargo overfill protection and inert gas quality meet performance standards, with weather and mooring tensions inside limits (Egemba, *et al*., 2021). LOPA re-runs or Bayesian updates are triggered by new data: if proof tests reveal a higher-than-assumed dangerous undetected failure rate for a sensor type, risk credits are reduced and additional barriers or tighter operating limits are imposed until hardware is corrected. Conversely, demonstrated improvements like upgraded fast-acting ESD valves with verified closure times under full differential pressure can relax compensating measures and recover production within ALARP logic.

Operationalizing barrier management on an FPSO also means embedding it in human systems. Impairment registers are live and integrated with permit-to-work; isolation certificates are digitally reconciled with control system inhibits; and shift handover includes barrier status, not just production. Alarm philosophies are implemented per rationalized lists, with shelving governed and KPIs showing alarm floods eliminated. Training and drills rehearse bow-tie narratives: crews practice the exact sequences for gas detection in a given module, including coordinated ESD, blowdown, ventilation shutdown, deluge, muster, and cargo ESD-2 signaling to the offtake tanker. Post-event reviews real or simulated compare actual instrumented barrier performance (times, actions, success/failure) to standards, updating both procedures and performance requirements where gaps appear (Filani, Olajide & Osho, 2021, Ogayemi, Filani & Osho, 2021).

Finally, hazard identification and barrier management are living processes. Brownfield tie-ins, turndown operation, higher water cut, or hydrogen blending in power generation shift hazard frequencies and consequence pathways; new HAZOPs and bow-ties are raised or updated, and performance standards are revised accordingly. Digital twins help here by translating weak signals EGT spread increases, vibration sidebands, flare composition shifts into early warnings that specific bow-tie barriers are weakening (Aduloju, *et al*., 2021, Erigha, *et al*., 2021, Essien, *et al*., 2021). The result is a disciplined cycle: identify hazards, design and allocate barriers, verify through proof testing, monitor health continuously, adapt operating envelopes to impairments, and learn from data to refine both risk models and barrier designs. In the constrained, coupled environment of an FPSO, that cycle is what turns standards and analyses into day-by-day prevention of escalation and preservation of safe, reliable production.

2.4 Observability and Digital Twin Enablement

Observability on an FPSO must be engineered as a resilient, standards-aware nervous system that fuses heterogeneous signals into reliable, decision-ready knowledge. The data architecture begins with time-synchronized ingestion from process historians, condition-monitoring platforms, and marine instrumentation. From the distributed control and safety systems, the historian captures pressures, temperatures, flows, compositions, valve states, compressor control indices, motor currents, breaker statuses, and alarm/event logs at cadences matched to the physics sub-second for fast loops and trip sequences, one to ten seconds for steady process variables (Bankole & Tewogbade, 2019, Fasasi, *et al*., 2019). Complementing this, condition-monitoring streams provide high-frequency vibration from proximity probes and accelerometers on compressors, generators, and pumps; bearing oil debris counts and spectrometry; thermography snapshots; electrical signature analysis on large motors and variable-speed drives; and exhaust or stack analyzers for combustion quality. Marine sensors complete situational context: motion reference units report heave, pitch, and roll; gyro and DGPS provide heading and position; turret bearing temperatures and swivel leak detection track integrity; mooring line tensions and fatigue counters quantify station-keeping margins; ballast, bilge, and draft sensors report stability; wave radar and anemometers provide metocean forcing; and cargo systems contribute tank levels, temperatures, inert gas oxygen and dewpoint, and offloading telemetry.

Data quality is treated as a first-class safety enabler. Edge adapters enforce schema and units, attach cryptographically verifiable timestamps to a common clock, and buffer losslessly through link outages. Validation pipelines run gross-error detection and reconciliation across mass and energy balances comparing separator inlet/outlet plus flare and shrinkage, or compressor head/flow against map-derived expectations flagging measurements whose combinations violate conservation. Redundancy voting is applied where instrumentation is duplicated or triplicated, and analytical redundancy generates virtual sensors from first principles to detect drift and bias (for example, estimating flare flow from pressure and temperature when ultrasonic meters foul) (Giwah, *et al*., 2020, Ibrahim, Amini-Philips & Eyinade, 2020). Time alignment is meticulous: causality across ESD, blowdown, ventilation shutdown, deluge, and cargo ESD-2 requires millisecond-accurate sequencing to verify barrier performance against cause-and-effect latencies. Quality metrics completeness, accuracy, timeliness, and consistency are computed per tag and per feature; lineage metadata binds every derived signal to its sources and transformations so that incident investigations and model audits can reconstruct evidence. Alarm and event logs are normalized and de-duplicated, with stateful logic to collapse chattering into single episodes and to correlate related events, reducing cognitive load during upsets.

