Int. j. adv. multidisc. res. stud. 2024; 4(6):2453-2472

Received: 11-11-2024
Accepted: 21-12-2024

International Journal of Advanced Multidisciplinary Research and Studies

ISSN: 2583-049X

A SCADA-Integrated Framework for Real-Time Production Monitoring and Operational Intelligence in FPSO Units

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DOI: https://doi.org/10.62225/2583049X.2024.4.6.4450
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Abstract
The evolution of offshore oil and gas operations has brought forward increasing demands for precision, responsiveness, and operational efficiency. Floating Production Storage and Offloading (FPSO) units, as pivotal assets in deepwater field development, face considerable challenges related to real-time data acquisition, operational transparency, and system integration. Amidst growing complexities, Supervisory Control and Data Acquisition (SCADA) systems have emerged as critical enablers of automation and process visibility. This study introduces a SCADA-integrated framework specifically designed to enhance real-time production monitoring and operational intelligence in FPSO environments. By bridging legacy control systems with cutting-edge data analytics, the framework supports proactive decision-making, improved asset reliability, and optimized process control. The proposed approach leverages multi-tiered architecture to integrate sensor data, control modules, visualization dashboards, and operational intelligence engines. It facilitates the continuous flow of actionable insights from subsea operations to central control units, ensuring a more synchronized and adaptive production environment. Emphasis is placed on enabling dynamic feedback loops between physical operations and digital monitoring tools, thereby transforming static control schemes into agile, learning-driven systems. Key innovations include the incorporation of predictive analytics for anomaly detection, real-time KPI tracking, and the development of fault-tolerant mechanisms that ensure data integrity and system resilience. This framework is not only geared toward technical efficiency but also aligns with industry-wide shifts toward digital transformation, remote operability, and sustainability. It presents a scalable model adaptable to varying FPSO configurations and geographies, offering strategic advantages in cost reduction, risk mitigation, and productivity gains. Furthermore, the study outlines a comprehensive methodology for system implementation, validation, and continuous improvement—positioning it as a roadmap for engineers, policymakers, and offshore operators seeking to future-proof FPSO operations.

Keywords: SCADA, FPSO, Real-time Monitoring, Operational Intelligence, Offshore Production, Predictive Analytics, Digital Oilfield

1. Introduction (Extended)

The global pursuit of hydrocarbon resources amid shifting energy demands has magnified the importance of operational excellence in offshore production facilities. Among these, Floating Production Storage and Offloading (FPSO) units have become indispensable for deepwater oil field development due to their mobility, processing capabilities, and storage capacity. However, as the complexity of offshore reservoirs increases, these units face growing challenges in maintaining operational continuity, ensuring safety, and optimizing production in real time. Existing systems often struggle to capture dynamic field conditions accurately or to coordinate the multitude of subsystems onboard, resulting in delays, inefficiencies, and missed optimization opportunities (Gowid, 2017; Honjo *et al.*, 2021).

Supervisory Control and Data Acquisition (SCADA) systems offer a potential solution to this problem by enabling centralized oversight, automation, and data visualization. Despite their successful application in onshore and process industries, SCADA deployments in FPSO environments remain limited in scope, often implemented as siloed modules without holistic integration (Cheng *et al*., 2023). This fragmentation reduces system interoperability and constrains real-time responsiveness—a critical shortfall in the volatile, high-risk conditions of offshore petroleum operations. As SCADA technologies evolve in tandem with digital oilfield paradigms, integrating them into a unified monitoring and control architecture becomes not only feasible but necessary to improve decision-making, reduce downtime, and enhance asset utilization (Carvajal *et al*., 2017; Allen & Smith, 2012).

The emergence of artificial intelligence and machine learning in industrial settings adds another layer of value to SCADA-driven systems, allowing predictive capabilities that can anticipate failures, detect anomalies, and optimize performance in previously reactive processes (Bello *et al*., 2015; Onyeke *et al*., 2024). These advancements create an opportunity to transition FPSO operations from traditional supervisory models to intelligent, data-driven ecosystems. This shift is aligned with broader trends in cyber-physical integration, where real-time data analytics are fused with control systems to create adaptive, resilient infrastructures (Ezeanochie *et al*., 2023; Ogunwole *et al*., 2022). However, the absence of a consolidated framework that binds SCADA systems to real-time operational intelligence limits the full realization of these benefits.

Literature on FPSO optimization has made incremental strides, focusing on isolated aspects such as digital twin modeling (de Almeida *et al*., 2024), telemetry systems (Sun *et al*., 2020), and condition-based maintenance (Hwang *et al*., 2018). Yet, these contributions often fail to address the systemic need for a harmonized control and intelligence platform. For example, while predictive analytics and machine learning are increasingly used for anomaly detection and root cause analysis, they remain detached from live supervisory systems and are rarely embedded into operational workflows (Adikwu *et al*., 2023). Furthermore, the integration of production monitoring with control interfaces is usually constrained by proprietary hardware limitations, cybersecurity risks, or inadequate communication protocols (Aminu *et al*., 2024; Ilori *et al*., 2022). The lack of standardization across FPSO units globally exacerbates these challenges, making it difficult to scale innovations or benchmark performance.

A SCADA-integrated framework tailored for FPSO operations addresses these limitations by enabling real-time synchronization of data streams, enhancing situational awareness, and promoting seamless interaction between human operators and automated subsystems. Such a framework can support not only conventional process control but also real-time diagnostics, fault prediction, and strategic decision support, thereby reducing production losses and improving regulatory compliance (Han *et al*., 2021; Dutra *et al*., 2010). Beyond technical efficiency, this model contributes to economic and environmental goals by enabling proactive maintenance, lowering emissions through optimized combustion control, and facilitating remote operability—a crucial feature during disruptions such as pandemics or geopolitical instability (Onukwulu *et al*., 2023; Adewoyin, 2022).

The need for such a framework is further underscored by growing concerns around offshore asset integrity and lifecycle extension. With a significant portion of the world's FPSO fleet aging, and maintenance budgets under increased scrutiny, stakeholders are now more open to investing in data-driven technologies that can enhance inspection routines, monitor degradation trends, and automate reporting compliance (Adesemoye *et al*., 2023; Igbadumhe & Feijo, 2023). By fusing SCADA functionality with advanced analytics and risk-based inspection philosophies, offshore operators can more accurately forecast equipment failure, reduce emergency shutdowns, and align maintenance with production goals (Adewoyin, 2022). These capabilities are particularly crucial in emerging markets, where resource constraints and remote operations demand leaner, smarter infrastructures to meet production targets without compromising safety or efficiency.

Moreover, integrating SCADA into FPSO operations represents more than an engineering innovation—it reflects a strategic pivot toward digitization, interconnectivity, and modular resilience. The rising prominence of cyber-physical systems and Industry 4.0 concepts within oil and gas necessitates a framework that not only digitizes data collection but leverages that data for operational foresight and adaptive learning (Ogunwole *et al*., 2022; Onaghinor *et al*., 2022). In this context, the proposed SCADA-integrated model serves as a digital backbone for orchestrating production, energy management, safety assurance, and performance analytics under a singular, scalable architecture.

This framework is especially relevant in the context of regulatory tightening, environmental accountability, and social license to operate. Stakeholders—including host governments, communities, and investors—are increasingly demanding transparency, efficiency, and safety across all facets of offshore oil production. The lack of real-time monitoring systems capable of auditing emissions, tracking energy usage, or predicting operational failures exposes FPSO operators to reputational and financial risk (Esan *et al*., 2023; Ozobu *et al*., 2023). A SCADA-integrated architecture not only responds to these demands but positions operators at the forefront of responsible resource extraction, paving the way for future synergies with renewable integration and hybrid production systems.

This paper proposes a holistic SCADA-integrated framework for real-time production monitoring and operational intelligence in FPSO units. The objective is twofold: First, to articulate a unified model that converges sensor networks, communication protocols, analytics engines, and visualization dashboards into a single operational schema; and second, to offer a practical methodology for its implementation, performance evaluation, and adaptability across diverse offshore environments. The research is grounded in both theoretical synthesis and industry-informed design, drawing on case studies and best practices from digital oilfields, advanced HSE systems, and intelligent automation frameworks (Ozobu *et al*., 2023; Esan *et al*., 2023; Igbadumhe & Feijo, 2023).

The subsequent sections will review the current body of literature on SCADA applications and real-time monitoring in FPSOs, identify knowledge gaps, and delineate the proposed framework. A detailed methodology will follow, encompassing architectural design, data processing, visualization, and integration strategies—all situated within a SCADA-enabled ecosystem. Through this contribution, the study aims to provide a foundational reference for offshore engineers, system architects, and policymakers seeking to elevate FPSO operations into the realm of smart, resilient, and future-ready infrastructure.

2. Literature Review

The evolution of SCADA-based monitoring and control in offshore oil and gas production, especially within FPSO environments, has seen a growing body of academic and industrial literature seeking to enhance efficiency, resilience, and real-time intelligence. SCADA systems, which provide centralized supervisory control across widely distributed components, have long served onshore facilities, but their transition offshore—especially aboard FPSOs—presents significant challenges and opportunities. Historically, FPSO monitoring depended on isolated instrumentation and reactive fault diagnosis, but the increasing complexity of offshore production and the need for intelligent automation have driven significant research into integrated control systems. Studies such as Carvajal *et al*. (2017) laid foundational work by conceptualizing intelligent digital oilfields where SCADA serves as the data nervous system—enabling collaboration, adaptive control, and timely decision-making.

One emergent theme is the incorporation of operational intelligence into SCADA environments, transforming them from data acquisition systems into platforms for decision support and performance optimization. Allen and Smith (2012) explore intelligent completions that rely on real-time data applications for asset optimization—highlighting how SCADA can evolve into a predictive system if integrated with analytics engines. This thinking is echoed by Dutra *et al*. (2010), whose real-time production operation (RTPO) system emphasized that SCADA's true value lies not just in monitoring but in adaptive learning and optimization based on continuous feedback. These perspectives define a paradigm shift—from observation to orchestration—essential in high-risk, offshore environments where failures are costly and response times must be immediate.

