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An Alarm Management and Decision Support Framework for Control Room Operations in Deepwater Production Vessels

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Abstract : Deepwater production vessels (DPVs), such as Floating Production Storage and Offloading units (FPSOs), operate under complex, high-risk conditions where effective control room operations are critical to safety and production continuity. A significant challenge in these environments is managing the overwhelming volume of alarms generated by distributed control systems (DCS), particularly during process upsets. Excessive alarm rates, poor prioritization, and nuisance alarms often lead to cognitive overload, alarm fatigue, and delayed or incorrect operator response. This presents a comprehensive Alarm Management and Decision Support Framework tailored to the operational realities of deepwater production environments. The proposed framework integrates best practices from ISA-18.2 and EEMUA 191 with intelligent technologies to enhance situational awareness and support real-time decision-making. Key components include an advanced alarm rationalization engine, dynamic thresholding based on process context, flood suppression strategies, and a decision support layer powered by machine learning. The framework interfaces directly with existing DCS and SCADA systems, leveraging real-time data, historical patterns, and operator inputs to improve alarm fidelity and reduce cognitive burden. A simulation case study involving a high-pressure riser failure scenario demonstrates the framework's effectiveness in reducing alarm volume, enhancing response time, and improving operator confidence. Performance metrics indicate substantial improvements in alarm relevance, system stability, and decision accuracy compared to traditional alarm handling methods. This work underscores the strategic importance of integrating intelligent alarm management with operator support tools in complex offshore systems. By aligning human factors engineering with real-time analytics and adaptive learning, the proposed framework contributes to safer and more resilient deepwater production operations. Future research will explore deeper integration with digital twin environments, adaptive alarm configurations, and advanced human-in-the-loop systems to further optimize offshore control room performance.

Keywords: Alarm management, Decision support framework, Control room operations, Deepwater production vessels

1.0 Introduction

Deepwater Production Vessels (DPVs) play a pivotal role in modern offshore oil and gas extraction. These floating platforms, which include Floating Production Storage and Offloading units (FPSOs), Tension Leg Platforms (TLPs), and Spars, enable hydrocarbon production in water depths exceeding 1,000 meters. Designed for long-term deployment in remote, hostile marine environments, DPVs must function autonomously with minimal downtime (ADIKWU *et al.*, 2023; Nwulu *et al.*, 2023). Their complex process infrastructure integrates subsea production systems, topside processing modules, and storage units, all of which are coordinated through a centralized control room (Okolo *et al.*, 2023; Nwulu *et al.*, 2023). Within this context, the control room becomes the nerve center, where operators are tasked with monitoring and responding to dynamic process variables, equipment states, and environmental inputs (Elete *et al.*, 2023; Nwulu *et al.*, 2023).

However, the operational complexity of DPVs is exacerbated by the challenges of alarm management. Control systems such as Distributed Control Systems (DCS) and Supervisory Control and Data Acquisition (SCADA) continuously generate alarms to indicate deviations or abnormal conditions (Elete *et al.*, 2023; Ogunwole *et al.*, 2023). In practice, these systems often produce excessive numbers of alarms—many of which are low-priority, spurious, or duplicated resulting in alarm floods during process upsets. Operators are frequently overwhelmed by this deluge of information, leading to alarm fatigue, missed critical alerts, and delayed response times (Ogunwole *et al.*, 2023; Ojika *et al.*, 2023). Moreover, the static configuration of most alarm systems fails to account for changing operational contexts, such as startup, shutdown, or maintenance modes, further eroding alarm system effectiveness (Ogunwole *et al.*, 2023; Egbuhuzor *et al.*, 2023).

In high-risk offshore environments, decision-making under pressure is both frequent and essential. Operators must distinguish between consequential and inconsequential alarms within seconds, often under conditions of extreme stress and uncertainty (Okolo *et al.*, 2023; Elete *et al.*, 2023). Without robust decision support mechanisms, the likelihood of human error increases significantly. There is a clear need for systems that can assist operators in prioritizing alarms, diagnosing root causes, and recommending responsive actions in real time (Nwulu *et al.*, 2023; Oyeyipo *et al.*, 2023).

To address these issues, this proposes an integrated Alarm Management and Decision Support Framework specifically designed for DPV control room operations. The framework combines industry-standard alarm management practices (such as those outlined in ISA-18.2 and EEMUA 191) with advanced technologies, including real-time data analytics, machine learning, and adaptive interface design. The aim is to rationalize and prioritize alarms based on operational context, suppress nuisance alerts, and provide actionable insights through decision support tools. These tools will guide operators through structured playbooks and dynamic risk assessments, improving response time, situational awareness, and overall system safety. By incorporating intelligent processing of alarm data and integrating seamlessly with existing control infrastructures, the proposed framework offers a pathway to more resilient and efficient offshore production management (Okolo *et al.*, 2023; Kokogho *et al.*, 2023).