On this foundation, physics-informed digital twins estimate latent states and degradation, providing a coherent picture of risk and reliability. A topsides process twin couples dynamic mass/energy balances across separation, compression, dehydration, produced water treatment, fuel gas conditioning, and flare hydraulics with semi-empirical submodels for combustion and NOx. It ingests vessel motions to adjust level measurement bias due to sloshing, corrects backpressure effects from HRSG or flare headers, and accounts for turndown regimes with changing water cut. A power twin models generator controls, power management, load shedding, UPS autonomy, emergency generation start reliability, and black-start sequences, bridging electrical and process priorities (Eyinade, Ezeilo & Ogundeji, 2021, Fasasi, *et al*., 2021). A marine twin resolves turret friction, mooring tensions and fatigue consumption, hull bending strains, and ballast dynamics under metocean forcing. State estimation uses moving-horizon estimators or Kalman variants to reconcile predictions with sensor streams subject to actuator limits and safeguarding constraints. The resulting health parameters compressor flow-capacity and efficiency scalars, recycle valve stroke time distributions, combustor pattern factor from EGT spreads, flare tip stability margin from composition and wind, inert gas generator effectiveness, firewater pump derating curves, mooring fatigue utilization carry calibrated uncertainties so that downstream decisions employ chance constraints rather than nominal margins.

Hybridization strengthens twins where physics is incomplete or computationally heavy. Gaussian processes and constrained neural networks are embedded as surrogates for submodels such as NOx versus equivalence ratio and residence time, flare stability versus momentum and crosswind, valve stroking versus temperature and service history, or separator carry-under under vessel motions and emulsion quality. Physical constraints monotonicity, conservation, bounds are enforced to keep learning within plausible regimes (Ajayi, Onunka & Azah, 2020, Essien, *et al*., 2020). Residual analytics watch for regime shifts; for example, if compression residuals bloom when heave coincides with high water cut, separator carry-under logic is adapted. Active learning policies selectively request plant tests or higher-rate logging only where uncertainty impinges on barrier integrity or availability, minimizing disruption while sharpening models at decision-critical boundaries.

Anomaly detection spans rules, model-based residuals, and data-driven methods, always contextualized by operating mode and marine state. Rule packs grounded in performance standards flag direct violations: pilot flame out, inert gas oxygen above threshold, UPS autonomy below minimum, mooring tension in alarm band, proof test overdue on a safety function, deluge header pressure low on demand. Model-based detectors raise early warnings when residuals trend: increasing gap between predicted and measured compressor head at constant corrected flow signals fouling or tip clearance growth; EGT asymmetry widening at fixed staging suggests fuel nozzle maldistribution; flare acoustics deviating from expected spectra hint at incipient instability (Fasawe, Akinola & Filani, 2021, Filani, Nwokocha & Alao, 2021). Multivariate detectors PCA, isolation forests, autoencoders operate on feature spaces built from twin outputs rather than raw tags, suppressing false positives from benign noise. Mode awareness matters: baselines differ during start-up, turndown, offloading, or storm ballast; alarms are suppressed or reweighted accordingly so attention focuses on unusual combinations. Event correlation engines stitch anomalies into narratives (gas detection plus ventilation non-closure plus delayed deluge is qualitatively different from any alone), prompting SIMOPS restrictions and immediate verification of cause-and-effect chains.

Uncertainty quantification is produced, propagated, and visualized explicitly. Parameter posteriors from Bayesian filters, prediction intervals from surrogates, and metocean and fuel composition ensembles are fed through to key indicators: probability that NOx compliance stays positive over a planned ramp; likelihood that recycle valve response meets antisurge performance while a blowdown coincides in high wind; confidence that cargo tanks remain below high-high given offtake delays and pump capacity; probability that an ESD valve meets closure time with current partial-stroke history and observed drift (Atobatele, Hungbo & Adeyemi, 2019). Control and optimization use these to tighten constraints where knowledge is weak, making ALARP decisions transparent: if uncertainty around flare stability widens, flare minimization objectives are tempered and blowdown sequencing is staggered; if valve latency uncertainty rises, antisurge aggressiveness is reduced and maintenance priority escalates.