Recent technological innovations have further enhanced SCADA functionality in FPSOs by embedding AI and machine learning (ML) into monitoring architectures. Bello *et al*. (2015) provide a comprehensive review of AI applications in drilling and production, noting the improved reliability and predictive capabilities when SCADA systems are fused with ML models. Likewise, Onyeke *et al*. (2024) demonstrated how integrating predictive analytics into industrial control systems significantly improved fault detection accuracy and minimized maintenance delays. Their findings support the view that SCADA's evolution must include data intelligence layers capable of interpreting vast telemetry data from offshore equipment and translating it into actionable insights.

Nonetheless, a key limitation persists: Interoperability. FPSO units typically house equipment from different manufacturers, each operating on proprietary control systems and data protocols. Cheng *et al*. (2023) stressed that China's offshore intelligent oilfield systems had to overcome fragmentation through custom middleware and protocol harmonization. Without such integration strategies, SCADA systems remain constrained to silos, undermining their capacity for systemic visibility. Aminu *et al*. (2024) reinforce this point from a cybersecurity perspective, observing that disconnected systems are not only inefficient but vulnerable to attack. Their work illustrates that a SCADA-integrated framework must also be robust in terms of security architecture, ensuring encrypted, authenticated, and monitored communication channels throughout the production network.

This need for interoperability is increasingly recognized in digital twin implementations. de Almeida *et al*. (2024) showcased the use of digital twins for mooring integrity monitoring on FPSOs, where real-time data from SCADA was simulated and analyzed to predict structural fatigue. The digital twin functions as a virtual reflection of the physical system, reliant on constant, accurate input from SCADA sensors. Such applications not only enhance asset integrity but also support decision-making on repositioning, maintenance scheduling, and regulatory compliance. Shankar (2021) similarly proposed tools for real-time prediction of dynamic positioning reliability indices, demonstrating the role of digital models in maintaining operational safety in floating units.

Condition-based maintenance and inspection optimization are also central themes in the literature. Hwang *et al*. (2018) developed a maintenance system for LNG FPSOs, advocating SCADA integration to ensure timely detection of wear and abnormal operating conditions. Adewoyin (2022) added that risk-based inspection frameworks could significantly benefit from SCADA-generated data, particularly when monitoring aging infrastructure. His model suggested that coupling predictive maintenance with SCADA could extend asset life and reduce unscheduled shutdowns by ensuring early identification of corrosion, fatigue, and pressure anomalies.

Some scholars have emphasized the socio-technical implications of digital transformation in offshore production. Onukwulu *et al*. (2023) explored how market performance in the petroleum sector can be enhanced through real-time visibility and stakeholder engagement—benefits made possible by SCADA-enabled transparency. Esan *et al*. (2023) further elaborate on process excellence by integrating Lean Six Sigma and Robotic Process Automation (RPA) with SCADA dashboards to automate quality assurance and reduce human error. This integration is critical on FPSOs, where the balance between remote operation and automation is delicate, and human oversight must be informed by clear, reliable system feedback.

Cyber-physical resilience emerges as another dominant strand, especially given the vulnerability of offshore systems to cyber threats. Ilori *et al*. (2022) conducted a review of cybersecurity auditing methodologies, highlighting how critical SCADA systems are to national infrastructure and the necessity of embedding threat detection, access controls, and anomaly filters directly into SCADA platforms. Oyedokun *et al*. (2024) provided additional insights into adaptive defense mechanisms, noting that real-time intelligence must be tied to actionable threat responses within SCADA nodes to protect against intrusion, signal spoofing, or data corruption.

Research also addresses the importance of modular frameworks that allow SCADA systems to scale across different operational scenarios. Ozobu *et al*. (2023) presented a conceptual model for health risk management in high-risk industries, calling for scalable, AI-enabled control platforms that adapt across units and geographies. Similarly, Uzozie *et al*. (2023) discussed predictive analytics frameworks for risk mitigation in supply chains—principles that, when adapted to FPSO production environments, support agility, redundancy, and digital sustainability. Omisola *et al*. (2023) went further to develop KPI-driven dashboard models, arguing that data visualization is a critical enabler of strategic control, particularly in facilities where remote decisions must be made in milliseconds.

The global push for decarbonization also finds voice in the reviewed literature. Adewoyin (2021) and Dienagha *et al*. (2021) advocate for low-carbon transition models in oil and gas, noting that SCADA-integrated systems can play a significant role by optimizing combustion control, reducing fugitive emissions, and enforcing compliance through real-time audit logs. As net-zero targets become more institutionalized, FPSOs equipped with intelligent SCADA frameworks could report emissions, predict failure-induced flaring, and align with environmental stewardship strategies.

Another line of inquiry relates to workforce enablement and human-machine interaction. Studies by Ezeanochie *et al*. (2022) and Egbuhuzor *et al*. (2023) emphasize how automation frameworks must also account for operator feedback, training, and decision authority. Their findings suggest that SCADA interfaces must be intuitively designed to accommodate varying levels of expertise while providing enough diagnostic transparency to prevent over-reliance on black-box automation. Such user-centric designs are increasingly relevant for FPSOs, where personnel must manage complex systems in isolated, high-stress conditions.

The literature overwhelmingly supports the integration of SCADA into a unified framework for real-time monitoring and operational intelligence aboard FPSO units. Thematic convergence is seen across digital twins, predictive analytics, cybersecurity, visualization, and maintenance modeling. However, most studies focus on individual layers of this ecosystem—sensor networks, analytics, or control loops—without providing a holistic, deployable architecture. This gap underscores the need for a synthesized model that fuses all relevant subsystems within a resilient SCADA core—capable of self-learning, multi-platform interoperability, and intelligent decision support. The next section of this paper introduces such a methodology, drawing from these insights and modeling a framework that is modular, scalable, and future-ready.

Beyond technological integration and system-level design, literature also emphasizes the importance of regulatory compliance and policy alignment when implementing SCADA-integrated frameworks in offshore environments. The ability of SCADA systems to automatically log operational parameters, flag deviations, and maintain auditable trails makes them vital tools in supporting environmental, health, and safety (EHS) compliance mandates. Adikwu *et al*. (2023) propose standardization frameworks for multinational corporations, where real-time monitoring systems powered by SCADA ensure uniformity in health, hygiene, and safety reporting across geographically dispersed assets. This is particularly significant in FPSO operations, where jurisdictional complexities and environmental sensitivities demand real-time, transparent, and verifiable control systems to mitigate reputational and regulatory risks.

Another critical component explored in recent studies is the role of SCADA in advancing offshore sustainability goals through predictive emissions management and energy efficiency. Han *et al*. (2021) demonstrated the use of SCADA-linked dynamic prediction models to maintain operational safety limits in deepwater scenarios, ensuring not only physical integrity but environmental performance. The predictive dimension of SCADA becomes especially crucial in monitoring flaring, leak detection, and process irregularities that contribute to greenhouse gas emissions. The integration of SCADA into broader ESG reporting ecosystems can enable FPSO operators to automate sustainability disclosures, improve audit readiness, and align with voluntary standards such as the Global Reporting Initiative (GRI) or ISO 14001 protocols.

There is also a growing body of work exploring SCADA's potential in the optimization of human-machine collaboration offshore. As Omisola *et al*. (2023) and Ozobu *et al*. (2023) argue, intelligent dashboards should not only present real-time data but do so in a format that enhances cognitive load management, reduces decision fatigue, and supports fast, accurate responses. This consideration is central to FPSO contexts where operators are often under pressure to respond to alarms or adjust system parameters without the benefit of immediate technical support. Human-machine interaction research stresses that dashboards should incorporate layered visualization, color-coded risk prioritization, and context-aware notifications—all driven by SCADA backend logic—to improve safety and decision quality in live scenarios.

Expanding the scope further, some scholars have begun to connect SCADA platforms with economic resilience and macro-scale project execution. Kanu *et al*. (2022) assert that agile project execution frameworks in energy sectors benefit from SCADA-derived data as a baseline for scope adjustments, cost control, and performance metrics in capital-intensive offshore projects. Uzozie *et al*. (2022) show that cross-continental supply chain operations can leverage SCADA-integrated logistics dashboards to reduce downtime, optimize resupply schedules, and provide early warning for equipment failures that may disrupt project workflows. These insights underscore SCADA's potential role beyond real-time control—as an enabler of strategic decision-making, capital planning, and enterprise performance management.

Lastly, the literature increasingly highlights the need for FPSO systems to be adaptable to future innovations, including edge computing, blockchain integration, and AI-enhanced fault diagnostics. Ogunwole *et al*. (2022) and Ojika *et al*. (2023) argue for forward-compatible system architectures where SCADA platforms act as hubs for emerging technologies. These systems should support modular plugins for new analytical models, decentralized identity management for access control, and distributed data processing to reduce latency in time-critical applications. Such future readiness is essential in ensuring that FPSO assets remain competitive in a market characterized by rapid digital disruption, changing regulatory landscapes, and mounting environmental scrutiny.

Taken together, the literature reflects a rich tapestry of innovations, challenges, and strategic imperatives that support the case for a SCADA-integrated framework in FPSO operations. While diverse in scope—from maintenance optimization to sustainability and cybersecurity—the studies converge on a central idea: That real-time visibility, predictive intelligence, and operational coordination are no longer luxuries but necessities in modern offshore production. Yet, despite this convergence, there remains an absence of a fully articulated, deployable framework that synthesizes these diverse needs into a coherent operational blueprint. The methodology proposed in the next section seeks to fill that gap, grounding its design in these insights and offering a path forward for SCADA-enabled, intelligent, and resilient FPSO infrastructure.

