A Conceptual Framework for Process Automation Maturity in Offshore Oil and Gas Floating Production Systems

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Abstract- The offshore oil and gas industry is increasingly dependent on Floating Production Systems (FPS) such as Floating Production, Storage, and Offloading units (FPSOs) and Floating Liquefied Natural Gas (FLNG) platforms to exploit remote and deepwater reserves. These complex, high-risk environments demand advanced process automation to ensure safe, efficient, and cost-effective operations. However, the adoption and effectiveness of automation technologies in these systems vary widely across the industry. There is a critical need for a structured approach to assess and guide the maturity of process automation capabilities specific to offshore floating production systems. This proposes a conceptual framework for evaluating and advancing process automation maturity in offshore FPS environments. The framework is structured around four key dimensions: technical capabilities, organizational readiness, process integration, and data/digitalization maturity. Each dimension is assessed across five maturity levels—Initial, Managed, Standardized, Integrated, and Optimized—providing a comprehensive view of an organization's current automation status and future development path. The framework draws from existing automation maturity models and adapts them to the unique operational, environmental, and safety challenges of offshore facilities. It emphasizes not only the technological components, such as control systems and real-time analytics, but also organizational factors like workforce competence, management support, and digital culture. By offering a diagnostic tool and roadmap, the proposed model enables offshore operators, engineers, and decision-makers to benchmark their automation practices, identify gaps, and prioritize investments. Furthermore, the framework supports strategic alignment between automation initiatives and broader goals such as digital transformation, operational excellence, and sustainability. The conceptual framework lays the foundation for future empirical validation and can be adapted for various offshore asset types. It serves as a valuable guide for enhancing automation maturity, ultimately improving safety, performance, and resilience in offshore oil and gas production operations.

Indexed Terms- Conceptual framework, Process automation, Maturity, Offshore oil, Gas floating, Production systems

I. INTRODUCTION

Offshore oil and gas production has become increasingly reliant on complex and remote installations to access deepwater hydrocarbon reserves (Awe, 2017; Oyedokun, 2019). Among these, Floating Production Systems (FPS), such as Floating Production, Storage, and Offloading units (FPSOs) and Floating Liquefied Natural Gas (FLNG) platforms, have emerged as critical infrastructure for the industry (Awe *et al*., 2017; ADEWOYIN *et al*., 2020). These systems are designed to operate autonomously or semi-autonomously in isolated environments for extended periods, often in challenging marine and meteorological conditions. The highly integrated and hazardous nature of offshore production processes makes automation a vital component for operational efficiency, safety, and reliability (Akpan *et al*., 2017; OGUNNOWO *et al*., 2020).

Process automation in offshore floating production systems addresses several key challenges, including remote operability, limited on-board manpower, and complex process control under dynamic environmental conditions (Omisola *et al*., 2020; ADEWOYIN *et al*., 2020). Automation supports real-time monitoring, predictive maintenance, emergency shutdown systems, and advanced process control, all of which are crucial for minimizing operational risks and optimizing resource utilization. Furthermore, with increasing pressure to reduce greenhouse gas emissions and improve energy efficiency, digital and automated solutions are becoming indispensable tools for offshore operators. Automation also plays a pivotal role in enabling digital transformation initiatives, which encompass data-driven decision-making, integrated asset management, and enhanced regulatory compliance (Solanke *et al*., 2014; Chudi *et al*., 2019).

Despite growing investments in digital technologies, the adoption and implementation of process automation across offshore floating production systems remain inconsistent (Magnus *et al*., 2011; Tofte *et al*., 2019). Operators face a range of barriers, from legacy systems and integration challenges to skill shortages and organizational resistance. Moreover, there is often a lack of strategic direction guiding the development of automation capabilities (Yeow *et al*., 2018; Szalavetz, 2019). Existing maturity models tend to be either too generic or too focused on onshore facilities, limiting their relevance to the unique context of offshore production (Awe *et al*., 2017; Akpan *et al*., 2019). This creates a pressing need for a structured framework tailored to assess and guide the maturity of process automation in floating production environments.

The primary objective of this review is to develop a conceptual framework that defines and evaluates the maturity of process automation in offshore floating production systems. The framework aims to provide a systematic approach to assess current capabilities, identify gaps, and inform targeted improvements. It encompasses technical dimensions (such as instrumentation and control systems), organizational readiness (including skills and leadership), process integration, and data/digitalization maturity. The scope includes various types of floating production units, focusing on upstream oil and gas operations. This framework is intended as a practical tool for engineers, asset managers, and decision-makers seeking to enhance automation maturity, improve operational resilience, and support digital transformation in offshore environments (Kuusk and Gao, 2019; Yang *et al*., 2019).