2.0 METHODOLOGY

The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology was employed to systematically review the literature and inform the development of the proposed Alarm Management and Decision Support Framework for control room operations in Deepwater Production Vessels (DPVs). The review process began with a comprehensive search strategy using multiple databases, including IEEE Xplore, ScienceDirect, SpringerLink, and Scopus, focusing on studies published between 2010 and 2024. Search terms included combinations of keywords such as “alarm management,” “offshore control systems,” “decision support systems,” “deepwater production,” “FPSO,” “human-machine interface,” and “real-time analytics.”

A total of 528 records were identified through database searching, and an additional 17 articles were sourced through reference mining and grey literature. After removing duplicates, 442 records remained. Titles and abstracts were screened for relevance, resulting in 165 full-text articles assessed for eligibility. Studies were included based on the following criteria: (1) focus on alarm systems or decision support in offshore or process industry settings, (2) inclusion of human factors or operator-centric insights, (3) discussion of control system integration, and (4) relevance to high-risk environments. Exclusion criteria included non-English language publications, purely theoretical works without implementation relevance, and papers lacking empirical or simulated validation.

After applying inclusion and exclusion criteria, 67 studies were selected for qualitative synthesis. The selected literature covered key thematic areas including dynamic alarm prioritization, contextual suppression strategies, cognitive ergonomics in control rooms, integration of machine learning in alarm filtering, and real-time operator support frameworks. The synthesized findings informed the architectural design and functional specifications of the proposed framework.

The systematic review ensures that the framework is grounded in evidence-based practices and contemporary technological advancements. It also identifies gaps in current alarm management and decision support systems, which the proposed solution aims to address through intelligent integration and operator-centered design.

2.1 Background and Motivation

Alarm systems are critical safety and operational components in industrial control environments, particularly in offshore production vessels such as Floating Production Storage and Offloading units (FPSOs), Tension Leg Platforms (TLPs), and Spars (Ojika *et al.*, 2023; Uzozie *et al.*, 2023). These vessels operate under complex, hazardous, and highly dynamic conditions that demand continuous vigilance by control room operators. To manage this complexity, alarm management practices have evolved significantly, guided by standards and best practices such as ISA-18.2 and EEMUA 191.

ISA-18.2 provides a lifecycle model for alarm system management, encompassing stages such as philosophy development, identification, rationalization, implementation, operation, and maintenance. The standard emphasizes the need for clear alarm objectives, prioritization, and periodic performance assessment. Similarly, the EEMUA 191 guideline focuses on human factors and usability in alarm systems, recommending limits on alarm rates, the use of suppression techniques, and the implementation of advanced alarm handling tools.

Both standards advocate for systematic alarm rationalization to reduce nuisance alarms and ensure that operators receive timely, relevant information for decision-making.

Despite the availability of these frameworks, many offshore alarm systems still suffer from serious deficiencies. Chief among these is the reliance on static threshold settings, which fail to account for the dynamic operational contexts in which alarms are generated. For example, alarm thresholds that are suitable during normal operation may become irrelevant or misleading during shutdowns, startups, or maintenance. As a result, control rooms often experience alarm floods periods when the number of alarms significantly exceeds manageable levels especially during abnormal conditions (Adesemoye *et al.*, 2023; Onukwulu *et al.*, 2023). These floods can overwhelm operators, obscure critical alarms, and increase the likelihood of operational errors.

A second critical limitation lies in the lack of contextual awareness in existing alarm systems. Traditional architectures treat alarms as isolated events without considering the interdependencies between process variables, equipment conditions, and operational modes. This myopic view reduces the alarm system's ability to filter noise, escalate priority based on evolving risk, or provide predictive guidance. Additionally, most systems operate without integration into higher-level analytics or machine learning models that could help classify and predict the progression of abnormal situations (Ogunwole *et al.*, 2022; Ojika *et al.*, 2022).

The human factors dimension further underscores the urgency of alarm system improvement. Cognitive overload is a well-documented risk in control rooms, particularly during high-stress events when multiple alarms are triggered simultaneously. Alarm fatigue the desensitization to alarms due to their sheer volume and frequent irrelevance has been implicated in numerous industrial incidents. Operators may become conditioned to ignore alarms, delay responses, or fail to distinguish critical warnings from minor deviations. Such behaviors, although understandable, erode the reliability of alarm systems as safety mechanisms and increase the risk of incidents (Fiemotongha *et al.*, 2023; Onukwulu *et al.*, 2023).