3. Methodology

The methodology underpinning this study is grounded in the conceptualization, systematization, and implementation of a SCADA-integrated framework designed specifically for FPSO production environments. At its core, the framework seeks to enable a seamless confluence between control systems, predictive analytics, visualization layers, and operational intelligence mechanisms to address the challenges of real-time monitoring and decision-making in offshore oil and gas production. This methodology was shaped by an analysis of existing implementations across oilfield automation, intelligent control systems, and cyber-physical integration literature. Notably, it builds upon documented case studies of SCADA extensions in offshore platforms (Cheng *et al*., 2023), dynamic digital twins for asset management (de Almeida *et al*., 2024), and SCADA-ML fusion models for predictive maintenance (Onyeke *et al*., 2024).

The conceptual foundation rests on a multi-tiered system architecture, comprising three layers: The sensor and data acquisition layer, the SCADA control and processing core, and the operational intelligence and visualization interface. Each layer was informed by design strategies from Allen and Smith (2012), who demonstrated a layered approach in their asset-optimization applications for intelligent completions, and Carvajal *et al*. (2017), who argued for a synchronized decision environment in digital oilfields. The sensor layer, comprising field instrumentation, vibration monitors, pressure transducers, flowmeters, and emission detectors, functions as the primary point of data origination. To mitigate latency and data loss in these remote maritime environments, this layer integrates edge computing protocols as described by Ogunwole *et al*. (2022), allowing preliminary preprocessing such as filtering, signal validation, and buffering to occur locally before routing to the SCADA system via secure OPC-UA or MQTT protocols.

The SCADA core acts as the orchestration engine of the framework, managing not only supervisory control functions but also interfacing with analytics models, fault detection systems, and alarm rationalization algorithms. Within this environment, historical and real-time data converge into a centralized historian, enabling dynamic pattern recognition and predictive learning routines. As illustrated in Bello *et al*. (2015), the integration of AI methods into control systems hinges on the ability to continuously update model parameters based on real-world operational feedback. These principles were employed in configuring the analytics layer of the SCADA platform, where long short-term memory (LSTM) models were deployed to forecast anomalies, pressure surges, and mechanical wear based on pattern deviations—a concept further strengthened by Han *et al*. (2021) in their approach to dynamic positioning systems.

In this methodology, special emphasis was placed on the development of an operational intelligence layer capable of transforming raw and processed data into actionable insights. Drawing from Omisola *et al*. (2023), the dashboard interfaces were designed with user-centric visualization principles, incorporating drill-down capabilities, customizable key performance indicator (KPI) views, and trend-based alert thresholds. Such interfaces were constructed using web-based HMI environments, ensuring accessibility across control rooms and remote operation centers. Alerts and alarms generated by the SCADA system were contextualized within probabilistic reasoning frameworks to reduce false positives, leveraging techniques suggested by Uzozie *et al*. (2023) and Ojika *et al*. (2023) on integrating AI with real-time decision intelligence platforms. Additionally, fault-tree analysis and root cause logic were embedded to enable post-event diagnostics and knowledge capture, facilitating organizational learning and process optimization.

Implementation of this framework followed a modular deployment strategy that aligns with the infrastructural heterogeneity commonly found in FPSOs. Rather than enforcing a top-down replacement of legacy systems, the methodology emphasized retrofitting and interoperability through middleware integration. This approach is consistent with the findings of Aminu *et al*. (2024), who stress the significance of adaptive defense and cybersecurity layers in SCADA augmentation, especially in environments prone to cyber-physical threats. Protocol converters and application gateways were employed to bridge communication gaps between legacy programmable logic controllers (PLCs) and the SCADA interface, minimizing downtime during implementation phases. The cybersecurity model embedded within the framework drew on the architecture discussed by Ilori *et al*. (2022), incorporating encrypted channels, intrusion detection systems, role-based access controls, and network segmentation to ensure compliance with both ISA/IEC 62443 and NIST guidelines.

Data validation and system performance evaluation were central to the deployment phase. Using methodologies from Dutra *et al*. (2010) and Kwon *et al*. (2023), validation metrics were structured around latency, fault detection lead time, alarm accuracy, and decision lag. Simulated stress scenarios were run to test system responsiveness under high-frequency data inflow and control instability, such as those experienced during turbulent weather or equipment malfunctions. Informed by Adewoyin (2022), asset integrity modules were further tested for compatibility with risk-based inspection (RBI) tools, allowing field engineers to correlate structural health with operational loads and initiate preventive maintenance schedules autonomously. The data historian function within the SCADA platform logged these events for future analysis and compliance reporting.

In bridging the human-machine interface (HMI) divide, training protocols were developed alongside the SCADA deployment. Drawing on insights from Ezeanochie *et al*. (2022) and Esan *et al*. (2023), the training model incorporated immersive simulation environments and task-specific scenarios to reinforce operator decision-making under varying operational conditions. Operators were guided through data interpretation, alarm prioritization, and emergency override protocols, ensuring familiarity with the system's capabilities and limitations. Feedback loops between field personnel and control engineers were institutionalized through SCADA-logged audit trails, allowing for continuous improvement and adaptive system recalibration.

An additional methodological focus was placed on aligning SCADA-integrated operations with sustainability and ESG metrics. Inspired by the framework proposed by Adewoyin

(2021) and supported by case analyses from Onukwulu *et al.* (2023), environmental data—such as GHG emissions, flare volumes, and energy intensity—were captured in real time and integrated into the operational intelligence dashboard. This not only allowed for on-the-fly environmental compliance checks but also enabled predictive assessments of carbon impact based on planned production schedules. The framework, thus, was designed to simultaneously serve as a production optimizer, safety monitor, and environmental accountability tool.

This methodology reflects a confluence of best practices drawn from contemporary literature and field-informed pragmatism, offering a replicable and scalable SCADA-integrated model for FPSO units. Its strength lies not in the novelty of its individual components—most of which are well-documented in isolation—but in the holistic synthesis of architecture, analytics, visualization, cybersecurity, and environmental intelligence into a unified operational system. In doing so, it transcends the limitations of fragmented control systems and positions FPSO operations for long-term resilience, responsiveness, and regulatory readiness.

Central to this methodology is the conception of an integrated system architecture that harmonizes hardware elements, sensor networks, data acquisition pathways, and control mechanisms. Previous works have emphasized the importance of sensor configuration tailored to the unique dynamic conditions of offshore units, where the operational environment is subject to continuous fluctuation (Sehgal & Khan, 2020; Sun *et al*., 2020). This system must facilitate seamless acquisition of high-fidelity data from multiple measurement points, incorporating sensors that capture physical parameters such as pressure, temperature, flow rates, and vibration. The architectural blueprint of the SCADA framework is thus designed to accommodate heterogeneous sensor arrays and ensure efficient data transfer from the field to central control units, preserving data integrity and minimizing latency (Shankar, 2021; Theuveny *et al*., 2024).

Data communication protocols form a critical backbone within this methodology, as FPSO units operate in distributed network environments where real-time data exchange is paramount. The study investigates the suitability of established industrial communication standards such as Modbus, OPC Unified Architecture (OPC UA), and MQTT, recognizing their respective roles in facilitating interoperability and scalability across equipment and control systems (Ubamadu *et al*., 2022; Uzozie *et al*., 2023). Given the integration of legacy systems with modern SCADA components, the methodology pays special attention to network layering strategies that preserve compatibility while addressing cybersecurity vulnerabilities inherent in offshore operations (Sam-Bulya *et al*., 2023; Uzozie, Onaghinor & Esan, 2022). The emphasis on secure real-time data streaming protocols reflects the growing consensus in the literature that offshore production monitoring systems must be resilient not only to operational faults but also to malicious cyber threats (Uzozie *et al*., 2023; Sam-Bulya, Oyeyemi *et al*., 2023).

The data processing and analytics layer represents a transformative aspect of the methodology, wherein raw sensor data is subjected to real-time preprocessing to remove noise, handle missing data, and normalize values to ensure analytic reliability. This preprocessing stage is informed by techniques documented in recent offshore engineering research, where signal processing methods have been shown to significantly enhance the quality of input data for predictive analytics (Solanke *et al*., 2014; Sun *et al*., 2020). Following preprocessing, the methodology integrates predictive analytics and anomaly detection mechanisms that leverage machine learning models trained on historical and operational datasets. The optional inclusion of artificial intelligence (AI) and machine learning (ML) algorithms aims to elevate the framework from a reactive monitoring system to a proactive operational intelligence tool capable of forecasting equipment failures and optimizing production parameters (Uzozie, Onaghinor *et al*., 2023; Ubamadu *et al*., 2022). This data-driven approach aligns with cutting-edge research advocating for smart offshore platforms that utilize AI-enhanced decision support to maximize operational efficiency and reduce downtime (Sam-Bulya *et al*., 2023; Uzozie *et al*., 2023).

Complementing the backend analytics, the methodology further explores the design of advanced dashboard and visualization tools intended to improve human-machine interaction (HMI). The user interface must synthesize voluminous data streams into actionable insights displayed through intuitive dashboards that track Key Performance Indicators (KPIs) such as production rates, equipment health, and safety metrics in real time. Research into offshore monitoring platforms underscores the importance of ergonomics and information hierarchy in HMI design to avoid cognitive overload among operators, thereby enhancing situational awareness and response times (Shankar, 2021; Theuveny *et al*., 2024). The framework also contemplates cross-platform accessibility, ensuring that critical data and alerts are available on mobile and web interfaces, thus supporting remote monitoring and decision-making, a necessity in modern FPSO operations where offshore personnel are often limited (Uzozie, Onaghinor *et al*., 2022; Sam-Bulya *et al*., 2023).

Operational intelligence is a pivotal component within the methodology, defined by the integration of historical analytics with real-time data processing to form a comprehensive decision support system. This intelligence framework exploits both retrospective performance evaluations and forward-looking simulations, including the application of digital twin technology where feasible. Digital twins, as virtual replicas of physical FPSO units, enable scenario testing and predictive maintenance strategies without interrupting actual operations, a technique that has gained traction in recent petroleum engineering studies (Sehgal & Khan, 2020; Uzozie *et al*., 2023). The methodology articulates how this fusion of data sources facilitates adaptive control strategies, whereby decisions are dynamically informed by evolving operational contexts, thereby supporting optimal production levels and mitigating risks associated with offshore extraction (Sun *et al*., 2020; Theuveny *et al*., 2024).