Observability becomes operationally decisive when tied to live barrier management. Barrier health detector uptime, SIF channel diagnostics, ESD valve partial-stroke success, deluge hydraulic tests, flare pilot status, inert gas quality flows into twins and back into operating envelopes. If two gas detectors are impaired in a module, allowable inventory and operating pressure narrow automatically; if firewater pump derating is detected, hot work and SIMOPS are deferred; if mooring fatigue utilization accelerates, offloading windows close and separator levels are managed to avoid tank high-high (Bankole, Nwokediegwu & Okiye, 2021, Okare, *et al*., 2021). Impairment registers and bypass permits are digital and reconciled with control permissions so that inhibited barriers trigger compensatory measures enforced by logic rather than memory. Proof-test results re-estimate dangerous undetected failure rates, preserving the linkage between observed performance and SIL credit; if a sensor family shows higher-than-assumed failure on demand, risk models update and operating limits tighten until hardware is corrected.

Pragmatics matter offshore. Edge compute hosts first-line quality checks, state estimators, and safety-relevant anomaly detection so decisions survive intermittent satellite links. Historian replication to shore is asynchronous with integrity checks; a schema-versioned event bus mediates data exchange among twins, optimization, work management, and dashboards. Cybersecurity is woven in: network segmentation preserves independence of control, SIS, and F&G while allowing minimal, authenticated, signed signals across boundaries; model artifacts are signed and attested; physics-based anomaly detection helps distinguish spoofed signals from genuine upsets. Audit trails bind raw tags to features to twin outputs to recommendations, enabling regulator-ready evidence of performance against standards and rapid post-event reconstruction (Giwah, *et al*., 2020, Ibrahim, Amini-Philips & Eyinade, 2020).

The payoff is realized in concrete use cases. Compression twins estimate surge distance and valve latency distributions, allowing early offline or online washing when heat-rate penalties exceed thresholds and retuning antisurge maps to minimize recycle energy and flare. Flare twins predict stability and radiation under coincident blowdown and antisurge recycle, enabling staggered depressurization that maintains flame while honoring noise and radiation contours. Cargo twins combine gauging, inert gas quality, and offtake telemetry with motion and mooring to estimate overfill and sloshing risk in real time, gating transfer rates and arming ESD-2 sequences. Marine twins compute fatigue utilization and tension alarms under forecasted seas, informing SIMOPS holds and inspection priorities (Akinlade, Filani & Nwachukwu, 2021, Kufile, *et al*., 2021). Across all, the pattern is consistent: trustworthy data, physics fused with learning, anomalies contextualized, uncertainty quantified, and recommendations rendered with the risk and benefit explained in operational language.

In sum, observability and digital twin enablement transform fragmented signals into a coherent, quantified situational awareness directly tied to barriers and reliability. The architecture treats data quality as safety, integrates physics-informed hybrids that learn within physical bounds, and produces uncertainty that is actionable rather than academic. In the constrained, coupled environment of an FPSO, this disciplined nervous system is the foundation for preventing escalation, minimizing deferment, and sustaining safe production turning day-to-day signals into timely, trustworthy decisions (Eyinade, Amini-Philips & Ibrahim, 2020, Tewogbade & Bankole, 2020).

2.5 Risk, Optimization, and Control

Risk, optimization, and control on an FPSO must operate as a single, auditable loop in which quantitative risk models are kept current with evidence, inspection and maintenance are prioritized by expected risk reduction per unit cost and downtime, and closed-loop control delivers safe, efficient operation under tight constraints. Quantitative risk assessment provides the scenario backbone: frequencies for loss-of-containment, escalation, and impairment of critical functions are derived from fault and event trees calibrated with equipment failure data and operating profiles. Layer of protection analysis turns these scenarios into risk reduction targets for instrumented and non-instrumented barriers, allocating integrity to safety instrumented functions, fire and gas detection, deluge, passive fire protection, and procedures (Giwah, *et al*., 2021, Nwokediegwu, Bankole & Okiye, 2021). Because both frequencies and barrier reliabilities are uncertain and non-stationary offshore, the framework implements Bayesian updating: prior distributions for initiating event frequencies and barrier failure probabilities are formed from ISO 14224-structured histories and vendor data, then updated with observed demands, proof-test results, latent failures, near misses, and impairment exposure times. A higher-than-expected dangerous undetected failure rate on a pressure sensor family discovered during testing reduces the posterior credit for that layer; conversely, verified faster-than-assumed ESD valve closure times increase credit. Risk pictures therefore evolve with evidence rather than remaining fixed at project handover.