II. METHODOLOGY

The methodology employed for this research follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) approach to ensure transparency, reproducibility, and rigor in the systematic literature review process. A comprehensive and structured search was conducted across multiple academic databases, including Scopus, Web of Science, IEEE Xplore, and ScienceDirect. The search strategy incorporated a combination of keywords and Boolean operators such as "process automation", "maturity models", "offshore oil and gas", "floating production systems", and "digital transformation".

Eligibility criteria were established to include peer-reviewed journal articles, conference proceedings, and technical reports published between 2000 and 2024, written in English, and directly addressing concepts related to automation maturity, offshore oil and gas production, or relevant digital technologies. Articles focused solely on onshore systems, unrelated manufacturing sectors, or lacking empirical or conceptual frameworks were excluded.

All identified records were first screened for relevance by reviewing titles and abstracts. Duplicates were removed using reference management software. Remaining articles underwent full-text screening to assess alignment with the inclusion criteria. The selection process was independently verified by multiple reviewers to ensure consistency and minimize bias.

Data were extracted from the final set of selected studies, capturing key elements such as study objectives, methodological approaches, automation dimensions, maturity levels, and application contexts in offshore oil and gas environments. The synthesis of the extracted data enabled the identification of recurring themes, gaps in current research, and critical factors influencing automation maturity in floating production systems.

The resulting body of literature informed the development of a conceptual framework for assessing process automation maturity specific to offshore floating production systems, incorporating insights on technological readiness, operational integration, and organizational capability. The PRISMA methodology thus ensured a robust foundation for constructing a domain-relevant and evidence-based framework.

2.1 Overview of Offshore Floating Production Systems

Offshore floating production systems (FPS) are critical infrastructures used for the extraction, processing, and storage of hydrocarbons in deep and ultra-deepwater environments. As global energy demands grow and onshore reserves become increasingly depleted, offshore developments—particularly in challenging and remote regions—have become more central to the oil and gas industry (Olah *et al*., 2018; Dinh and McKeogh, 2019). Floating production systems offer a flexible and scalable solution for developing subsea resources without the need for fixed platforms, making them indispensable in modern offshore operations.

One of the primary classifications of FPS includes Floating Production Storage and Offloading units (FPSOs). FPSOs are ship-shaped vessels equipped to process and store hydrocarbons extracted from subsea wells. These vessels can offload processed oil directly to tankers or via pipelines. FPSOs are widely used due to their storage capabilities and mobility, making them particularly suitable for marginal fields and locations lacking pipeline infrastructure. Another type, Floating Liquefied Natural Gas units (FLNGs), are specialized platforms designed for the offshore processing and liquefaction of natural gas. FLNGs eliminate the need for onshore LNG plants and enable direct export of liquefied gas from offshore locations. Semi-submersibles represent another common FPS type, characterized by their partially submerged structures that provide stability in rough seas (Liu and Li, 2017; Randolph and Gourvenec, 2017). These are typically used in deeper waters where more robust station-keeping is required and are often deployed for both drilling and production purposes. Tension Leg Platforms (TLPs) and Spar platforms are additional FPS variants, each suited to specific water depths and operational requirements.

Despite their versatility, floating production systems face a variety of operational challenges in offshore environments. Harsh weather conditions, high-pressure reservoirs, and deepwater operations increase the technical complexity and risk profile of these systems. Remote locations often limit access for maintenance, supply, and emergency response. Environmental factors such as wave loading, marine corrosion, and biofouling affect structural integrity and equipment lifespan. Additionally, the dynamic motion of floating systems introduces difficulties in maintaining the stability and precision required for subsea operations, riser systems, and topside processing. The complexity of integrating subsea infrastructure with surface facilities further demands advanced engineering and robust system reliability (Yasseri *et al*., 2018; Zhang *et al*., 2018). These challenges necessitate continuous monitoring, real-time decision-making, and high levels of operational resilience.

To mitigate these issues and optimize performance, automation plays a vital role in enhancing safety, reliability, and efficiency in offshore floating production systems. Automation enables real-time monitoring of process parameters, structural health, and environmental conditions, allowing for proactive maintenance and early fault detection. Advanced control systems reduce the risk of human error, especially during critical operations such as startup, shutdown, and emergency response. Safety instrumented systems (SIS) and automated emergency shutdown systems (ESD) enhance personnel safety and environmental protection. Moreover, the integration of distributed control systems (DCS), supervisory control and data acquisition (SCADA) systems, and digital twins facilitates better process optimization, energy efficiency, and cost reduction (Gambhir, 2018; Kapadia and Elliott, 2018). Remote operation centers, enabled by high-speed communications and data analytics, allow for centralized supervision and decision-making across multiple assets.