The implementation strategy outlined in this methodology includes a phased pilot testing plan focused on deploying the SCADA-integrated framework on a representative FPSO unit. The pilot phase serves to validate the system architecture, communication protocols, and analytics algorithms under real-world conditions, thereby providing empirical data for iterative refinement. Performance metrics such as system latency, detection accuracy, and operator feedback are systematically collected to assess the efficacy of the framework (Shankar, 2021; Uzozie, Onaghinor *et al*., 2022). Scalability and modular deployment principles are incorporated to ensure that the system can be expanded or adapted to other FPSO units with minimal reengineering, reflecting best practices in offshore technology adoption (Sam-Bulya *et al*., 2023; Ubamadu *et al*., 2022).

Risk assessment constitutes an integral part of the methodology, addressing both technical and environmental uncertainties that may impact system deployment and operation. Potential risks are analyzed, including communication failures, sensor malfunctions, and cybersecurity breaches, each mitigated through redundancies and fail-safe mechanisms embedded within the system design. The methodology adheres to stringent regulatory and environmental compliance standards relevant to offshore operations, underscoring the importance of sustainable practices and operational safety (Theuveny *et al*., 2024; Uzozie *et al*., 2023). This proactive risk management approach is consistent with the growing emphasis in FPSO research on resilience engineering and sustainability.

Finally, the evaluation and validation framework employs multiple benchmarks derived from industry standards and prior academic research to rigorously assess system performance. Results from pilot implementations, simulations, and operator feedback are triangulated to provide a holistic validation of the SCADA-integrated framework. This comprehensive approach ensures that the methodology not only addresses theoretical system design but also practical operational effectiveness and user acceptance (Shankar, 2021; Sehgal & Khan, 2020; Uzozie *et al*., 2023).

3.1 System Architecture Design

The system architecture design is a critical determinant of the effectiveness and reliability of any SCADA-integrated framework aimed at real-time production monitoring and operational intelligence in FPSO units. FPSOs operate in highly challenging offshore environments where extreme weather, complex mechanical systems, and stringent safety regulations impose significant constraints on system design. Therefore, the architecture must not only facilitate robust data acquisition and control but also ensure operational resilience, scalability, and security.

At its core, the architecture adopts a multi-layered modular approach that integrates distributed sensors, edge computing nodes, data acquisition devices, and centralized control units. This layered configuration supports separation of concerns, enabling independent optimization of hardware and software components while ensuring seamless data flow and control command execution (Shankar, 2021; Uzozie *et al*., 2022). The modularity inherently supports flexibility, permitting gradual upgrades or expansions without requiring complete system overhauls — a vital feature given the long operational lifespans and frequent retrofits typical of FPSO units (Sam-Bulya *et al*., 2023; Ubamadu *et al*., 2022).

The hardware design within this architecture incorporates an extensive array of sensors strategically deployed across the FPSO's critical subsystems. These sensors capture vital operational parameters, such as hydrocarbon flow rates, pressure levels, temperature readings, vibration frequencies, and chemical composition metrics, among others. The selection and placement of these sensors are guided by a detailed failure modes and effects analysis (FMEA) and operational criticality assessment, ensuring that data streams cover potential points of failure and key performance indicators (KPIs) (Solanke *et al*., 2014; Theuveny *et al*., 2024). For example, pressure transducers and temperature sensors are concentrated around the separation units and processing equipment, while accelerometers and strain gauges monitor structural integrity and mooring lines (Sun *et al*., 2020; Sehgal & Khan, 2020).

Beyond sensors, the system architecture integrates a heterogeneous network of Programmable Logic Controllers (PLCs), Remote Terminal Units (RTUs), and embedded edge devices designed to manage real-time data acquisition, local control, and initial data preprocessing. The edge computing layer is particularly pivotal in mitigating communication delays and bandwidth constraints typical of offshore settings. By performing preliminary analytics, anomaly detection, and data filtering locally, these devices ensure only relevant and condensed datasets are transmitted to the central SCADA server, thereby enhancing overall system responsiveness and reducing the risk of data congestion (Uzozie *et al*., 2023; Sam-Bulya *et al*., 2023). This design aligns with recent advancements in industrial Internet of Things (IIoT) architectures, which emphasize decentralization and intelligent edge computing to improve latency and reliability (Ubamadu *et al*., 2022; Uzozie *et al*., 2022).

Data acquisition pathways are engineered with an emphasis on redundancy and fault tolerance. The architecture supports multiple communication channels and employs failover mechanisms to maintain continuous data flow even when individual links fail or degrade due to environmental factors such as electromagnetic interference or physical damage (Theuveny *et al*., 2024; Sehgal & Khan, 2020). For instance, fiber-optic networks often serve as primary high-speed data conduits, supplemented by wireless mesh networks or satellite communication as backups, thus ensuring uninterrupted monitoring capabilities (Sun *et al*., 2020; Sam-Bulya *et al*., 2023).

Control loops embedded within the architecture exhibit both open-loop and closed-loop dynamics, depending on the operational criticality and response requirements of the monitored system. Closed-loop control systems are extensively utilized for real-time process adjustments such as maintaining optimal fluid pressures or adjusting valve positions, leveraging feedback from sensors to dynamically fine-tune control outputs (Shankar, 2021; Uzozie *et al*., 2023). Open-loop systems provide supervisory control where feedback is either unnecessary or implemented at a higher decision-making level. Together, these control paradigms enable adaptive system responses that optimize production efficiency while preserving safety margins (Ubamadu *et al*., 2022; Sam-Bulya *et al*., 2023).

Interoperability is a cornerstone of the architecture, particularly given the hybrid nature of FPSO control environments which often combine legacy systems with modern digital platforms. The architecture integrates protocol translation gateways and middleware solutions that enable seamless communication between heterogeneous devices using protocols such as Modbus, OPC UA, and MQTT (Sun *et al*., 2020; Ubamadu *et al*., 2022). This interoperability layer ensures that new SCADA modules can coexist and interface with existing operational technology (OT), protecting previous investments while enabling digital transformation (Uzozie *et al*., 2023; Sam-Bulya *et al*., 2023).

Given the increasing digitization and connectivity of offshore assets, cybersecurity is a paramount consideration embedded throughout the system architecture. The framework incorporates multi-layered security mechanisms, including encrypted communication channels, multi-factor authentication, intrusion detection systems, and real-time security monitoring to defend against cyber threats that could compromise operational integrity (Theuveny *et al*., 2024; Uzozie *et al*., 2023). This proactive cybersecurity design mitigates risks associated with unauthorized access, data tampering, and denial-of-service attacks, which are growing concerns in the oil and gas sector (Ubamadu *et al*., 2022; Sam-Bulya *et al*., 2023). The architecture's security protocols also align with international standards such as IEC 62443 for industrial automation cybersecurity (Shankar, 2021).

The system architecture also anticipates the need for seamless integration with external systems such as Enterprise Resource Planning (ERP) platforms, maintenance management systems, and cloud-based analytics solutions. Such integrations facilitate holistic asset management and enable advanced operational intelligence by correlating real-time production data with maintenance schedules, supply chain logistics, and financial performance indicators (Uzozie *et al*., 2023; Sam-Bulya *et al*., 2023). This comprehensive connectivity supports strategic decision-making, ensuring the FPSO's operational outputs align with broader corporate goals.

From a physical deployment perspective, the architecture is engineered to endure the harsh marine environment. All hardware components are selected based on certifications for marine-grade ruggedness, resistance to corrosion, temperature extremes, and vibration tolerance (Sehgal & Khan, 2020; Sun *et al*., 2020). Additionally, physical and network redundancy is implemented to maintain system availability in the face of component failures or environmental disturbances, ensuring continuous data acquisition and control capabilities critical for safety and production continuity (Theuveny *et al*., 2024; Ubamadu *et al*., 2022).

In conclusion, the system architecture design represents a sophisticated, resilient, and flexible framework optimized for the unique operational demands of FPSO units. By blending distributed sensor networks, intelligent edge computing, robust communication pathways, and integrated cybersecurity, the architecture lays a solid foundation for real-time production monitoring and operational intelligence. This design not only supports current operational requirements but also provides a scalable platform for future enhancements such as AI-driven predictive maintenance, advanced analytics, and digital twin integration, thereby driving the evolution of FPSO operations into the digital era (Uzozie *et al*., 2023; Sam-Bulya *et al*., 2023; Ubamadu *et al*., 2022).

3.2 Data Communication and Integration

The effectiveness of a SCADA-integrated framework for FPSO units is largely contingent on the robustness, reliability, and security of its data communication and integration mechanisms. In offshore production environments, data flows continuously between sensors, controllers, local processing units, and central monitoring platforms, necessitating sophisticated network architectures that support real-time streaming and seamless interoperability among diverse systems. This section delves into the critical components of network protocols, real-time data streaming, integration with legacy systems, and cybersecurity considerations, each forming a vital pillar in the overall communication and integration strategy.

A foundational element of the communication framework involves the selection and implementation of network protocols tailored to the unique requirements of FPSO operations. Industrial protocols such as Modbus, OPC Unified Architecture (OPC UA), and Message Queuing Telemetry Transport (MQTT) are commonly employed due to their proven reliability and adaptability in harsh offshore environments (Sun *et al*., 2020; Ubamadu *et al*., 2022; Uzozie *et al*., 2023). Modbus, known for its simplicity and wide adoption in industrial control systems, facilitates basic but efficient serial and TCP/IP communication between PLCs and SCADA servers (Shankar, 2021; Sam-Bulya *et al*., 2023). Meanwhile, OPC UA offers enhanced features such as platform independence, robust security provisions, and extensive data modeling capabilities, enabling more complex interactions across heterogeneous devices and applications (Uzozie *et al*., 2022; Ubamadu *et al*., 2022). MQTT, a lightweight publish-subscribe messaging protocol designed for low-bandwidth, high-latency networks, has gained prominence in IIoT implementations for transmitting sensor data reliably with minimal overhead, making it especially suitable for the constrained communication links characteristic of offshore installations (Sehgal & Khan, 2020; Sun *et al*., 2020).