Given these limitations, there is a strong motivation to evolve from traditional, threshold-based alarm systems toward intelligent, adaptive frameworks that support operators through real-time decision aids. A successful approach must not only conform to established standards like ISA-18.2 and EEMUA 191 but also incorporate modern technologies such as machine learning, contextual analytics, and human-centered interface design (Ojika *et al.*, 2022; Uzozie *et al.*, 2022). The objective is to reduce the cognitive burden on operators while increasing system responsiveness, reliability, and predictive capability.

This aims to address these challenges by proposing an Alarm Management and Decision Support Framework tailored to the unique demands of deepwater production vessels. The framework leverages the structure provided by industry standards while embedding adaptive, context-aware technologies that improve alarm fidelity and enhance human decision-making. Through the integration of data-driven analytics, intelligent suppression mechanisms, and decision support tools, the framework seeks to transform alarm handling from a reactive, overloaded task into a proactive, informed process that contributes to operational safety and efficiency (Ozobu *et al.*, 2023; Ogunnowo *et al.*, 2023).

2.2 System Architecture

The proposed Alarm Management and Decision Support Framework for control room operations in deepwater production vessels is designed to address the high alarm burden, contextual limitations, and decision-making challenges prevalent in current offshore operations. This system architecture is modular, scalable, and built for integration with existing control environments such as Distributed Control Systems (DCS) and Supervisory Control and Data Acquisition (SCADA) platforms. Its goal is to enhance real-time operational awareness and reduce alarm fatigue through intelligent processing and actionable insights (Ojika *et al.*, 2023; Uzozie *et al.*, 2023).

At a high level, the framework comprises three primary architectural layers: Data Ingestion, Alarm Processing, and Decision Support. Each layer is logically decoupled to allow flexibility, maintainability, and ease of integration with diverse technological ecosystems found in offshore platforms.

The Data Ingestion Layer acts as the foundational tier. It captures, consolidates, and normalizes real-time and historical data from various sources. These include field instrumentation (pressure, temperature, flow, vibration sensors), DCS/SCADA signals, alarm/event logs, and human-machine interface (HMI) interactions (Omisola *et al.*, 2020; ADEWOYIN *et al.*, 2020). Edge computing nodes, located on the vessel, pre-process data to reduce latency and bandwidth consumption before streaming it to central repositories or cloud-based analytics platforms. This layer also includes data quality checks, timestamp synchronization, and tagging for traceability—ensuring that subsequent analytics are based on reliable and context-rich data (Uzozie *et al.*, 2022; Onaghinor *et al.*, 2022).

The Alarm Processing Layer is the system's core. This layer performs alarm filtering, prioritization, rationalization, and contextual analysis. Advanced algorithms including rule-based logic, state-based suppression mechanisms, and machine learning classifiers evaluate alarms in real time. By incorporating operational context such as startup or shutdown modes, process interlocks, and concurrent maintenance activities, the system suppresses irrelevant or low-priority alarms while elevating those critical to safety or operational continuity (Komi *et al.*, 2023; Uzozie *et al.*, 2023). A key innovation in this layer is dynamic alarm thresholding, which adjusts alarm setpoints based on time-varying process conditions rather than static configurations.

The Decision Support Layer transforms processed alarms and raw data into operator-centric insights. It features predictive analytics, visual dashboards, and recommendation engines. Real-time alarm trends are displayed alongside risk scores, root cause hypotheses, and suggested mitigation actions. Integration with digital procedures enables the system to prompt step-by-step operational guidance based on detected anomalies (Esan *et al.*, 2022; Adedokun *et al.*, 2022). Decision support is further enhanced by learning algorithms that adapt recommendations based on operator feedback and post-event evaluations, thereby forming a closed-loop learning environment. This layer is also responsible for interfacing with operator consoles through custom HMI visualizations, mobile alerts, and audio-visual cues designed to direct attention efficiently during critical events.

Integration Points are a vital aspect of the architecture. The framework is built to seamlessly interoperate with existing DCS and SCADA systems through standard industrial protocols such as OPC UA, Modbus, and MQTT. It accesses historical data archives to train predictive models and evaluate long-term alarm performance trends. The system also interacts with HMI platforms to overlay contextual information, support user-configurable alarm views, and present adaptive alerts based on operator workload or shift patterns

(Uzozie *et al.*, 2023; Omisola *et al.*, 2023). Cybersecurity and redundancy measures are embedded at all levels to ensure availability and integrity in offshore, bandwidth-constrained environments.

The proposed system architecture offers a robust and extensible solution for managing alarm complexity and supporting operator decisions in offshore production vessels (Komi *et al.*, 2022). By combining layered modularity with deep integration capabilities, it addresses both the technical and human-centric challenges of modern alarm management. This architecture forms the foundation for resilient, adaptive, and intelligent control room operations in high-risk offshore environments.