As offshore developments push further into deeper and more complex environments, the role of automation becomes even more pronounced. The industry is increasingly investing in intelligent systems, robotics, and AI-driven diagnostics to reduce offshore personnel exposure and extend asset life (Gil and Selman, 2019; Dizon, 2019). In this context, the maturity and integration of automation technologies will continue to define the operational viability and competitiveness of offshore floating production systems.

Floating production systems are essential to the offshore oil and gas sector, offering adaptability and economic feasibility in diverse marine settings. While they face significant operational challenges, advancements in automation have become key enablers for enhancing system safety, performance, and sustainability.

2.2 Process Automation in Offshore Production

Process automation refers to the application of technologies and systems to monitor, control, and optimize industrial operations with minimal human intervention (Rogers *et al*., 2019; Kokina and Blanchette, 2019). In offshore oil and gas production, automation encompasses a wide range of functions, from basic instrumentation to advanced data analytics and autonomous decision-making. The scope includes automated control of process variables such as pressure, temperature, and flow; integration of safety systems; and the coordination of complex subsystems across topside processing facilities, subsea infrastructure, and utilities. Offshore environments, characterized by their remoteness and operational complexity, require robust, reliable, and adaptive automation systems to maintain safety, maximize efficiency, and reduce human error. Automation in this context supports continuous production, reduces downtime, and enhances the operability of floating production systems like FPSOs, FLNGs, and semi-submersibles as shown in figure 1.

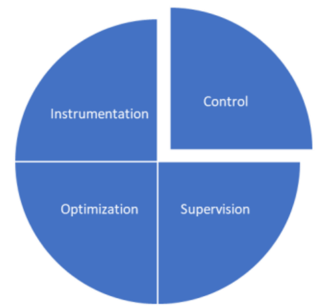

Figure 1: Layers of Automation

Process automation in offshore systems can be conceptualized in hierarchical layers, each building upon the capabilities of the preceding one; Instrumentation Layer, this is the foundational layer, consisting of field devices such as sensors, transmitters, and actuators that collect real-time data and execute control commands. Accurate and reliable instrumentation is essential for effective process control and safety management. Control Layer, this layer includes control systems such as Programmable Logic Controllers (PLCs) and Distributed Control Systems (DCSs) that execute predefined logic to regulate processes (Hudedmani *et al*., 2017; Chen *et al*., 2017). Closed-loop control strategies ensure stability and responsiveness to dynamic operating conditions.

Supervisory Control and Data Acquisition (SCADA) systems, Human-Machine Interfaces (HMIs), and control room operations fall into this category. Operators monitor system performance, respond to alarms, and make higher-level decisions based on data visualization and trend analysis. Optimization Layer, at the highest level, advanced process control (APC), real-time optimization, and predictive analytics are employed to enhance performance, reduce energy consumption, and extend equipment life. These systems leverage historical and real-time data to make intelligent adjustments that go beyond manual or reactive control.

Recent technological advances are reshaping automation strategies in offshore production; Digital Twins, these are virtual representations of physical assets or systems that are continuously updated with real-time data. Digital twins enable simulation, performance monitoring, and predictive maintenance, allowing operators to anticipate issues before they escalate. Artificial Intelligence and Machine Learning (AI/M), algorithms are increasingly applied for anomaly detection, fault diagnosis, and optimization of production parameters (Aldinucci *et al*., 2018; Horowitz, 2018). These technologies can identify patterns in large datasets that are beyond human analytical capabilities, enhancing operational intelligence. Robotics and Remote Operations, the deployment of autonomous or remotely operated robots for inspection, maintenance, and intervention reduces the need for human presence in hazardous areas. This is particularly valuable in offshore contexts where accessibility is limited and safety risks are high. Edge and Cloud Computing, distributed computing architectures enable real-time data processing at the edge (on-site) and deeper analytics in the cloud, facilitating faster decision-making and scalable system management.

In offshore production, automation systems are not only responsible for process efficiency but also play a central role in ensuring safety and maintaining asset integrity. Safety Instrumented Systems (SIS), Emergency Shutdown Systems (ESD), Fire and Gas Detection Systems (FGDS), and Condition Monitoring Systems are tightly integrated with automation architectures. These systems must function reliably under all operating scenarios, including abnormal conditions, to prevent incidents and ensure regulatory compliance.