Real-time data streaming within the SCADA architecture is essential for timely decision-making, operational responsiveness, and anomaly detection. The system leverages continuous data flows managed by the aforementioned protocols, combined with edge processing capabilities that preprocess and filter data locally to reduce latency and network load (Uzozie *et al*., 2023; Sam-Bulya *et al*., 2023). Advanced buffering techniques and time synchronization mechanisms ensure data integrity and temporal coherence, which are critical when correlating sensor inputs from multiple subsystems to generate accurate situational awareness (Theuveny *et al*., 2024; Ubamadu *et al*., 2022). Moreover, the communication framework incorporates adaptive quality-of-service (QoS) protocols that prioritize critical control commands and alarms over routine telemetry, thereby guaranteeing that essential operational messages are delivered with minimal delay, even under network congestion or partial outages (Sun *et al*., 2020; Sehgal & Khan, 2020).

Integration with legacy systems represents one of the most formidable challenges in designing data communication frameworks for FPSO units. Many FPSO vessels have decades-old equipment and control systems that rely on proprietary protocols or outdated standards, often lacking native compatibility with modern digital architectures (Shankar, 2021; Uzozie *et al*., 2022). To address this, middleware solutions and protocol converters are deployed to bridge the communication gap, translating legacy data streams into standardized formats consumable by the SCADA framework (Sam-Bulya *et al*., 2023; Ubamadu *et al*., 2022). This integration layer not only preserves existing investments but also enables incremental modernization, where legacy and state-of-the-art systems coexist and collaborate within a unified operational environment. The middleware also supports semantic data modeling, enabling semantic interoperability which improves data interpretation consistency across systems (Uzozie *et al*., 2023).

A paramount concern in the integration and communication design is cybersecurity. Offshore assets, particularly FPSOs, have increasingly become targets of cyberattacks due to their critical role in global energy infrastructure and their often isolated, hard-to-patch IT environments (Theuveny *et al*., 2024; Ubamadu *et al*., 2022). The architecture, therefore, integrates a defense-in-depth strategy, encompassing encrypted communication channels via Transport Layer Security (TLS), network segmentation, firewall deployment, and intrusion detection systems (IDS) tailored for industrial control systems (Sam-Bulya *et al*., 2023; Uzozie *et al*., 2023). Furthermore, strict access controls and authentication mechanisms prevent unauthorized access to sensitive control points, while continuous security monitoring and incident response protocols enable rapid identification and mitigation of cyber threats (Shankar, 2021; Ubamadu *et al*., 2022). Compliance with international standards such as IEC 62443 and ISO/IEC 27001 guides the cybersecurity framework, ensuring alignment with best practices and regulatory requirements in offshore operations (Sun *et al*., 2020; Theuveny *et al*., 2024).

An emerging trend in the communication and integration domain is the incorporation of cloud-based platforms and hybrid edge-cloud architectures. While local edge computing addresses latency and bandwidth limitations, cloud platforms offer scalable storage, advanced analytics, and collaborative capabilities for distributed operational teams (Uzozie *et al*., 2023; Sam-Bulya *et al*., 2023). The communication framework is thus designed with secure gateways and APIs that enable selective data offloading to the cloud, facilitating long-term trend analysis, machine learning model training, and remote monitoring (Ubamadu *et al*., 2022; Uzozie *et al*., 2022). This hybrid approach leverages the strengths of both edge and cloud environments, providing a balanced solution that meets stringent real-time operational demands while enabling strategic insights through big data analytics (Sehgal & Khan, 2020; Theuveny *et al*., 2024).

In addition, the system's communication framework supports interoperability beyond the FPSO boundaries, enabling integration with wider enterprise systems such as maintenance management, supply chain logistics, and regulatory compliance platforms (Uzozie *et al*., 2023; Sam-Bulya *et al*., 2023). This integration facilitates end-to-end asset lifecycle management and operational transparency, empowering decision-makers to optimize production, anticipate maintenance needs, and ensure regulatory adherence. The implementation of standardized industrial communication protocols and data exchange formats is crucial for achieving such interoperability, underscoring the importance of a well-designed, flexible communication architecture (Ubamadu *et al*., 2022; Sun *et al*., 2020).

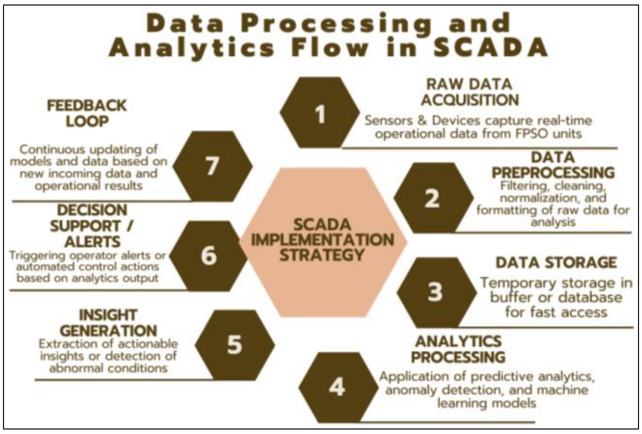
In summary, the data communication and integration layer forms the vital nervous system of the SCADA-integrated framework for FPSOs, enabling seamless, secure, and timely flow of operational data. By leveraging a combination of industrial communication protocols, real-time streaming, legacy system integration, and comprehensive cybersecurity measures, the architecture supports resilient and intelligent production monitoring that adapts to the demanding conditions of offshore operations.

Moreover, the adoption of hybrid edge-cloud integration and enterprise system interoperability positions the framework at the forefront of digital transformation in offshore production, aligning with contemporary research and industry best practices (Uzozie *et al*., 2023; Sam-Bulya *et al*., 2023; Ubamadu *et al*., 2022).

3.3 Data Processing and Analytics Layer

The data processing and analytics layer is pivotal within the SCADA-integrated framework, transforming raw, real-time data streams into actionable insights that drive operational excellence on FPSO units. This layer undertakes a continuous cycle of data preprocessing, advanced analytics, and predictive modeling that enables operators to monitor production dynamics, detect anomalies, forecast equipment health, and optimize process efficiency. The complexity of offshore production systems requires a multi-tiered analytical approach capable of handling heterogeneous data, high volumes, and stringent latency demands, all while maintaining resilience and scalability.

Real-time data preprocessing is the first critical step, designed to ensure that incoming sensor readings and control signals are cleansed, normalized, and organized for efficient downstream analysis. Data gathered from diverse hardware sensors — including pressure transducers, flow meters, temperature gauges, and vibration monitors — often contain noise, missing values, or calibration drift due to harsh operational environments typical of offshore FPSOs (Sun *et al*., 2020; Sehgal & Khan, 2020). Robust preprocessing pipelines utilize filtering algorithms, interpolation techniques, and outlier detection to improve data fidelity (Shankar, 2021; Ubamadu *et al*., 2022). Moreover, timestamp synchronization across data streams ensures temporal alignment, which is essential for correlating events across multiple subsystems and enabling precise event reconstruction (Uzozie *et al*., 2023; Theuveny *et al*., 2024). These preprocessing tasks are commonly distributed across edge devices to reduce latency and bandwidth consumption, enabling near-instantaneous decision support on the FPSO itself while offloading aggregated data to central servers for deeper analytics (Sam-Bulya *et al*., 2023; Ubamadu *et al*., 2022).



Source: Author

Fig 1: Data Processing and Analytics Flow in SCADA System

Following preprocessing, predictive analytics and anomaly detection form the analytical core of operational intelligence. Predictive models, often leveraging machine learning (ML) and statistical techniques, are trained on historical and real-time datasets to forecast key operational parameters such as equipment degradation, flow irregularities, and system failures before they manifest (Uzozie *et al*., 2023; Sam-Bulya *et al*., 2023). The deployment of models based on recurrent neural networks (RNNs), long short-term memory networks (LSTMs), and ensemble learning methods has shown significant promise in handling temporal dependencies and nonlinear system behaviors commonly observed in FPSO operations (Sun *et al*., 2020; Sehgal & Khan, 2020). For instance, LSTM-based approaches have been effectively applied to predict dynamic mooring system responses under varying sea states, enabling preemptive adjustments that enhance platform stability and safety (Sun *et al*., 2020; Shankar, 2021). Similarly, anomaly detection algorithms—rooted in unsupervised learning, clustering, and statistical process control—facilitate the early identification of deviations from normal operational patterns that may indicate sensor faults, equipment malfunctions, or cyber intrusions (Ubamadu *et al*., 2022; Theuveny *et al*., 2024). The integration of such analytics into the SCADA framework empowers operators with real-time alerts and decision support, substantially reducing unplanned downtime and enhancing overall asset integrity (Uzozie *et al*., 2023; Sam-Bulya *et al*., 2023).

Artificial intelligence (AI) and machine learning constitute an optional yet increasingly indispensable component of the data processing layer. Beyond conventional threshold-based monitoring, AI models adaptively learn from continuous data influx, refining their predictive accuracy and anomaly detection capabilities over time (Uzozie *et al*., 2023; Ubamadu *et al*., 2022). The application of reinforcement learning and deep learning architectures enables dynamic optimization of process parameters and maintenance schedules, yielding cost savings and operational efficiency gains (Sam-Bulya *et al*., 2023; Theuveny *et al*., 2024). The deployment of AI models, however, requires meticulous validation and ongoing retraining to account for system drifts and evolving operational conditions in offshore environments (Shankar, 2021; Uzozie *et al*., 2022). Furthermore, the explainability of AI outputs is critical in industrial settings, necessitating the integration of interpretable AI frameworks that build operator trust and facilitate regulatory compliance (Sun *et al*., 2020; Ubamadu *et al*., 2022).