2.3 Alarm Management Module

The Alarm Management Module is a central component of the proposed framework for enhancing control room operations in deepwater production vessels (DPVs). Its primary function is to reduce alarm overload, improve signal-to-noise ratio, and support timely and accurate operator responses as shown in figure 1. This module leverages industry best practices such as ISA-18.2 and EEMUA 191, while introducing advanced capabilities including contextual awareness, dynamic thresholding, and intelligent flood management (Shiyanbola *et al.*, 2023; Omisola *et al.*, 2023). The goal is to ensure that alarms serve their intended purpose: alerting operators only to abnormal situations that require timely attention and action.

Alarm rationalization is the foundation of effective alarm management. It involves systematically reviewing each alarm to ensure its necessity, proper classification, and appropriate prioritization. Alarms are classified based on consequence severity, urgency, and operational context—typically as high, medium, or low priority. The rationalization process also involves identifying alarm suppression logic for specific operational conditions such as equipment downtime, manual overrides, or planned maintenance. Suppression can be either static, based on predefined equipment states, or dynamic, determined by real-time data inputs and logic. The module supports state-based alarm management, in which alarms are automatically enabled or disabled depending on the current operating mode (e.g., startup, normal, shutdown), thereby reducing unnecessary alerts and improving relevance.

Traditional alarm systems rely on fixed thresholds that fail to account for normal process variability during transient states. Dynamic alarm thresholding addresses this limitation by adjusting setpoints based on real-time operating conditions. For example, pressure fluctuations during startup are expected and should not trigger alarms unless they exceed statistically or physically defined limits. This capability is enabled by integrating process historians, machine learning models, and operational context indicators (e.g., control valve positions, pump status). By learning patterns from historical and real-time data, the system establishes context-aware limits that reduce false positives and improve operator trust. Dynamic thresholding also allows for the customization of alarm behavior per process unit, accommodating differing stability characteristics across the production system (Esan *et al.*, 2023; Chianumba *et al.*, 2023).

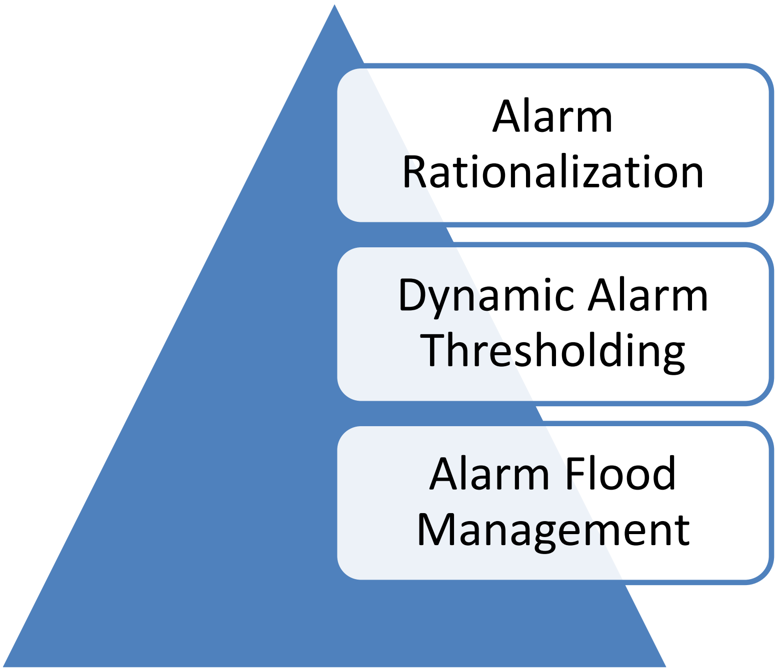

Figure 1: Alarm Management Module

Alarm floods—where a large number of alarms are generated in a short period—are a major challenge in offshore control environments. They can overwhelm operators and obscure the root cause of incidents. The Alarm Management Module incorporates advanced flood detection algorithms, which identify abnormal surges in alarm activity by analyzing alarm frequency, clustering, and co-occurrence patterns. Once detected, flood mitigation strategies are activated, such as suppression groups and alarm shelving. Suppression groups are predefined sets of alarms linked to common causes; for instance, if a power failure is detected, associated downstream alarms (e.g., pump trips, low flows) are automatically suppressed, assuming they stem from the primary event. Shelving allows non-critical alarms to be temporarily hidden based on operator discretion or automated rules, freeing cognitive bandwidth for critical decision-making.

Further, the module includes a real-time alarm analytics dashboard that displays metrics such as alarm rate, standing alarms, and top frequent alarms. This supports alarm performance auditing and continuous improvement. The dashboard also provides operator feedback loops, enabling operators to rate alarm usefulness or request reclassification, fostering an adaptive and human-centric alarm environment.