Moreover, automated asset integrity management tools, such as vibration monitoring, corrosion detection, and thermal imaging, are increasingly used to predict and prevent equipment failures. Integration between automation and safety systems enables proactive risk management, ensuring that the floating production unit remains within safe operational boundaries.

Process automation in offshore production is a multilayered and rapidly evolving domain, essential for safe, efficient, and intelligent operations. As technology advances and offshore fields become more complex, automation will play an even more central role in enabling resilient and sustainable energy production (LiVecchi *et al*., 2019; Andoni *et al*., 2019).

2.3 Review of Existing Maturity Models

Maturity models have become essential tools for evaluating technological capabilities and guiding the structured advancement of systems and processes in complex industrial environments (Mittal *et al*., 2018; Colli *et al*., 2019). These models provide a framework to assess the current state of automation and identify opportunities for improvement, thus supporting decision-making in technology investment and operational strategy. In the context of offshore oil and gas floating production systems, a comprehensive understanding of existing maturity models is critical for assessing their applicability and identifying gaps in current practices.

Several well-established general automation maturity models are commonly referenced in industrial automation. The ISA-95 framework, developed by the International Society of Automation, is one of the most widely used standards for integrating enterprise and control systems. It defines a hierarchical model that structures production operations into five levels, from the physical process (Level 0) up to enterprise-level systems (Level 4). ISA-95 helps align IT and OT (Operational Technology) and provides a basis for evaluating automation integration maturity.

The Capability Maturity Model Integration (CMMI), originally designed for software engineering, has been adapted for broader applications including systems engineering and project management. CMMI defines five maturity levels—ranging from "Initial" to "Optimizing"—to assess process maturity and continuous improvement capabilities (Söylemez and Tarhan, 2017; Doss *et al*., 2017). While CMMI is not automation-specific, its emphasis on process discipline and incremental improvement has influenced industrial maturity assessments.

Industry 4.0 frameworks, such as the Plattform Industrie 4.0 reference model, focus on digital transformation in manufacturing and heavy industry. These frameworks often incorporate dimensions like interoperability, data analytics, and cyber-physical systems, aiming to assess readiness for smart manufacturing. They emphasize connectivity, automation, and data-driven decision-making, aligning closely with the goals of digital oilfields and intelligent offshore platforms.

However, despite their utility, there are significant limitations of current models for offshore applications. Most of these frameworks were designed with onshore manufacturing environments in mind, where infrastructure is relatively stable, accessible, and standardized. Offshore environments, especially floating production systems, introduce unique operational and environmental complexities that are not adequately captured by general models. These include dynamic marine conditions, extreme weather exposure, regulatory constraints, and the integration of subsea systems with topside facilities. Additionally, offshore operations are constrained by space, limited personnel, and safety-critical conditions that necessitate high levels of automation reliability and fail-safe mechanisms.

General models also tend to underrepresent the specific needs of asset lifecycle management in offshore contexts, such as the transition from commissioning to decommissioning, or the importance of real-time remote operations. Furthermore, many frameworks lack a detailed focus on energy systems integration, subsea automation, and floating platform-specific control dynamics—all of which are central to offshore oil and gas production (Yogi and Vachhani, 2019; Carotenuto *et al*., 2019).

Given these shortcomings, there is a clear need for a domain-specific framework tailored to offshore floating production systems. Such a framework should incorporate the distinct technical, operational, and environmental challenges of offshore production, while aligning with industry goals for safety, sustainability, and efficiency. A domain-specific maturity model would need to include criteria for dynamic positioning systems, integrated asset management, subsea-to-surface automation interfaces, and resilience to harsh marine conditions. Additionally, it should emphasize the role of remote operations centers, predictive maintenance, and cybersecurity—key enablers of future offshore automation strategies.

Importantly, a customized maturity model could serve not only as a diagnostic tool but also as a roadmap for offshore operators seeking to benchmark their automation capabilities and prioritize technology investments. By addressing the gaps left by generic models, a domain-specific framework would support more informed, context-sensitive decision-making and accelerate the adoption of advanced automation in the offshore oil and gas industry.

While general maturity models offer foundational guidance, their applicability to offshore floating production systems is limited. The development of a domain-specific framework is both timely and necessary to fully leverage automation in this complex and critical sector (Keliris and Maniatakos, 2018; Digmayer and Jakobs, 2018).