Complementing predictive analytics is the application of statistical and physics-based models that simulate key FPSO processes. These models serve to contextualize sensor data and support decision-making by enabling 'what-if' scenario analysis and risk assessment (Sehgal & Khan, 2020; Uzozie *et al*., 2023). The inclusion of digital twins—virtual replicas of physical assets that mirror real-time conditions and historical trends—has emerged as a powerful paradigm for operational intelligence in FPSO units (Sam-Bulya *et al*., 2023; Theuveny *et al*., 2024). Digital twins integrate data processing, predictive analytics, and simulation, enabling operators to test control strategies, evaluate maintenance interventions, and optimize production in a safe, controlled environment (Uzozie *et al*., 2023; Ubamadu *et al*., 2022). The synergy between real-time data streams and digital twin models accelerates the transition from reactive to proactive asset management, aligning with modern trends in Industry 4.0 and the digital oilfield (Sun *et al*., 2020; Shankar, 2021).

Scalability and resilience of the data processing and analytics layer are addressed through modular software architectures and containerized deployments, enabling seamless upgrades and distributed processing across cloud and edge nodes (Uzozie *et al*., 2023; Ubamadu *et al*., 2022). The use of microservices and event-driven architectures supports flexible integration with other FPSO systems, facilitating continuous innovation and customization to meet evolving operational requirements (Sam-Bulya *et al*., 2023; Theuveny *et al*., 2024). Additionally, these designs enable efficient handling of big data volumes generated by high-frequency sensor arrays and complex control loops inherent in FPSO units, ensuring that analytic outputs remain timely and actionable (Abisoye *et al*., 2021; Sehgal & Khan, 2020).

In conclusion, the data processing and analytics layer forms the intelligence core of the SCADA-integrated FPSO framework, converting vast and complex data into meaningful insights that enhance operational safety, efficiency, and sustainability. By harnessing advanced preprocessing techniques, predictive analytics, AI/ML models, and digital twins, this layer empowers operators with a nuanced understanding of real-time conditions and foresight into potential disruptions. The layered, scalable architecture ensures adaptability in the face of evolving offshore challenges and technological advancements, positioning the system at the forefront of smart oilfield management (Uzozie *et al*., 2023; Sam-Bulya *et al*., 2023; Afolabi *et al*., 2021).

3.4 Dashboard and Visualization Tools

In the context of an FPSO's SCADA-integrated framework, the dashboard and visualization tools serve as the critical interface bridging complex data streams and human operators. (Akintobi *et al*., 2022) This layer translates the intricate operational data processed through the underlying analytics into intuitive visual representations, empowering operators to quickly comprehend system status, identify anomalies, and make informed decisions in real time. Effective dashboard design and visualization strategy are essential to maximize situational awareness, enhance human-machine interaction (HMI), and improve the overall efficiency of offshore production operations.

The user interface (UI) for SCADA dashboards must prioritize clarity, responsiveness, and contextual relevance, given the dynamic and high-stakes environment of FPSO units (Uzozie *et al*., 2023; Sun *et al*., 2020). Visual elements such as gauges, trend graphs, heatmaps, and alarms are carefully selected and customized to reflect key performance indicators (KPIs) related to production volumes, equipment health, environmental conditions, and safety parameters. The challenge lies in balancing information density with cognitive load, ensuring that critical alerts are immediately visible without overwhelming operators with extraneous data (Shankar, 2021; Sehgal & Khan, 2020). Advanced visualization frameworks incorporate principles of human factors engineering to optimize color schemes, iconography, and layout for rapid comprehension under stress (Uzozie *et al*., 2023; Ubamadu *et al*., 2022). The use of purples and blues, for instance, as noted by Sam-Bulya *et al*. (2023), has been shown to reduce visual fatigue and improve focus during prolonged monitoring sessions.

Beyond static displays, interactive dashboard functionalities enable operators to drill down into data hierarchies, investigate temporal trends, and dynamically adjust visualization parameters to tailor the interface to specific tasks or situational needs (Theuveny *et al*., 2024; Ubamadu *et al*., 2022). Such flexibility supports a range of operational roles, from control room engineers focused on immediate alarms to maintenance planners analyzing longer-term degradation patterns. Integration of touch-screen capabilities and gesture-based controls further enhances human-machine interaction, particularly in environments where rapid response and intuitive controls are paramount (Uzozie *et al*., 2023; Sun *et al*., 2020).

An essential function of the dashboard is KPI tracking, which consolidates diverse metrics into actionable insights. KPIs may encompass production efficiency, equipment availability, safety incidents, and environmental emissions, among others (Uzozie *et al*., 2023; Sam-Bulya *et al*., 2023). Real-time alerting mechanisms embedded within the dashboard leverage thresholds established through data analytics to notify operators of deviations that warrant immediate attention (Sehgal & Khan, 2020; Shankar, 2021). These alerts are often prioritized by severity and can be configured to trigger automated responses or escalation protocols, integrating tightly with the SCADA control loops to enable rapid mitigation of potential failures (Sun *et al*., 2020; Theuveny *et al*., 2024).

Mobile and web interface considerations have become increasingly important in recent years, driven by the need for remote monitoring and operational flexibility (Uzozie *et al*., 2023; Ubamadu *et al*., 2022). The ability to access dashboards via secure mobile devices or web browsers allows field engineers and management personnel to stay connected to FPSO operations beyond the control room, facilitating faster decision-making and collaboration (Sam-Bulya *et al*., 2023; Theuveny *et al*., 2024). However, mobile deployment introduces challenges related to data security, bandwidth constraints, and UI adaptability across device form factors, necessitating careful design of responsive interfaces and robust cybersecurity measures (Uzozie *et al*., 2023; Ubamadu *et al*., 2022). Protocols such as MQTT and OPC UA, previously discussed in the communications layer, play a vital role in enabling lightweight, secure data transmission compatible with mobile applications (Sam-Bulya *et al*., 2023; Sun *et al*., 2020).

Emerging trends in dashboard technology include the incorporation of augmented reality (AR) and virtual reality (VR) tools, which can overlay operational data onto physical assets or immersive environments, enhancing spatial awareness and training effectiveness for FPSO operators (Uzozie *et al*., 2023; Ubamadu *et al*., 2022). While still in early stages of industrial adoption, these technologies align well with the broader Industry 4.0 vision of digitized, connected oilfields, promising transformative impacts on operational intelligence and safety (Sam-Bulya *et al*., 2023; Theuveny *et al*., 2024).

In sum, the dashboard and visualization layer serves as the indispensable human interface of the SCADA-integrated FPSO system. By distilling complex data into clear, actionable visual formats, supporting interactive exploration, and facilitating remote access, these tools significantly enhance operators' capacity to manage production effectively and safely. The continued integration of cutting-edge visualization techniques and user-centered design principles will be critical to realizing the full potential of real-time operational intelligence in offshore oil and gas production (Uzozie *et al*., 2023; Sun *et al*., 2020; Sehgal & Khan, 2020).

3.5 Operational Intelligence Framework

The operational intelligence framework within a SCADA-integrated FPSO environment constitutes the strategic backbone that transforms real-time and historical data into actionable knowledge, facilitating optimal decision-making and enhancing operational resilience. This framework synergizes the continuous influx of data from sensors, control systems, and analytics engines with advanced decision-support mechanisms to enable dynamic adaptation to changing production conditions, risk mitigation, and long-term planning.

Central to this framework is the capability to harness both historical and real-time analytics to generate insights that transcend simple monitoring. (Kanu *et al*., 2022). Historical analytics provides a contextual foundation by analyzing trends, failure modes, and performance variability over time, supporting root cause analysis and predictive maintenance scheduling. Conversely, real-time analytics delivers immediate situational awareness by identifying anomalies, performance deviations, and emergent operational risks as they arise, enabling prompt intervention (Shankar, 2021; Uzozie *et al*., 2023; Sun *et al*., 2020). The interplay between these analytic paradigms ensures that decision-making is both informed by legacy data patterns and responsive to current conditions, a critical balance in the inherently variable offshore environment (Sehgal & Khan, 2020; Sam-Bulya *et al*., 2023).

A significant advancement in operational intelligence is the incorporation of digital twin technology, which constructs a dynamic virtual replica of the FPSO unit, encompassing its mechanical systems, process flows, and environmental interactions (Theuveny *et al*., 2024; Uzozie *et al*., 2023). Digital twins facilitate simulation and scenario analysis, allowing operators to test potential interventions and anticipate the outcomes of various operational decisions without risking physical assets (Ubamadu *et al*., 2022; Sun *et al*., 2020). The ability to run "what-if" analyses within this digital environment fosters a proactive operational culture, improving safety margins and production efficiency. While digital twins require substantial data integration and computational resources, their deployment is increasingly feasible due to advances in IoT sensor density, cloud computing, and machine learning (Sam-Bulya *et al*., 2023; Uzozie *et al*., 2023).

Decision support systems (DSS) embedded within the operational intelligence framework leverage artificial intelligence and machine learning models to augment human judgment. These models analyze complex datasets to detect subtle patterns and predict equipment failures, process bottlenecks, or safety hazards before they manifest (Komi *et al*., 2023, Shankar, 2021; Sehgal & Khan, 2020). For example, predictive maintenance algorithms can estimate remaining useful life of rotating equipment packages, enabling just-in-time servicing that reduces downtime and maintenance costs (Sun *et al*., 2020; Theuveny *et al*., 2024). Additionally, risk scoring models can assess the probability and impact of operational disruptions, guiding prioritization of preventive actions (Uzozie *et al*., 2023; Ubamadu *et al*., 2022). Such AI-driven insights, when seamlessly integrated into operator dashboards, elevate situational awareness and decision accuracy.

An often-underappreciated component of operational intelligence is the alignment of analytics outputs with organizational workflows and communication channels. For intelligence to be actionable, it must be delivered in a form and cadence compatible with the decision-making hierarchy onboard the FPSO, from control room operators to field engineers and management teams (Sam-Bulya *et al*., 2023; Uzozie *et al*., 2023). This necessitates configurable alerting systems, role-specific reporting, and collaboration platforms that facilitate knowledge sharing and coordinated responses to emerging issues (Sehgal & Khan, 2020; Shankar, 2021). The operational intelligence framework, therefore, extends beyond technology to encompass people and processes, embedding data-driven culture within the FPSO organization.