The Alarm Management Module transforms traditional alarm handling into a dynamic, intelligent, and context-aware process. By combining rationalization, dynamic thresholding, and flood control within a unified architecture, it addresses the core pain points in offshore alarm management namely alarm fatigue, response delays, and safety risks. This not only enhances control room effectiveness but also supports compliance with regulatory standards and promotes a proactive safety culture in deepwater operations (Okolo *et al.*, 2023; ADIKWU *et al.*, 2023).

2.4 Decision Support Engine

The Decision Support Engine (DSE) serves as the cognitive core of the proposed alarm management and decision framework for deepwater production vessel (DPV) control rooms. Its role is to transform raw alarms and process data into actionable insights by providing operators with real-time situational awareness, intelligent guidance, and adaptive learning capabilities. In high-risk, high-complexity offshore environments characterized by rapid process fluctuations, tightly coupled systems, and limited intervention time the DSE enhances decision-making accuracy, speed, and consistency (Onyeke *et al.*, 2023; Ozobu *et al.*, 2023).

At the heart of the DSE is a real-time situational awareness system that integrates live data streams from distributed control systems (DCS), supervisory control and data acquisition (SCADA) systems, process historians, and safety instrumentation. This component employs event correlation and pattern recognition algorithms to detect anomalies, identify cascading failures, and contextualize events. By analyzing temporal and spatial relationships among alarms and operational parameters, the DSE builds a dynamic model of the plant state, highlighting root causes and distinguishing primary alarms from consequential ones. This capability significantly reduces diagnostic time and supports timely, informed interventions.

Once the situation is understood, the DSE provides operator guidance tools that translate complex alarm data into intuitive, prioritized recommendations. These include automated playbooks, which are predefined or dynamically generated sets of corrective actions based on current scenarios. Playbooks incorporate standard operating procedures, hazard analyses, and regulatory guidelines, ensuring that suggested responses align with safety and compliance requirements (Akintobi *et al.*, 2023; Onyeke *et al.*, 2023). Alongside each recommendation, the system provides real-time risk estimates, quantified through probabilistic models and historical event outcomes, enabling operators to assess the severity and urgency of the situation.

The DSE's interface offers contextual insights such as links to relevant process schematics, trending data, and past incident reports that allow operators to validate system suggestions. Additionally, adaptive decision trees guide the user through step-by-step diagnostic and response paths, tailored to specific alarm clusters or system failures. By minimizing reliance on memory or external references, these tools reduce cognitive workload and promote standardization of emergency responses.

The effectiveness of the DSE is further enhanced by its learning mechanisms, which ensure continuous improvement in system performance and relevance. Central to this is case-based reasoning, where the engine compares current alarm and process patterns to a repository of past incidents, drawing analogies to similar situations. The outcomes of those past cases successful interventions, near-misses, or failures inform the recommendations generated for the current event. Over time, this historical learning base becomes richer and more robust, enhancing the predictive power of the engine.

To augment adaptability, the DSE integrates machine learning techniques that adjust its internal models based on feedback from operator actions, system outcomes, and post-event analyses. Conversely, actions that correlate with escalation or unmitigated risk are flagged for review. This reinforcement learning paradigm supports the evolution of a semi-autonomous decision support system that remains aligned with operational realities and changing system behavior.

The Decision Support Engine represents a transformative element in offshore control room operations, bridging the gap between alarm generation and operator response. By combining real-time situational analysis, intelligent guidance, and continuous learning, the DSE not only enhances safety and reliability but also empowers operators to perform more effectively under pressure. As deepwater production systems grow in scale and complexity, such intelligent decision support will be essential in managing operational risk and sustaining performance in critical offshore environments (Onukwulu *et al.*, 2023; Onyeke *et al.*, 2023).

2.5 Enabling Technologies

The development and deployment of an Alarm Management and Decision Support Framework for control room operations in Deepwater Production Vessels (DPVs) rely heavily on a suite of enabling technologies. These technologies serve as the foundation for realizing a system that is adaptive, intelligent, and responsive under demanding offshore conditions. Central to this framework are advancements in artificial intelligence (AI) and machine learning (ML), edge and cloud computing infrastructures, and user-centric interface design as shown in figure 2. Each of these components plays a vital role in transforming vast and complex alarm datasets into actionable insights while maintaining operator trust, system reliability, and real-time performance (Osimobi *et al.*, 2023; Onukwulu *et al.*, 2023).

AI and ML technologies are integral to improving alarm quality, situational awareness, and predictive capability in control room environments. Clustering algorithms such as k-means and hierarchical clustering are used to group related alarms and process variables based on their spatial, temporal, and logical proximity. This helps in identifying patterns of cascading failures or alarm floods that would otherwise overwhelm operators.