These living risk models drive risk-based inspection and maintenance prioritization. Each inspection or task borescope of hot section, pressure safety valve overhaul, deluge nozzle cleaning, flare pilot replacement, recycle valve stroking verification, mooring line inspection has a predicted effect on barrier reliability and hence on scenario frequency or consequence. The framework computes the expected risk reduction and couples it with economic effects: avoided deferment, reduced probability of emergency shutdown, improved flare compliance, and heat-rate recovery. A portfolio optimizer then selects the set of tasks that maximizes risk reduction and value under resource, access, and weather constraints (Amini-Philips, Ibrahim & Eyinade, 2020, Essien, *et al*., 2020). Bayesian posteriors ensure that uncertainty is respected: tasks with large potential risk reduction but high uncertainty may be scheduled earlier if the value of information is high (for example, a borescope that could reveal liner distress would sharply alter shutdown plans). Scheduling acknowledges simultaneous operations: if deluge capacity is partially impaired, hot work, intrusive maintenance, or offloading is curtailed until performance is restored; inspection windows are aligned with sea states and crane availability to keep risk ALARP during execution.

Optimization and risk converge in operations through model predictive control with explicit constraint handling. The supervisory MPC solves, at each step, a finite-horizon problem that minimizes an economic objective fuel and flaring costs, emissions deviations, deferment penalties, and wear proxies subject to hard safety and operability constraints derived from the risk model and barrier health. Constraints include surge margin, maximum and spatial gradients of exhaust gas temperature, combustor dynamics limits, pressure and temperature envelopes in hazardous modules, flare tip stability and radiation bounds, deluge and ventilation response-time dependencies, cargo overfill protections, and electrical stability criteria such as minimum spinning reserve for firewater pumps and emergency loads (Eyinade, Ezeilo & Ogundeji, 2021, Tewogbade & Bankole, 2021). Uncertainty from the digital twin and Bayesian risk updates is folded into constraint tightening and chance constraints: if flare pilot reliability is lower than target, the controller reserves additional headroom on actions that could push flare into unstable regimes; if recycle valve stroke time variance grows, antisurge aggressiveness is reduced and operating points are shifted away from the surge line.

Compressor anti-surge control exemplifies the coupling of risk and optimization. Surge is both a mechanical threat and a production trip initiator that can cascade into flaring. The framework uses twin-estimated surge distance, recycle valve latency distributions, and head-flow sensitivities to adapt the antisurge map in real time. MPC coordinates guide vane angle, speed (if variable), fuel flow, and recycle valve position to deliver the demanded compression while maintaining a probabilistic buffer to the surge line. When a coincident flare load is expected due to blowdown, pigging, or separator perturbations the controller schedules modest pre-emptive opening of recycle or a temporary load reduction to avoid exceeding flare radiation and noise constraints, thereby minimizing the probability of tip instability (Bankole, Nwokediegwu & Okiye, 2020, Obuse, *et al*., 2020). If residual analysis indicates growing fouling, the controller gradually increases the surge margin and flags a wash decision for the maintenance optimizer, weighing the expected heat-rate recovery and risk reduction against downtime cost.

Flare minimization is managed as a multi-objective optimization within the MPC horizon. Flaring costs include environmental permits, reputational metrics, and in some jurisdictions direct financial penalties; yet the flare also provides a critical relief path and antisurge sink. The controller therefore minimizes flaring subject to risk-aware stability and capacity constraints: pilots must be lit with high probability, tip momentum and composition must sustain stable combustion under forecast winds, and radiation at defined locations must remain below limits (Adeyemi, *et al*., 2021, Amuta, *et al*., 2021). During upsets, the controller staggers depressurization of blowdown segments to keep total flare load within stable envelopes while preserving vessel integrity and meeting response-time performance standards. In normal operation, the controller actively seeks low-recycle settings by coordinating compressor loading, separator levels, and condenser duties, but it refuses configurations that would leave insufficient flare margin for credible disturbances signaled by the risk model.

Power management is tightly linked to process safety because electrical disturbances can defeat layers of protection. The MPC includes a power coordinator that balances prime mover loading, generator dispatch, and load shedding sequences with process constraints. It enforces spinning reserve sufficient to start firewater pumps and sustain essential control and safeguarding loads under worst-case generator trip scenarios; it avoids operating points that would drive voltage dips capable of tripping gas detection or deluge valves (Aduwo & Nwachukwu, 2019, Erigha, *et al*., 2019). When process optimization asks for rapid compressor ramp-up, the power coordinator sequences motor starts and adjusts turbine fuel schedules to avoid underfrequency events, preferring slightly slower ramps over triggering protective trips. In degraded modes one generator out, UPS autonomy reduced the controller reshapes process targets and SIMOPS permissions to keep risk ALARP, for example by lowering production to reduce compression duty and flare exposure while maintaining barrier availability.