2.4 Proposed Conceptual Framework for Automation Maturity

The proposed conceptual framework for process automation maturity in offshore floating production systems is structured around four interdependent dimensions; Technical, Organizational, Process, and Data & Digitalization. Each dimension addresses key enablers of automation and reflects the multifaceted nature of modern offshore operations.

Technical Dimension, this dimension captures the maturity of instrumentation, control logic, and the degree of operational autonomy (Wekerle *et al*., 2017; Wood *et al*., 2017). It assesses the deployment of field devices, real-time monitoring systems, and programmable automation systems (e.g., PLCs, DCS). Higher maturity levels in this dimension are characterized by the use of advanced control systems, self-diagnostics, machine learning integration, and autonomous decision-making capabilities. The reliability, scalability, and interoperability of these technologies are essential metrics.

Organizational readiness is fundamental to automation success. This dimension examines workforce skills, training programs, organizational culture, and leadership commitment. Key indicators include staff competence in digital tools, openness to innovation, and the presence of change management strategies. Mature organizations demonstrate strong interdisciplinary collaboration, continuous learning environments, and alignment between automation goals and strategic objectives.

Process Dimension, this dimension evaluates the maturity of standardized procedures, automation governance, and the integration of automation across the asset lifecycle. It includes the use of documented automation protocols, project execution standards, and alignment with industry best practices. High maturity levels involve cross-functional process integration, automation lifecycle management, and feedback loops that continuously refine system performance. Data quality, accessibility, and the use of analytics tools are central to this dimension. It includes data governance practices, real-time data availability, and the application of AI/ML for predictive analytics. Mature systems leverage digital twins, cloud computing, and integrated digital platforms for decision support. Interoperability and cybersecurity are also critical evaluation factors.

The framework defines five levels of maturity, offering a progression pathway from basic to advanced automation capabilities; Level 1 – Initial, automation is minimal or reactive, with fragmented systems and limited instrumentation. Manual operations dominate, and there is little awareness or planning for automation. Level 2 – Managed, basic instrumentation and control systems are in place. Automation is applied selectively, with some formalized procedures. Data use is still limited and mostly historical. Level 3 – Standardized, automation practices are standardized across similar operations. Integration between subsystems begins, supported by digital monitoring and structured governance. Level 4 – Integrated, automation systems are fully integrated with operations, safety, and maintenance functions (Hu *et al*., 2018; Cohen *et al*., 2019). Real-time data drives decision-making, and AI/ML tools are increasingly adopted. Organizational processes support collaboration and digital readiness. Level 5 – Optimized, automation is optimized across all dimensions. Systems are adaptive, predictive, and capable of self-learning. The organization uses digital twins and advanced analytics to continuously enhance performance and resilience.

To apply the framework, a set of qualitative and quantitative indicators is used to assess maturity across each dimension; Technical Indicators, number and types of automated devices, system uptime, percentage of control loops in closed-loop operation, fault detection capabilities. Organizational Indicators, percentage of staff trained in automation systems, existence of an automation strategy, leadership support for digital initiatives, change management effectiveness. Process Indicators, degree of standardization in automation processes, presence of automation lifecycle documentation, alignment with industry standards such as ISA-95 or IEC 61511. Data quality metrics (accuracy, completeness), availability of real-time analytics tools, usage of digital twins, level of system integration and cybersecurity protocols. By combining these dimensions and indicators, the framework offers a holistic assessment tool to benchmark current automation maturity, identify improvement opportunities, and guide strategic investments in offshore floating production systems (Wu *et al*., 2017; Schuh *et al*., 2017). This structured approach enables stakeholders to transition from isolated automation efforts to a coherent, high-performance automation environment aligned with long-term operational goals.

2.5 Application of the Framework

The application of a process automation maturity framework in offshore floating production systems enables operators to assess their current automation capabilities, identify gaps, and plan strategic improvements. Given the complex nature of offshore environments—characterized by remote operations, high safety requirements, and the integration of diverse subsystems—a structured and context-specific maturity assessment methodology is essential (Moan, 2018; Itiki *et al*., 2019). This section outlines a suitable methodology for framework application, demonstrates its utility through a hypothetical case study, and proposes a roadmap for systematic advancement across maturity levels.

A robust methodology for assessment combines qualitative and quantitative approaches to evaluate the dimensions of automation maturity. Surveys and structured interviews with operations, maintenance, and control system personnel form the foundation for data collection. Surveys are designed with Likert-scale items covering key dimensions such as system integration, process control, data analytics, cybersecurity, and remote monitoring. These responses provide quantifiable indicators of automation capability at various levels of the framework.