Anomaly detection techniques, including autoencoders, isolation forests, and statistical process control methods, are used to differentiate between normal process variations and significant deviations. These algorithms, when trained on historical operational data, can trigger early warnings for events such as equipment degradation, sensor drift, or impending shutdowns—enhancing preventive action and reducing false positives.

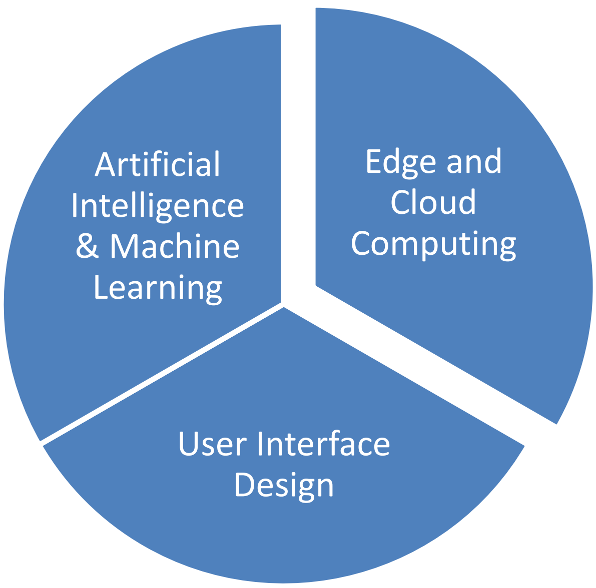

Figure 2: Enabling Technologies

Moreover, predictive analytics, powered by time-series forecasting models (e.g., LSTM networks or ARIMA models), offer the capability to anticipate alarm activations or process instabilities based on current trends. By integrating predictive outputs with alarm thresholds, the system can shift from a reactive to a proactive operational posture, allowing operators more time to plan and act effectively (Nwulu *et al.*, 2022; Awe *et al.*, 2023).

To support real-time decision-making in distributed offshore environments, a hybrid computing model is essential. Edge computing, which involves deploying computational resources close to the data source (e.g., control room servers or offshore rigs), enables low-latency processing for time-critical tasks such as alarm filtering, anomaly detection, and visualization updates. Edge devices ensure operational continuity even when communication with centralized systems is limited or disrupted.

Conversely, cloud computing offers scalable storage and processing power for tasks that require deeper analysis or historical data correlation. For instance, training ML models, conducting long-term trend analysis, and storing large-scale alarm event logs are best managed through cloud infrastructure. The cloud also supports cross-asset learning by aggregating and analyzing data from multiple DPVs or production fields, enhancing model generalizability.

Through edge-cloud orchestration, tasks are allocated based on latency sensitivity and computational complexity, creating a responsive yet robust backbone for the alarm management and decision support system.

The effectiveness of any advanced technological solution in a control room ultimately depends on the quality of its user interface (UI). Operators must be able to comprehend and respond to information rapidly, especially under stressful or abnormal conditions (Nwulu *et al.*, 2022; Elete *et al.*, 2022). Therefore, intuitive display design is a critical enabler of system usability and safety.

Modern interfaces incorporate alarm timelines, which visually represent alarm sequences over time, helping operators discern causal relationships and escalation patterns. Additionally, confidence indicators, which quantify the certainty of system-generated insights using probabilistic scores or machine learning confidence metrics, support trust in the recommendations without obscuring human judgment.

Other key UI features include interactive dashboards with drill-down capabilities, contextual menus linked to equipment data, and color-coded severity indicators that align with international standards such as ISA-18.2 and EEMUA 191. Responsive UI design also accounts for touch-screen use, remote accessibility, and ergonomic considerations tailored to marine environments.

The convergence of AI/ML, edge-cloud computing, and advanced user interface design is central to enabling intelligent alarm management and decision support in offshore control rooms. These technologies collectively empower operators with the tools to manage complex alarm environments, make informed decisions, and enhance operational safety and efficiency (Elete *et al.*, 2022; Nwulu *et al.*, 2022). Their careful integration into the broader system architecture marks a significant evolution in the digitalization of deepwater production operations.

2.6 Benefits and Performance Metrics

The deployment of an advanced alarm management and decision support framework in deepwater production vessels (DPVs) significantly enhances operational efficiency, process safety, and human-machine interaction in high-risk offshore environments as shown in figure 3. By integrating intelligent alarm handling with real-time decision support, such a system addresses critical limitations of traditional alarm systems and brings measurable improvements in safety, reliability, and operator performance (Ajiga *et al.*, 2022; Akintobi *et al*., 2022). This examines the core benefits and associated performance metrics, focusing on enhanced safety and reliability, reduced operator workload and stress, and improved response time and accuracy.