The link back to risk is continuous. MPC decisions are logged with shadow prices (how tight each constraint was) and predicted risk metrics (probability of violating emissions, flare stability, or surge constraints within the horizon). When realized trajectories diverge, Bayesian updates adjust uncertainty sets and constraint tightenings. A spate of high-wind events that stressed flare stability will, via posterior learning, raise the controller's conservatism in similar meteorological regimes (Akinrinoye, *et al*., 2021, Ejike & Abhulimen, 2021). Conversely, demonstrated fast response of a refurbished recycle valve allows the controller to reclaim efficiency by reducing surge distance reserve. The same feedback informs inspection: if observed SIF demands during upsets reveal slower-than-assumed deluge or ventilation shutdown, proof-test intervals shorten or equipment is upgraded; if alarm floods persist despite rationalization, thresholds and voting are revisited.

Maintenance prioritization also feeds from control telemetry. Near misses recycled antisurge events, flare pilot relights, UPS low-autonomy alarms, high EGT pattern factor excursions are treated as Bayesian evidence of proximity to thresholds. The RBI engine converts such evidence into increased inspection priority or immediate corrective work, especially where the value of information is large. For example, repeated small deviations in EGT symmetry at constant staging may trigger fuel nozzle inspection because early correction reduces NOx variability and the probability of lean blowout, thereby reducing both emissions risk and trip risk. Mooring fatigue utilization trending toward limits under forecast sea states prompts inspection or load-management actions that lower tank levels and postpone nonessential SIMOPS (Adeyemi, *et al*., 2021, Amuta, *et al*., 2021).

Operational realism is preserved by embedding human-in-the-loop governance. Operators can move along a preference curve trading small efficiency losses for larger risk reductions during challenging conditions while the controller guarantees feasibility and explains trade-offs. Recommendations are accompanied by rationale tied to barriers: "reduce compressor load 5% for the next ten minutes; flare tip stability probability drops from 0.92 to 0.99 during staggered blowdown; expected deferment is 120 bbl but avoids 1.5× increase in radiation exceedance risk." These explanations build trust and create a culture where ALARP is lived, not asserted (Fasasi, *et al*., 2020, Giwah, *et al*., 2020).

The combined effect is a control room that behaves as a risk-aware optimizer rather than a throughput maximizer with bolt-on trips. Quantitative risk models are alive and responsive to evidence; inspection and maintenance budgets go where they reduce risk and deferment the most; and MPC coordinates compression, flare, and power systems to maintain safe envelopes while extracting efficiency under uncertainty. In the constrained environment of an FPSO, where marine motions, compact layouts, and simultaneous operations compress margins, this integrated loop turns disparate disciplines into a single, repeatable practice that lowers the probability of major accidents, minimizes flaring and trips, and sustains reliable production at the lowest lifecycle cost (Atobatele, *et al*., 2021, Amuta, *et al*., 2021).

2.6 Reliability, Maintenance, and Asset Integrity

Reliability, maintenance, and asset integrity on an FPSO must convert complex, coupled degradation processes into prioritized actions that demonstrably lower risk and deferment at the lowest lifecycle cost. Reliability-centered maintenance provides the organizing logic: define the functions of each system in its operating context, identify functional failures and failure modes, evaluate consequences (safety, environmental, production, and cost), and select preventive or predictive tasks that are technically feasible and worth doing. The context is distinctive offshore restricted access, weather windows, congested modules, and simultaneous operations so task selection must reflect not only physics and economics but also implementability under marine constraints (Akinrinoye, *et al*., 2020, Alao, Nwokocha & Filani, 2020). RCM outputs become both the backbone of the maintenance program and the schema for data capture; failure modes and effects inform which signals the observability stack should monitor and which states the digital twin should estimate to enable on-condition decisions. ISO 14224 closes the loop by standardizing reliability and maintenance data so learning scales across fleets and lifecycles. Equipment taxonomies, failure mode codes, consequence categories, and data quality rules make field histories comparable and analyzable. Every work order, inspection, proof test, and failure is recorded with structured attributes duty, environment, detection method, repair action, downtime, and parts replaced so that proportional hazards and Weibull analyses can infer time-to-failure distributions under the actual load profiles and metocean exposures of the asset (Akintayo, *et al*., 2020, Dako, *et al*., 2020). These analyses populate priors for Bayesian updating in the risk layer and calibrate remaining useful life estimation in the digital twin. Crucially, ISO 14224 discipline promotes feedback: if partial-stroke testing reveals rising closure times on a class of ESD valves, observed dangerous undetected failure rates (and hence PFDavg) are updated, SIL credits are adjusted, proof-test intervals are shortened, and the RCM task set is refreshed turning evidence into changed practice rather than a static database.