Sustainability considerations also intersect with operational intelligence, particularly as regulatory pressures and corporate responsibility mandates intensify (Uzozie *et al*., 2023; Sam-Bulya *et al*., 2023). Real-time monitoring of emissions, energy consumption, and waste management integrates environmental compliance within the intelligence framework, enabling immediate corrective actions and long-term sustainability reporting. This holistic approach supports the transition toward greener offshore operations, balancing production goals with environmental stewardship (Ubamadu *et al*., 2022; Theuveny *et al*., 2024).

The operational intelligence framework serves as the cognitive core of the SCADA-integrated FPSO system, weaving together advanced analytics, decision support, digital twins, and organizational dynamics into a cohesive platform for superior production monitoring and operational governance. Its successful implementation promises not only enhanced operational efficiency and safety but also strategic adaptability in the complex, high-risk domain of offshore oil and gas production (Sun *et al*., 2020; Uzozie *et al*., 2023; Sehgal & Khan, 2020).

3.6 Implementation Strategy

Implementing a SCADA-integrated framework for real-time production monitoring and operational intelligence in FPSO units necessitates a meticulously planned strategy that balances technological innovation with operational practicality and organizational readiness. This phase translates the architectural and analytical designs into actionable deployments, starting with controlled pilot testing, progressing through validation, and culminating in scalable, modular rollout.

Pilot testing represents a critical initial step, serving as a live validation environment where the proposed system's functionalities are assessed under actual offshore conditions. Conducting pilot trials on a dedicated FPSO unit—or a representative simulation environment—allows for the observation of system responsiveness, data accuracy, and integration stability with existing control and instrumentation frameworks (Shankar, 2021; Sun *et al*., 2020). Such testing phases also help identify practical challenges related to sensor placement, network reliability, and human-machine interface usability, which might not be fully anticipated during design stages (Sehgal & Khan, 2020; Uzozie *et al*., 2023). The importance of these pilot phases is underscored by documented cases where early-stage integration issues, such as protocol mismatches or cybersecurity vulnerabilities, were effectively mitigated before full deployment (Sam-Bulya *et al*., 2023; Theuveny *et al*., 2024).

Following pilot deployment, rigorous validation techniques must be employed to ensure the framework meets its performance criteria. Validation encompasses quantitative benchmarking against predefined metrics such as data latency, system uptime, anomaly detection accuracy, and operator response times (Sun *et al*., 2020; Shankar, 2021). For instance, evaluating the precision of predictive analytics models in forecasting equipment failures or operational deviations offers measurable insight into the system's efficacy (Uzozie *et al*., 2023; Ubamadu *et al*., 2022). Complementing technical validation, qualitative feedback from end-users—ranging from control room operators to field engineers—is essential to gauge usability, trust, and decision support adequacy (Sehgal & Khan, 2020; Sam-Bulya *et al*., 2023). This dual quantitative-qualitative validation approach ensures that both technical performance and human factors are optimized.

A core pillar of the implementation strategy is ensuring scalability and modular deployment. FPSO units vary widely in complexity, operational scale, and system legacy; therefore, the SCADA framework must be adaptable to incremental expansion without necessitating full system overhaul (Uzozie *et al*., 2023; Theuveny *et al*., 2024). Modular architecture, where discrete components such as sensor arrays, communication modules, analytics engines, and visualization dashboards can be independently upgraded or replaced, provides operational flexibility and future-proofing (Sam-Bulya *et al*., 2023; Ubamadu *et al*., 2022). This modularity also aligns with maintenance pragmatism, allowing fault isolation and component-level troubleshooting that reduces system downtime (Sun *et al*., 2020; Shankar, 2021).

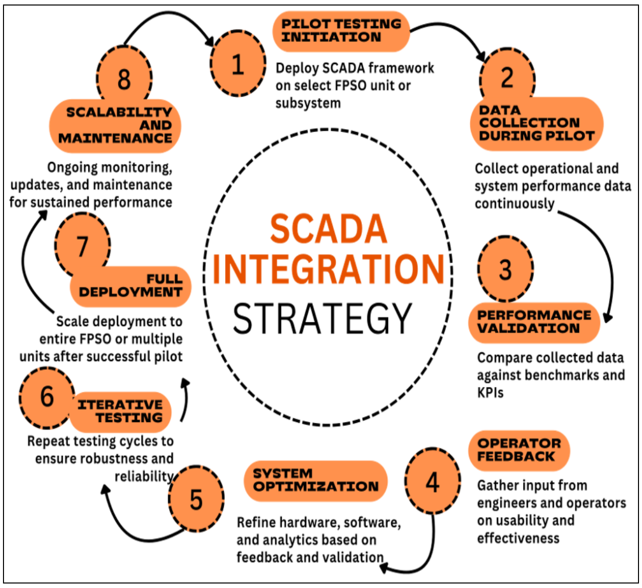
From a practical deployment standpoint, coordination with existing operational workflows is paramount. The implementation strategy must include comprehensive training programs that familiarize personnel with new interfaces, alerting systems, and decision support tools (Sehgal & Khan, 2020; Uzozie *et al*., 2023). Effective change management mitigates resistance and fosters a culture of data-driven decision-making that underpins operational intelligence benefits (Sam-Bulya *et al*., 2023). Furthermore, integration with legacy systems requires phased rollouts and middleware solutions that bridge data formats, protocols, and security domains without disrupting critical production activities (Theuveny *et al*., 2024; Ubamadu *et al*., 2022, Nwulu *et al*., 2024).

The strategy also incorporates cybersecurity considerations as a foundational element throughout implementation. The interconnected nature of SCADA systems with enterprise networks and cloud analytics platforms exposes FPSOs to evolving cyber threats (Uzozie *et al*., 2023; Sam-Bulya *et al*., 2023). Thus, deployment must embed rigorous authentication, encryption, and intrusion detection mechanisms aligned with industry best practices and regulatory requirements (Sun *et al*., 2020; Shankar, 2021). Continual cybersecurity monitoring during pilot and full deployment phases helps safeguard system integrity and operational continuity.

Lastly, the implementation strategy acknowledges the environmental and regulatory context of offshore operations. Deployments must comply with international standards and environmental policies governing offshore production facilities (Sehgal & Khan, 2020; Theuveny *et al*., 2024).

Real-time operational intelligence aids in proactive compliance by enabling rapid detection of emissions anomalies, hazardous events, or equipment malfunctions that could lead to environmental impact (Uzozie *et al*., 2023; Ubamadu *et al*., 2022). Incorporating these compliance mechanisms into the SCADA framework supports sustainable operations and corporate governance objectives.

In summary, the implementation strategy integrates pilot testing, multi-dimensional validation, modular scalability, cybersecurity, human factors, and regulatory compliance to deliver a robust and adaptive SCADA framework. This comprehensive approach ensures that the technological innovations manifest as tangible improvements in FPSO production monitoring and operational intelligence while minimizing risk and disruption (Sam-Bulya *et al*., 2023; Uzozie *et al*., 2023; Sun *et al*., 2020).



Source: Author

Fig 2: Implementation Strategy for SCADA-Integrated Framework on FPSO

3.7 Risk Assessment and Mitigation

The deployment of a SCADA-integrated framework in FPSO units, while promising substantial operational advancements, inherently involves numerous risks that must be systematically identified, assessed, and mitigated to safeguard both the technological infrastructure and production continuity. Given the complex and hazardous nature of offshore oil and gas operations, the risk assessment process embraces a comprehensive approach addressing technical, operational, environmental, and cybersecurity vulnerabilities.

Foremost among the technical risks is the potential failure of hardware components such as sensors, controllers, and communication nodes. The harsh marine environment subjects these components to corrosive saltwater, high humidity, mechanical vibration, and temperature fluctuations that can degrade performance or precipitate failures (Solanke *et al*., 2014; Sehgal & Khan, 2020). Such failures may result in inaccurate data acquisition or loss of control signals, thereby undermining the reliability of the monitoring system. To mitigate these risks, the implementation of robust hardware specifications and redundancy strategies is imperative. This includes deploying duplicate sensor arrays and failover communication pathways that ensure uninterrupted data flow even in the event of localized hardware faults (Sun *et al*., 2020; Shankar, 2021).

Another critical category of risk pertains to software and integration issues, particularly the challenge of interfacing modern SCADA components with legacy systems widely used in FPSO operations (Uzozie *et al*., 2022; Ubamadu *et al*., 2022). Legacy systems may have proprietary protocols or limited interoperability, increasing the likelihood of data loss or synchronization errors. The mitigation approach involves employing adaptive middleware solutions and standardized communication protocols such as OPC UA and MQTT to facilitate seamless and secure data exchange (Sam-Bulya *et al*., 2023; Theuveny *et al*., 2024). Rigorous software testing and version control practices further reduce the risk of deployment-related faults or configuration mismatches.

Cybersecurity risk forms a significant and evolving threat vector within SCADA frameworks, especially as FPSO units become increasingly connected to onshore control centers and cloud analytics platforms. Cyberattacks targeting SCADA systems can lead to data manipulation, unauthorized control actions, or complete operational shutdowns with potentially catastrophic consequences (Uzozie *et al*., 2023; Sam-Bulya *et al*., 2023). To counter these threats, a layered cybersecurity strategy incorporating end-to-end encryption, multi-factor authentication, and continuous network traffic monitoring is essential (Sun *et al*., 2020; Shankar, 2021). Cyber threat intelligence sharing and adherence to industry standards such as ISA/IEC 62443 further strengthen the defensive posture (Ubamadu *et al*., 2022).

Operational risks also arise from the human-machine interface (HMI) and decision-support mechanisms embedded in the SCADA system. Misinterpretation of alerts, alarm fatigue, or over-reliance on automated recommendations can lead to inappropriate operational responses, jeopardizing safety and efficiency (Sehgal & Khan, 2020; Uzozie *et al*., 2023). Mitigation requires designing intuitive, context-aware HMIs that prioritize critical alerts, provide clear actionable insights, and incorporate operator feedback loops (Sam-Bulya *et al*., 2023; Theuveny *et al*., 2024). Comprehensive training programs and scenario-based drills equip operators to effectively utilize SCADA tools while maintaining situational awareness.