Figure 3: Benefits and Performance Metrics

One of the most consequential benefits of a robust alarm management system is enhanced operational safety. Conventional alarm systems in DPVs often suffer from alarm floods, nuisance alarms, and non-prioritized alerts, leading to a desensitized response by control room operators. By implementing alarm rationalization, dynamic thresholding, and contextual filtering, the proposed framework ensures that only meaningful, actionable alarms are presented, reducing the probability of missing critical events.

Real-time situational awareness modules further augment safety by correlating events and identifying abnormal conditions before they escalate. When paired with predictive analytics and machine learning, the system can forecast potential equipment failures or process deviations, enabling preemptive intervention. Performance metrics such as Mean Time Between Alarms (MTBA), reduction in nuisance alarms, and alarm accuracy rates serve as quantitative indicators of improved safety and system reliability.

Furthermore, improved alarm integrity reduces the likelihood of shutdowns or catastrophic incidents, which are costly and dangerous in remote deepwater environments (Adeniji *et al*., 2022; Sobowale *et al*., 2022). Reliability is also enhanced through adaptive learning, which continuously refines alarm logic based on operational history and human feedback.

Deepwater production operations are characterized by complex, high-stakes scenarios that demand continuous monitoring by a limited number of control room staff. Alarm fatigue a recognized issue in process industries emerges when operators are exposed to an overwhelming number of irrelevant or redundant alarms. This contributes to cognitive overload, reduced situational awareness, and potential human error during emergency conditions.

The proposed decision support framework directly targets this challenge by automating alarm prioritization, grouping, and suppression, thereby significantly reducing the volume of alarms presented during both normal and abnormal operating conditions. Coupled with intelligent user interface design featuring clear visualizations, decision timelines, and confidence metrics—operators are empowered to focus their attention on high-risk scenarios without being distracted by low-priority or spurious alerts.

Metrics such as Alarm Load Index (ALI), Alarm Response Time, and operator reaction efficiency can be employed to evaluate reductions in workload and improved operator engagement. Qualitative assessments from human factors studies and stress monitoring (e.g., heart rate variability, subjective workload assessments) further substantiate the framework's impact on operator well-being (Akintobi *et al.*, 2022; Adewoyin, 2022).

Timely and accurate responses are critical to maintaining safe operations and minimizing production downtime in offshore facilities. The decision support layer in the proposed framework enhances operator decision-making by offering contextual recommendations, risk assessments, and procedural playbooks during both routine and emergency conditions. These suggestions are generated using real-time data analytics and historical incident libraries, thereby grounding decisions in both data-driven and experience-based reasoning. By minimizing the time needed to diagnose issues and identify corrective actions, the framework significantly reduces Mean Time to Detect (MTTD) and Mean Time to Respond (MTTR) two key performance indicators in alarm handling. Additional metrics such as decision support system accuracy, success rate of operator interventions, and incident resolution times provide a comprehensive view of response improvement.

Moreover, adaptive learning mechanisms refine system suggestions based on outcomes of past interventions, creating a continuous feedback loop that improves accuracy and effectiveness over time.

The integration of advanced alarm management and decision support systems into DPVs results in demonstrable benefits across safety, operator performance, and system responsiveness. Through performance metrics that capture alarm quality, workload reduction, and response efficacy, stakeholders can evaluate the impact of the framework and guide continuous improvement (Onukwulu *et al.*, 2022; Ogunnowo *et al.*, 2022). As offshore operations grow more complex, such intelligent systems will be pivotal in ensuring resilient, safe, and efficient production environments.

2.7 Challenges and Considerations

The successful deployment of an alarm management and decision support framework aboard deepwater production vessels (DPVs) involves overcoming several technical, operational, and human-centered challenges. While such systems promise significant improvements in safety, efficiency, and operator responsiveness, their real-world implementation in offshore environments requires careful attention to legacy system compatibility, data integrity, personnel readiness, and cybersecurity (Oyedokun, 2019, Okolo *et al.*, 2022). This explores four primary considerations: system integration with legacy infrastructure, data quality and availability, operator acceptance and training, and cybersecurity in connected environments.

A major technical hurdle lies in integrating the proposed framework with existing Distributed Control Systems (DCS), Supervisory Control and Data Acquisition (SCADA) systems, and other legacy control architectures commonly found on DPVs. Many offshore production units operate with systems that were not originally designed for real-time analytics, machine learning, or cloud-based processing. Retrofitting these environments to support dynamic alarm thresholding, contextual decision support, and data-intensive computations presents both architectural and interoperability challenges.

Compatibility issues can arise from proprietary protocols, limited data interfaces, and hardware constraints. Integration may require developing middleware, adopting standardized communication protocols such as OPC UA, or implementing edge computing nodes to bridge gaps between legacy infrastructure and modern analytics platforms. Without careful planning, these integration efforts can lead to system instability or unintended disruptions in critical operations.