Interviews allow deeper insights into operational challenges, user perceptions, and organizational readiness, which are not always captured through surveys. They help validate survey results and uncover context-specific factors such as cultural resistance, training needs, or legacy system limitations. In parallel, technical audits and site-level data collection can be conducted to evaluate current system architectures, control logic, failure response mechanisms, and digital infrastructure. This triangulated approach ensures that the maturity assessment is both evidence-based and contextually grounded.

To illustrate the practical application of the framework, consider a hypothetical example of a semi-submersible floating production platform operating in a deepwater oil field. The platform has a legacy distributed control system (DCS), limited data integration with the corporate enterprise systems, and relies heavily on manual intervention for maintenance decisions (Foehr *et al*., 2017; Li *et al*., 2017). The operator seeks to improve automation maturity to reduce downtime and enhance operational efficiency.

Using the assessment methodology, surveys and interviews reveal low maturity in areas such as predictive maintenance, data-driven decision-making, and IT/OT integration. However, higher scores are found in safety systems and basic process control. Technical audits further confirm the presence of siloed data sources and a lack of real-time analytics capability. Based on the assessment, the platform is categorized at Level 2 (Basic Automation) of the five-level maturity model.

The framework then provides a roadmap for progression across maturity levels, guiding the operator toward a higher level of automation maturity. For instance, to transition from Level 2 to Level 3 (Integrated Automation), the roadmap may include initiatives such as implementing a centralized data historian, integrating condition monitoring systems, and deploying a unified control interface for subsea and topside systems. Training programs for operators and engineers would also be recommended to support system adoption and capability development.

Further progression to Level 4 (Predictive Automation) would involve deploying machine learning models for failure prediction, adopting digital twin technologies, and establishing remote support centers with real-time access to performance metrics. At Level 5 (Autonomous Operations), the platform would achieve adaptive control capabilities, minimal human intervention, and a fully integrated digital ecosystem (Mostafa *et al*., 2019; Roldán *et al*., 2019). The roadmap emphasizes phased implementation, risk mitigation, and alignment with business goals to ensure sustainable transformation.

Applying a domain-specific automation maturity framework enables offshore operators to systematically assess their current capabilities, identify improvement areas, and plan targeted interventions. By combining surveys, interviews, and technical audits, the methodology ensures a comprehensive evaluation. Through hypothetical and real-world cases, the framework demonstrates its potential to guide the offshore industry through a structured digital transformation, enhancing safety, efficiency, and operational resilience.

2.6 Challenges and Enablers

The advancement of process automation maturity in offshore oil and gas floating production systems is accompanied by numerous challenges that span technical, organizational, regulatory, and cultural domains. Recognizing these barriers and understanding the critical enablers is essential to facilitate successful automation implementation and optimization as shown in figure 2(Good *et al*., 2017'; Harris *et al*., 2018).

Figure 2: Challenges and Enablers

One of the predominant technical challenges is the presence of legacy systems. Many offshore platforms were commissioned decades ago and operate with outdated control hardware and software that are often proprietary and difficult to integrate with modern automation technologies. These legacy systems limit scalability, reduce flexibility, and increase maintenance complexity. Additionally, interoperability issues arise from heterogeneous equipment and protocols used across different vendors and system generations. Without seamless integration, data silos emerge, hampering real-time data exchange and comprehensive automation control. Furthermore, offshore systems are subject to harsh marine environments, which impose strict requirements on the robustness and reliability of instrumentation and control devices. Cybersecurity threats also pose a growing concern, as increasing digitalization expands the attack surface. These technical barriers collectively constrain the deployment of advanced automation solutions and undermine operational efficiency.

Organizational culture and human factors significantly influence the pace of automation adoption. Offshore operations are traditionally labor-intensive, with a workforce accustomed to manual control and physical presence. Resistance to change may stem from fear of job displacement, distrust in automated systems, or lack of digital skills. Moreover, hierarchical structures and siloed departments impede cross-functional collaboration needed for integrated automation initiatives. Insufficient management support and unclear communication of automation benefits exacerbate skepticism and reduce employee engagement. Cultural resistance often results in underutilization of automation capabilities and delays in implementation, highlighting the need for change management programs that foster a digital mindset, inclusivity, and continuous learning (Engel *et al*., 2017; Kothandapani, 2019).