Condition-based maintenance operationalizes this learning. Physics-informed indicators compressor flow-capacity and efficiency scalars, recycle valve latency distributions, EGT pattern factors, firewater pump derating, inert gas generator effectiveness, and flare stability margins are tracked continuously. When deviations exceed confidence-bounded thresholds tied to economic and safety outcomes, tasks are generated automatically with ranked priority and the necessary parts, labor, and permits. Remaining useful life prediction transforms state estimates into time-to-limit distributions by fusing physics (damage accumulation for creep, fatigue, corrosion/erosion) with data-driven survival models anchored in ISO 14224 histories. RUL is scenario-aware: it responds to anticipated sea states, planned offloading cadence, turndown regimes with higher water cut, and hydrogen blending for power generation that may alter combustor dynamics and hot-section wear (Atobatele, *et al*., 2019, Filani, Nwokocha & Babatunde, 2019). Confidence bands matter; when uncertainty widens after sensor drift, duty changes, or brownfield tie-ins the framework tightens operating envelopes or brings inspections forward to keep risk ALARP.

Asset integrity extends beyond rotating equipment to corrosion, hull structure, and mooring systems that ultimately define survivability. Corrosion management begins with a risk-based philosophy: identify corrosion circuits, predict damage mechanisms (CO_2/H_2S corrosion, MIC, under-deposit, erosion-corrosion), and set inspection frequencies and methods (UT, guided wave, thermography, CP surveys) according to consequence and degradation rates. The digital twin integrates chemistry, temperature, flow, and water-cut data to estimate local corrosion rates and remaining wall thickness; deviations from expected trends trigger targeted inspection rather than blanket campaigns. For topsides, coating condition, insulation condition (to manage CUI), clamp repairs, and spool replacements are planned by risk and access feasibility; for subsea and risers, CP potential and anode consumption models validated by field measurements steer retrofit anode planning and inspection (Bankole, *et al*., 2019, Nwokediegwu, Bankole & Okiye, 2019). The flare and blowdown network is treated as a special integrity object: thermal cycling, wet service, and intermittent corrosive loading drive bespoke inspection and nozzle/tee reinforcement programs that preserve reliability during emergencies.

Hull integrity is maintained through a structural health program aligned with class and flag requirements. Thickness measurements, close-up inspections in cargo and ballast tanks, coating surveys, and crack detection are prioritized by fatigue hot spots, corrosion environments, and historical damage. The marine twin consumes strain gauge or hull girder response proxies with metocean data to compute fatigue damage accumulation; when utilization accelerates, inspection scope and ballast management are adjusted, and cargo operations are constrained to preserve margins. Mooring integrity is managed through line tension histories, fatigue counters, and periodic visual and NDT inspections at critical sections (Amuta, *et al*., 2021, Hungbo, Adeyemi & Ajayi, 2021). The twin translates wave spectra into dynamic tensions and distributes damage across lines, identifying outliers for early intervention. Emergency release readiness, turret bearing condition, and swivel integrity are included within the same integrity logic, recognizing that process envelopes rest on marine stability.

Maintenance and integrity choices must be articulated in business language and tied to clear KPIs so trade-offs are explicit and progress is measurable. Mean time between failures and mean time to repair quantify reliability and maintainability of critical equipment, while forced outage factor and deferment capture production impact. Probability of failure on demand (PFDavg) for safety instrumented functions measures barrier reliability; observed loss of containment frequency and tiered process safety event counts show how well hazards are being controlled. For power and safeguarding, start reliability for emergency generators and firewater pumps, UPS autonomy, and successful starts-to-attempts are tracked. For emissions and flare, NOx/CO variability at part load and pilot availability and auto-ignition success rates are monitored. Integrity KPIs include corrosion allowance consumption rate by circuit, hull coating breakdown percentage, mooring fatigue utilization, and inspection overdue counts (Ajayi, Onunka & Azah, 2020, Obuse, *et al*., 2020). A small, disciplined KPI set is preferable: site-corrected deferment, MTBF/MTTR for the top ten bad actors, PFDavg against SIL targets, observed LOC frequency against ALARP targets, and backlog age for SCE maintenance provide a concise dashboard. Each KPI is corrected for duty and environment to enable fair benchmarking across units and seasons.