The effectiveness of any data-driven decision support system is fundamentally tied to the quality, resolution, and continuity of input data. In offshore environments, data acquisition is often challenged by harsh operating conditions, equipment degradation, and limited bandwidth for transmitting large datasets in real time (Awe, 2017; Okolo *et al.*, 2022).

Incomplete, noisy, or miscalibrated sensor data can lead to inaccurate alarm classifications and suboptimal recommendations. Furthermore, operational context such as maintenance activities or transient startup conditions is not always properly captured or tagged in existing data streams. These limitations reduce the system's ability to perform real-time inference and learn effectively from historical events.

Addressing this issue requires implementing robust data preprocessing pipelines, sensor validation routines, and redundancy in critical measurements. Data governance policies should be established to ensure consistent timestamping, labeling, and retention practices, enabling the system to support both real-time operations and long-term model refinement.

Even the most advanced automation systems can fail if not embraced by their human operators. Operator acceptance is often hindered by unfamiliarity with new interfaces, skepticism toward machine-generated guidance, or concerns over loss of autonomy. Given the high-stakes nature of offshore control room operations, personnel must maintain trust in their systems and retain the ability to override automated recommendations when necessary (Nwulu *et al.*, 2022; Ogunwole *et al.*, 2022).

Effective deployment must therefore include a comprehensive training program, designed to familiarize operators with new alarm hierarchies, decision support tools, and interface workflows. Human factors engineering should be employed in the design phase to ensure usability, cognitive compatibility, and minimal disruption to established routines.

Training programs should incorporate scenario-based simulations, hands-on sessions, and continuous feedback loops to improve adoption and identify usability bottlenecks. Additionally, involving operators early in the design and pilot phases can help tailor the system to their needs, fostering ownership and confidence.

The introduction of cloud computing, remote access, and IoT-enabled analytics into offshore environments expands the system’s attack surface and raises significant cybersecurity concerns. As alarm management and decision support frameworks rely on constant data exchange across multiple layers edge devices, control systems, and cloud infrastructure robust cybersecurity mechanisms must be built in from the outset (ADEWOYIN *et al.*, 2020; OGUNNOWO *et al.*, 2020).

Threats such as data breaches, ransomware attacks, and system spoofing can compromise system integrity and endanger personnel safety. To mitigate these risks, the framework should implement multi-layered security protocols, including end-to-end encryption, intrusion detection systems, role-based access control, and secure firmware updates. Additionally, compliance with international cybersecurity standards such as IEC 62443 ensures that the system meets industrial-grade protection requirements.

Deploying an alarm management and decision support framework for DPVs is a complex but rewarding endeavor. Addressing the challenges of system integration, data quality, operator training, and cybersecurity is essential for ensuring the system's effectiveness, reliability, and adoption (Awe *et al.*, 2017; Akpan *et al.*, 2017). With proper planning, stakeholder engagement, and engineering discipline, these barriers can be transformed into opportunities for innovation in offshore safety and operational excellence.

Conclusion

This study has presented a comprehensive alarm management and decision support framework tailored for control room operations in deepwater production vessels (DPVs), addressing the growing need for intelligent, operator-centric solutions in increasingly complex offshore environments. The framework integrates dynamic alarm rationalization, real-time situational awareness, and machine-guided decision support to mitigate common challenges such as alarm flooding, operator overload, and delayed responses during critical events.

By aligning with industry standards like ISA-18.2 and EEMUA 191, and incorporating enabling technologies such as machine learning, edge computing, and intuitive human-machine interfaces, the framework enhances the effectiveness, reliability, and safety of offshore control room operations. The modular architecture allows seamless integration with legacy systems and supports contextual alarm thresholding, event correlation, and adaptive learning, contributing to improved response times and reduced operational risks.

The implications for offshore operations are significant. The framework reduces cognitive burden on control room operators, improves alarm signal-to-noise ratio, and enables faster, data-informed decision-making. It supports a transition from reactive to proactive safety and operational management strategies, which is vital in deepwater environments where system failure can result in catastrophic outcomes.

Future work will focus on three key areas. First, the integration of digital twin technology can enhance simulation-based diagnostics and enable predictive alarm behavior modeling. Second, the development of advanced human-in-the-loop (HITL) interfaces will promote better interaction between operators and intelligent systems, preserving trust and control authority. Third, the implementation of continuous learning alarm systems leveraging real-time data and operator feedback will enable the framework to evolve with changing operational conditions and improve its predictive capabilities. Collectively, these advancements will further embed intelligence, resilience, and human adaptability into the heart of offshore production operations.

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