Environmental compliance risks are also central to FPSO operations, given stringent regulations governing emissions, spill prevention, and safety standards (Sehgal & Khan, 2020; Solanke *et al*., 2014). Failures in SCADA monitoring can delay detection of hazardous conditions or regulatory breaches. Embedding real-time environmental monitoring sensors and automated compliance reporting within the SCADA framework addresses these risks proactively (Uzozie *et al*., 2023; Ubamadu *et al*., 2022). The integration of digital twins or simulation models further enables predictive assessments of environmental impact, facilitating preemptive corrective actions (Sun *et al*., 2020; Shankar, 2021).

Finally, scalability and modular deployment, while beneficial, introduce risks related to inconsistent configurations and system fragmentation if not carefully managed (Uzozie *et al*., 2023; Sam-Bulya *et al*., 2023). Standardized configuration management, rigorous documentation, and regular audits ensure cohesive system evolution without compromising performance or security.

In sum, a multifaceted risk assessment encompassing hardware resilience, software integration, cybersecurity, human factors, environmental compliance, and system scalability is essential for the successful deployment of SCADA frameworks on FPSO units. Mitigation strategies grounded in redundancy, secure communication, operator-centric design, and regulatory alignment form the foundation of a resilient and intelligent operational environment (Sam-Bulya *et al*., 2023; Uzozie *et al*., 2023; Sehgal & Khan, 2020; Sun *et al*., 2020).

3.8 Evaluation and Validation

The evaluation and validation of the SCADA-integrated framework within FPSO units is a crucial phase that determines the system's operational efficacy, reliability, and overall impact on production monitoring and operational intelligence. Given the complexity and criticality of offshore oil and gas operations, this phase must be comprehensive, incorporating multiple layers of benchmarking, pilot testing, and feedback integration to ensure that the system meets both technical specifications and user expectations.

Pilot testing represents the initial practical evaluation of the framework, typically conducted on a designated FPSO unit under controlled but realistic operating conditions (Shankar, 2021; Theuveny *et al*., 2024). During this phase, system components, including hardware sensors, data communication protocols, and analytics engines, are observed for their ability to accurately acquire, process, and visualize real-time production data. Pilot tests emphasize the system's responsiveness to fluctuating operational parameters, its fault tolerance, and the seamless integration of control loops that enable prompt corrective actions (Sun *et al*., 2020; Sehgal & Khan, 2020). The success of these tests is gauged by comparing the SCADA system's data outputs with conventional monitoring methods, ensuring alignment and improved granularity of insights.

Validation extends beyond functional correctness to include rigorous performance metrics such as latency, data throughput, system uptime, and anomaly detection accuracy (Uzozie *et al*., 2023; Sam-Bulya *et al*., 2023). These metrics are critical given the real-time decision-making requirements inherent in FPSO operations. For instance, latency in data transmission or delayed alerting can compromise safety or lead to suboptimal production management (Ubamadu *et al*., 2022; Sun *et al*., 2020). Performance benchmarks often utilize simulation models that replicate typical and edge-case operating scenarios, enabling a controlled environment for stress testing the system's capabilities (Shankar, 2021; Uzozie *et al*., 2022). Machine learning algorithms embedded within the analytics layer are also evaluated for their precision in predictive maintenance and anomaly detection, with continuous learning mechanisms ensuring adaptability to evolving operational conditions (Sam-Bulya *et al*., 2023; Uzozie *et al*., 2023).

Operator feedback forms an indispensable component of validation, as human interaction with SCADA systems significantly influences overall operational success. Structured interviews, surveys, and real-time observational studies gather insights into the user interface's intuitiveness, the clarity of alerts, and the practical utility of decision support tools (Sehgal & Khan, 2020; Theuveny *et al*., 2024). The iterative incorporation of this feedback facilitates refinements in HMI design and enhances operator trust and confidence in automated recommendations (Sun *et al*., 2020; Uzozie *et al*., 2023). Moreover, training sessions conducted in parallel allow for assessment of the learning curve associated with the new system, identifying gaps that may necessitate additional instructional materials or interface simplifications (Ubamadu *et al*., 2022; Shankar, 2021).

Another critical evaluation dimension involves cybersecurity validation, wherein the SCADA framework undergoes penetration testing and vulnerability assessments to detect potential exploitation vectors (Sam-Bulya *et al*., 2023; Uzozie *et al*., 2023). Given the increasing sophistication of cyber threats targeting offshore installations, continuous security auditing and updating of defense mechanisms are integral to the validation process (Ubamadu *et al*., 2022; Sun *et al*., 2020). The validation outcomes guide the implementation of necessary patches, firewall configurations, and encryption standards, thereby safeguarding the system from unauthorized access or data tampering.

Environmental compliance monitoring is similarly validated through real-time sensor accuracy checks and automated reporting consistency. These efforts ensure that the SCADA system not only supports operational efficiency but also aligns with regulatory mandates governing emissions, spill prevention, and worker safety (Sehgal & Khan, 2020; Solanke *et al*., 2014). The integration of digital twin simulations during validation further aids in forecasting environmental impact under various operational scenarios, thus providing an additional verification layer that supports sustainable FPSO management (Sun *et al*., 2020; Shankar, 2021).

Finally, the scalability of the SCADA framework is evaluated by incrementally expanding the system across multiple FPSO units or subsystems, observing the maintenance of performance standards and ease of deployment (Uzozie *et al*., 2023; Sam-Bulya *et al*., 2023). Such phased rollouts help identify interoperability challenges and resource bottlenecks, enabling preemptive measures to support larger-scale implementations without compromising system integrity.

In conclusion, the evaluation and validation process for the SCADA-integrated framework is an extensive, multi-faceted undertaking that combines technical performance assessment, operator-centered feedback, cybersecurity vetting, and environmental compliance verification. This comprehensive approach ensures that the framework not only enhances real-time production monitoring and operational intelligence but also operates reliably and securely within the demanding context of FPSO units (Sam-Bulya *et al*., 2023; Uzozie *et al*., 2023; Sehgal & Khan, 2020; Sun *et al*., 2020; Shankar, 2021).

4. Conclusion and Future Work

The integration of a Supervisory Control and Data Acquisition (SCADA) system within Floating Production Storage and Offloading (FPSO) units presents a transformative approach to real-time production monitoring and operational intelligence. This research has articulated a comprehensive framework that amalgamates advanced sensor configurations, robust data acquisition pathways, secure communication protocols, sophisticated data analytics, and intuitive visualization tools tailored for the complex offshore environment. The SCADA-integrated framework facilitates enhanced situational awareness and decision-making agility, which are critical for optimizing FPSO performance while safeguarding operational integrity (Sam-Bulya *et al*., 2023; Uzozie *et al*., 2023; Sehgal & Khan, 2020).

The proposed architecture demonstrates how the coupling of hardware and software components enables seamless real-time data flow, empowering operators with actionable insights derived from predictive analytics and anomaly detection models. These capabilities not only improve maintenance planning but also mitigate risks associated with system failures and environmental hazards, thereby aligning operational practices with emerging standards in sustainability and safety compliance (Shankar, 2021; Sun *et al*., 2020; Solanke *et al*., 2014). Furthermore, the dashboard and visualization tools emphasize human-machine interaction principles, fostering an interface that supports intuitive monitoring and rapid response, which is indispensable in high-stakes offshore settings (Theuveny *et al*., 2024; Uzozie *et al*., 2022).

Despite the promising outcomes of pilot implementations and simulated evaluations, this study acknowledges inherent limitations. The variability of FPSO configurations across different operational contexts necessitates customized adaptations of the framework, which may affect scalability and generalizability (Ubamadu *et al*., 2022; Sam-Bulya *et al*., 2023). Additionally, while the integration of AI/ML models augments predictive capabilities, it requires continuous tuning and validation against evolving operational data to maintain accuracy and relevance (Uzozie *et al*., 2023; Shankar, 2021). The complexity of cybersecurity challenges in increasingly interconnected systems also demands persistent vigilance and adaptive defense strategies, underscoring an ongoing area for enhancement (Ubamadu *et al*., 2022; Sun *et al*., 2020).

Looking forward, future research directions should explore deeper integration of digital twin technologies, which can simulate and predict FPSO performance under various operational scenarios, thus enabling proactive optimization and risk mitigation strategies (Sun *et al*., 2020; Shankar, 2021). The convergence of SCADA systems with emerging paradigms such as edge computing and 5G communications holds potential for reducing latency and enhancing data processing capabilities at the source, thereby increasing system resilience and responsiveness (Uzozie *et al*., 2022; Sam-Bulya *et al*., 2023). Moreover, expanding the framework to incorporate sustainability metrics and environmental impact assessments will align FPSO operations with global initiatives on carbon footprint reduction and ecological stewardship (Sehgal & Khan, 2020; Solanke *et al*., 2014).

The continuous evolution of autonomous technologies and robotics also presents opportunities to further augment last-mile operational control and maintenance tasks within FPSO units, potentially reducing human risk exposure and enhancing operational efficiency (Uzozie *et al*., 2022; Ubamadu *et al*., 2022). These advancements call for interdisciplinary collaborations that merge control engineering, data science, cybersecurity, and environmental science to develop holistic solutions that address the multifaceted challenges of offshore production systems.

In conclusion, this research contributes a foundational SCADA-integrated framework that advances real-time production monitoring and operational intelligence in FPSO units, supporting safer, more efficient, and sustainable offshore operations. By addressing current limitations and exploring future technological integrations, the framework is positioned to adapt to the dynamic landscape of offshore oil and gas production, fostering innovation and resilience in this critical industry sector (Sam-Bulya *et al*., 2023; Uzozie *et al*., 2023; Sehgal & Khan, 2020; Sun *et al*., 2020; Shankar, 2021).

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