The offshore oil and gas industry is heavily regulated to ensure operational safety, environmental protection, and workforce welfare. Automation systems must comply with stringent standards such as IEC 61508/61511 for functional safety and ISO 27001 for information security. Compliance imposes rigorous design, testing, and certification processes that increase project complexity and cost. Furthermore, safety-critical automation components require fail-safe architectures and redundancy, which limit flexibility in system design. Regulators may also be cautious about endorsing fully autonomous operations due to perceived risks, creating uncertainty around permissible automation levels. The need to maintain safety integrity and regulatory compliance can slow innovation and necessitate careful balancing between automation advancement and risk mitigation.

Despite these challenges, several enablers can accelerate process automation maturity. Strong leadership commitment is paramount to champion digital transformation, allocate resources, and set strategic direction. Investment in modern infrastructure—including upgradable control systems, open communication protocols, and cloud platforms—facilitates scalability and interoperability. Adoption of industry standards and best practices, such as ISA-95 for automation integration and API standards for subsea equipment, provides a foundation for consistent, interoperable solutions. Additionally, comprehensive training programs build workforce competencies in automation technologies and foster a culture receptive to innovation. Change management initiatives that include stakeholder engagement, transparent communication, and demonstration of tangible benefits further reduce resistance. Collaborative partnerships with technology vendors, academia, and industry consortia also promote knowledge sharing and development of tailored solutions for offshore challenges.

The path to enhanced automation maturity in offshore floating production systems is complex but navigable. Addressing technical limitations and cultural resistance through strategic leadership, investments, standardization, and training can unlock the full potential of automation technologies. Aligning these enablers with regulatory requirements ensures safe, reliable, and sustainable offshore operations, ultimately contributing to the industry's resilience and competitiveness in an increasingly digital era (Yang, 2019; Enemosah, 2019).

2.7 Implications for Industry

The evolution and application of process automation maturity frameworks in offshore floating production systems carry significant implications for the oil and gas industry (Grange, 2018; Bento and Fontes, 2019). As the sector increasingly grapples with complex operational environments and fluctuating market conditions, such frameworks provide strategic value in guiding decision-making, enhancing risk management, and driving digital transformation as shown in figure 3. This explores how these implications manifest in strategic planning, operational efficiency, and the ongoing digital evolution of offshore operations.

Figure 3: Implications for Industry

Strategic decision-making represents a critical area where automation maturity frameworks exert profound influence. Offshore oil and gas operators face multifaceted challenges—from capital-intensive investments to stringent regulatory compliance and environmental concerns. A maturity framework equips decision-makers with structured insights into current automation capabilities, enabling more informed allocation of resources and prioritization of initiatives. By benchmarking an asset's automation maturity, executives can identify capability gaps and forecast the return on investment (ROI) of adopting advanced technologies. This data-driven approach helps to align operational improvements with broader corporate objectives such as cost reduction, sustainability, and competitive advantage.

Furthermore, the framework supports long-term strategic planning by mapping a clear progression path across maturity levels. Organizations can develop staged digital transformation roadmaps, balancing incremental upgrades with breakthrough innovations. This systematic approach mitigates the risks associated with technology adoption by avoiding overextension of resources and ensuring workforce readiness (Gefen *et al*., 2019; Nave and Ferreira, 2019). In addition, automation maturity assessments provide a foundation for collaboration among multidisciplinary stakeholders—including engineering, IT, safety, and finance—fostering a unified vision for operational excellence.

Risk management and operational efficiency are intimately linked domains that benefit substantially from the implementation of automation maturity frameworks. Offshore environments are inherently high-risk due to their remote location, exposure to harsh weather, and complex mechanical systems. Mature automation systems enhance risk mitigation by providing real-time monitoring, predictive maintenance, and automated safety controls. These capabilities reduce the likelihood of catastrophic failures, environmental incidents, and unscheduled downtime.

Automation maturity also correlates with improved operational efficiency by optimizing process control and asset utilization. Advanced automation enables precise control over production parameters, reducing variability and improving throughput. Integration of data analytics and machine learning allows for early detection of equipment degradation and process anomalies, facilitating proactive interventions. Consequently, operational expenditures decrease while production reliability improves, directly impacting profitability.

Moreover, mature automation systems facilitate regulatory compliance by ensuring accurate reporting, traceability, and audit readiness. Given the increasing emphasis on environmental stewardship and safety standards in offshore operations, automation maturity supports adherence to evolving legal and industry requirements (Lindøe and Baram, 2019; Pearlman *et al*., 2019). This compliance not only mitigates financial penalties but also enhances corporate reputation and social license to operate.