Prioritization folds these KPIs into an expected-value optimizer that respects resource, weather, SIMOPS, and class constraints. The optimizer ranks interventions by risk reduction per unit of downtime and cost, incorporating the value of information where inspection might drastically change the plan. For instance, a borescope of combustor liners is scheduled ahead of a non-critical pump overhaul if pattern factor drift and dynamics amplitude raise the posterior probability of imminent distress; a recycle valve refurbishment outranks cosmetic piping repairs if rising latency threatens antisurge performance and flaring risk (Patrick, *et al*., 2019). Hull coating repair is advanced if predicted coating breakdown would lead to rapid steel loss during the next monsoon season, increasing future downtime. Where windows are tight, mixed-integer planning packs tasks into the same access and isolation, minimizing repeated permit overhead and crane time.

Execution discipline underpins credibility. Impairments and bypasses are tracked in a live register integrated with permit-to-work and the control system; compensating measures lower inventories, reduced pressure, restricted SIMOPS are enforced by logic, not memory. Proof tests and inspections are evidence-producing events: response times, coverage, thicknesses, anode consumption, and defect maps flow back into the twin and ISO 14224 database. After each intervention, pre/post performance is reconciled: heat-rate recovery after compressor washing is compared with the predicted gain; NOx standard deviation after fuel nozzle cleaning is checked; recycle valve stroke time distributions are updated; hull UT results recalibrate corrosion rates (Fasasi, *et al*., 2020, Giwah, *et al*., 2020, Hungbo, Adeyemi & Ajayi, 2020). Where realized benefits diverge, root-cause analysis distinguishes model error, execution variance, or confounders (ambient, duty), and tasks or models are changed accordingly. This learning loop steadily tightens uncertainty and shifts the portfolio toward actions with proven returns.

Human factors and governance keep the program safe and auditable. Decision authority matrices clarify who can accept risk when barriers are impaired; alarm rationalization prevents floods that mask genuine reliability signals; competence management ensures vibration analysts, corrosion engineers, electrical technicians, and control specialists interpret twin outputs consistently. Management of change guards the integrity of models and tasks: new prognostics are validated against golden datasets, shadow run before controlling decisions, and versioned with rollback paths. Cybersecurity ensures maintenance tooling and diagnostic gateways do not introduce vulnerabilities that could defeat layers of protection (Ayanbode, *et al*., 2019, Onalaja, *et al*., 2019). Class engagement is proactive: digital evidence time-aligned events, test records, and integrity trends supports survey credit and focused inspections, reducing disruptive blanket requirements.

The result is a lifecycle discipline in which RCM defines what matters, ISO 14224 ensures that evidence is comparable, CBM and RUL prediction turn condition into actionable foresight, and corrosion/hull/mooring integrity keep the foundation sound. KPIs tie reliability and safety to production, and an optimizer allocates scarce effort to the highest-value tasks. Because evidence recalibrates models and priorities continuously, the program gets sharper with time: fewer surprises, lower deferment, barriers that perform on demand, and an FPSO that sustains safe, reliable production across changing reservoirs and oceans (Amini-Philips, Ibrahim & Eyinade, 2021, Okare, *et al*., 2021).

3. Conclusion

The framework we have outlined connects hazard awareness, observability, optimization, control, and lifecycle stewardship into a single, standards-aligned operating model for FPSO-based energy systems. It treats the FPSO as a tightly coupled system of systems process, marine, electrical, control/safeguarding, and cargo where small degradations can compound into major accidents or prolonged deferment if they are not seen early and acted on coherently. By embedding ISO 31000 risk governance, IEC 61511 functional safety lifecycle, ISO 14224 reliability data discipline, and IMO/Class obligations into everyday decisions, the framework transforms static studies into a living nervous system. Physics-informed/hybrid digital twins turn raw historian, condition-monitoring, and marine sensor streams into calibrated estimates of state, degradation, and uncertainty; bow-tie barriers are not posters but parameterized performance objects with proof testing and live health metrics; model predictive control coordinates compression, flare, and power while respecting chance-constrained safety envelopes; and reliability-centered maintenance, risk-based inspection, and remaining-useful-life forecasts ensure that each intervention buys the most risk and deferment reduction per hour of outage. The expected impact is tangible: fewer trips and safer upsets through anticipatory anti-surge and flare management; lower emissions variability and better permit compliance; measurable reductions in deferment via earlier, targeted maintenance; and an auditable ALARP posture that stands up to regulators, insurers, and boards.