Digital transformation in offshore operations is arguably the most transformative implication of adopting an automation maturity framework. The offshore oil and gas sector is undergoing a paradigm shift driven by advances in digital technologies such as the Industrial Internet of Things (IIoT), artificial intelligence (AI), cloud computing, and augmented reality (AR). These technologies promise to revolutionize how offshore assets are monitored, controlled, and maintained.

A maturity framework guides the integration of these digital technologies by providing a structured pathway that aligns technological adoption with organizational capabilities and operational needs (Issa *et al*., 2018; Williams *et al*., 2019). More advanced stages incorporate predictive analytics, autonomous control systems, and fully integrated digital twins that simulate and optimize production in real time.

This staged approach facilitates the gradual transformation of offshore operations from labor-intensive, manual processes to highly automated, intelligent systems. It also addresses workforce challenges by supporting upskilling and reskilling initiatives, thereby preparing personnel for new roles in data analysis, remote operations, and digital maintenance.

In addition, digital transformation driven by mature automation fosters innovation in business models. Concepts such as remote operation centers, virtual asset management, and digital collaboration platforms enable operators to reduce offshore personnel exposure, improve emergency response, and enhance asset life-cycle management (Oliver, 2018; Settemsdal, 2019; Evans, 2019).

The implications of applying process automation maturity frameworks in offshore floating production systems are profound and multifaceted. They empower strategic decision-making by providing clarity and direction for technology investments. They strengthen risk management and operational efficiency through enhanced control and predictive capabilities. Finally, they accelerate digital transformation by providing a roadmap for integrating emerging technologies in a manner that is sustainable, scalable, and aligned with organizational objectives (Ismail *et al*., 2017; Zimmermann *et al*., 2018). As the offshore industry continues to evolve, embracing automation maturity frameworks will be pivotal to maintaining safety, competitiveness, and resilience in an increasingly complex energy landscape.

CONCLUSION

This has presented a conceptual framework for assessing and advancing process automation maturity in offshore oil and gas floating production systems. The framework is structured around four critical dimensions—technical capabilities, organizational readiness, process integration, and data-driven digitalization—providing a comprehensive lens through which automation maturity can be evaluated. By delineating five progressive maturity levels from Initial to Optimized, the framework offers a structured pathway for operators to benchmark their current status, identify gaps, and formulate strategic initiatives to enhance automation performance. Key insights highlight that automation maturity in offshore environments is not merely a function of technological deployment but is equally dependent on organizational culture, process standardization, and the effective management and utilization of data. The framework emphasizes the importance of integration across these dimensions to achieve operational excellence, safety, and resilience in the demanding offshore context. Despite its comprehensive approach, the proposed framework has certain limitations. First, it is conceptual and primarily based on literature review and expert knowledge rather than extensive empirical validation. This limits its immediate applicability and may affect the precision of maturity assessments in diverse operational contexts. Second, the framework's generic design aims to be applicable across a broad range of floating production systems but may overlook unique characteristics specific to certain asset types, geographies, or operators. Third, rapid technological evolution, especially in digitalization and AI, may outpace the framework's adaptability unless periodically updated. Finally, the framework focuses predominantly on upstream floating production operations, with limited consideration for downstream or other subsea systems, restricting its full lifecycle coverage.

Future work should focus on validating and refining the framework through empirical studies involving offshore operators and case applications. Quantitative assessments and benchmarking exercises can provide practical insights, identify dimension weighting factors, and improve assessment accuracy. Longitudinal studies could capture maturity progression over time and highlight best practices. Additionally, the framework could be extended to encompass other offshore asset types, such as fixed platforms and subsea processing units, to offer a holistic automation maturity model for the entire offshore production ecosystem. Integration with emerging industry standards and digital transformation roadmaps will enhance its relevance.

Research can also explore the interplay between automation maturity and broader industry challenges such as decarbonization, cybersecurity, and workforce transformation. Advanced technologies, including digital twins, AI-driven predictive maintenance, and autonomous robotics, should be integrated into the framework's technical and data dimensions to reflect state-of-the-art capabilities. Cross-industry comparisons and adaptation to related sectors such as offshore wind energy or marine transportation present additional opportunities to broaden the framework's impact. Ultimately, continued interdisciplinary collaboration among academia, industry, and regulatory bodies will be crucial to ensure that automation maturity frameworks remain robust, adaptive, and aligned with evolving offshore operational demands.

The proposed framework provides a foundational step toward systematic evaluation and enhancement of process automation maturity in offshore floating production systems, offering a valuable tool for guiding digital transformation and operational excellence in this critical sector.

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