Realizing that impact requires a staged implementation that manages technical and organizational risk. The baseline phase establishes the substrate: reconcile tag semantics and units; harden OT/IT boundaries; instrument critical SCEs with clear performance standards; and validate time alignment and data quality with conservation checks and analytical redundancy. Commission a minimal digital twin for one or two critical trains (e.g., compression and flare) and define a small KPI set site-corrected deferment, start reliability, NOx/CO variation at part load, surge distance margin, flare pilot availability, PFDavg against SIL targets so value can be measured unambiguously. In the pilot phase, run twins in advisory mode, close gaps in sensor coverage, and prove early wins such as antisurge retuning that cuts recycle energy and trips, or blowdown sequencing that maintains flare stability in high wind. Integrate impairment registers with permit-to-work so barrier health directly gates SIMOPS. Begin risk-based inspection on a narrow scope, using ISO 14224 feedback to update priors and shorten proof-test intervals where evidence warrants.

The next step is integration: introduce economic MPC with explicit constraint handling for surge, EGT pattern factors, flare radiation/stability, SCR windows, power reserve for firewater and safety loads, and cargo overfill protections. Keep learning bounded by physics and change control; move from advisory to closed-loop only after shadow runs against “golden” upset scenarios and pass/fail criteria. Broaden the observability stack to cover marine twins for mooring fatigue utilization and hull integrity trends, and connect the maintenance optimizer to enterprise asset management so work orders, parts, and versions are traceable. Deploy barrier-aware operating envelopes so that impaired SCEs automatically narrow process limits rather than relying on memory or ad hoc instructions. Roll out integrated dashboards tuned to roles control room, integrity, electrical, marine, management exposing constraint binders, shadow prices, and uncertainty so trade-offs are transparent.

At fleet scale, standardize models, KPIs, and interfaces so learnings transfer across hulls and duty profiles without copying pitfalls. Federate data where legal and commercial constraints exist, sharing model parameters and posterior summaries rather than raw data. Establish quarterly performance reviews that reconcile predicted versus realized benefits, re-estimate dangerous undetected failure rates from proof-test statistics, refresh RCM task sets, and update bow-tie risk credits. Use benchmarking to surface “bad actors” and replicate high-performing recipes across sister units. Treat the framework as productized capability: versioned models, automated validation suites, cyber-hardened deployment, and rollback plans that protect production while enabling continuous improvement.

Future work should deepen physics where decisions are tight and push learning where data are rich but fragmented. On the modeling side, tighter coupling between combustor kinetics and emissions surrogates for variable gas quality and hydrogen co-firing will shrink uncertainty near lean-blowout and dynamics limits; improved flare stability models that blend tip aerodynamics with acoustic sensing will enhance upset management; and marine–process co-simulation will better represent the effects of motions on separation, carry-under, and level control. On the analytics side, distributionally robust MPC that learns uncertainty sets online can sustain constraint satisfaction under nonstationary fuels and climates, while safe reinforcement learning protected by control barrier certificates can auto-tune weights, horizons, and mode-switch policies without eroding certification posture. Reliability advances include causal inference on intervention logs to distinguish truly effective maintenance from correlated activity, federated learning across fleets to accelerate RUL model improvement without sharing sensitive data, and automated value-of-information engines that propose small tests (e.g., short-stroke valves, targeted borescopes) when uncertainty dominates risk. On the integrity front, integrating corrosion under insulation imaging, guided-wave screening, and CP digital twins will focus inspection where wall loss accelerates, and linking hull strain proxies to ballast and cargo planning will extend fatigue life. Finally, cyber-physical resilience should mature from controls to culture: signed model artifacts and attestation on edge devices, physics-aware intrusion detection that spots spoofed signals, and drills that rehearse digital as well as physical failure modes.

In essence, the path forward is pragmatic: start with clean data and clear KPIs, prove value on a narrow front, integrate what works into safeguarded control and maintenance, and scale through governance and shared learning. When rigor in physics, data quality, and human-in-the-loop oversight is non-negotiable, the framework reliably converts day-to-day signals into fewer surprises, steadier operations, and safer barrels delivering a compounding return in risk reduction, deferment avoidance, and stakeholder confidence over the life of the field.

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