●●● **ARTICLE 5**

TECHNOLOGICAL STANDARDIZATION IN SUBMARINE SYSTEMS: HOW TO INNOVATE WITHOUT LOSING SCALABILITY IN OFFSHORE OPERATIONS

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Abstract: Offshore operations in deep and ultra-deep waters are increasing in volume and complexity every day and are more dependent on integrated subsea systems, involving process, control, power, communication, sensor, and robotic inspection and intervention platforms. Given this, technological standardization emerges as a strategic vector to increase standardization, improve cost predictability, accelerate engineering cycles, and facilitate operational scalability. Despite this, the advancement of new solutions poses the challenge of innovating without compromising operational integration, functional safety, asset integrity, and data governance. This article analyzes this balance based on a review of the literature and documentation, combining standards and practices, sectoral harmonization initiatives, and academic literature on modularity, reliability, and subsea systems. It proposes an analytical framework of "layered standardization," in which interfaces, data, and integrity requirements are stabilized, while modules and applications maintain room for incremental and, in specific cases, disruptive innovation. It is concluded that scalability in offshore operations does not depend on eliminating customizations, but on shifting them to controlled points in the architecture, preserving a standardized core of integration, security, and traceability.

Keywords: subsea systems; technological standardization; offshore scalability; modularity; innovation.

Introduction

Offshore subsea operations have evolved from isolated arrangements to highly integrated ecosystems, in which production equipment, control systems, lines, pipelines, power, instrumentation, and robotics coexist under tremendous conditions of pressure, corrosion, logistical constraints, and high intervention costs. This environment makes technical variability particularly costly: small differences in interface, documentation, protocol, or testing requirements can lead to integration delays, engineering rework, increased inventory, and greater exposure to commissioning and operational failures. (ISO, 2018; DNV, [n.d.-a]).

Therefore, technological standardization in subsea systems should not be understood merely as "component uniformity," but as a technical governance strategy to support repeatability, interoperability, and scalability. In practical terms, standardization means reducing uncertainty in interfaces, making data comparable throughout the life cycle, facilitating technology qualification, improving maintenance, and allowing the reuse of solutions between projects. This perspective is consistent with guidelines for reliability management and production assurance throughout the life cycle of offshore assets, as emphasized by ISO 20815 (ISO, 2018).

At the same time, the offshore sector faces growing pressure for innovation: advanced automation, remote operation centers, real-time data integration, industrial cybersecurity, digital twins, distributed sensors, and modular architectures are being incorporated to reduce operating expenses (opex), improve availability, and increase operational safety. The revision of IMCA R 004 for ROV operations, for example, already incorporates contemporary topics such as remote operations and remote operations centers (ROCs), signaling that the digitization of subsea operations is no lon-

ger a trend but has become part of standard operating practice (IMCA, 2024).

The central challenge, therefore, is not to choose between standardization and innovation, but to define how to standardize enough to scale without blocking technological evolution. In many cases, the tension stems from an architectural error: attempts are made to freeze layers that should remain adaptable (algorithms, sensors, analysis software), while neglecting to standardize layers that should be stable (interfaces, data taxonomies, testing criteria, integrity, and cybersecurity). This inversion compromises performance, increases dependence on suppliers, and reduces the ability to replicate between assets and fields.

A structured reading of this problem is proposed, articulating international standards, sectoral initiatives, and recent academic literature to answer the following question: how to innovate in submarine systems without losing operational scalability in offshore environments? The focus is on the following interdependent dimensions : architecture and modularity; integrity, reliability, and technological qualification; and data, interoperability, and digital governance.

Methodology

The research was conducted as a qualitative bibliographic and documentary review, with an emphasis on technical and academic sources capable of supporting an article applied to the engineering and management of offshore subsea operations.

Three groups of sources were combined: international and Brazilian technical standards and documents, international academic literature, and Brazilian academic production.

International academic literature on modularity, systems engineering, and reliability applied to underwater vehicles and subsystems, with an emphasis on studies on modular architecture of underwater vehicles and reliability modeling based on dynamic Bayesian networks and digital twins.

Brazilian academic production and previously mapped references (theses, dissertations, and survey materials), especially related to submarine inspection, ROVs/AUVs, integrity, and applications in CO_2 environments, used to contextualize applicability and potential for adaptation to the scenario.

Theoretical Framework

Technological standardization as scalability infrastructure

In submarine systems, scalability cannot be summarized as the ability to "install more equipment" in a system. The most important thing is to replicate solutions with adequate control of integration, operation, maintenance, and supplies. In other words, offshore scalability depends on standardization of interfaces, documentation, testing criteria, data structures, and integrity practices as if everything had been done with the same logic or even creator.

DNV, with nearly two centuries of experience, emphasizes that its standards and recommended practices are developed with the industry and used globally to reduce cost and risk, improve safety and quality, and increase consistency and performance in technology and operations (DNV, [n.d.-a]).

Similarly, ISO 20815 treats production assurance and reliability management as a process throughout the asset lifecycle, reinforcing that availability and performance are not the result of a single phase (such as design or operation), but of a set of decisions. This is particularly important in subsea systems, where intervention costs and the consequences of failures make interface and data errors that are "cheap" on land extremely expensive or unfeasible at sea (ISO, 2018).

The practical implication is clear: standardizing design, especially in the specification and integration phase, increases the ability to scale later, building today with tomorrow in mind. When this standardization is ignored, the price paid is a tendency toward arrangements and exceptions, multiplying customizations, non-equivalent contracts, specific inventories, and unorthodox maintenance procedures.

Sectoral harmonization and reduction of variability

One of the most relevant proposals for the discussion of scalability is in the sectoral harmonization initiatives brought by the JIP33 (IOGP) consortium, which aims to develop and harmonize purchasing specifications for global industry, seeking to reduce variation and complexity in the supply chain (IOGP, [n.d.-a]).

The JIP33 FAQ is even more instructive for management purposes: it recognizes that most engineering products are reused as-is and that standardized specifications can capture a significant portion of equipment costs, making specification harmonization a direct mechanism for efficiency and predictability (IOGP, [n.d.-b]).

For subsea systems, this means that standardization should not be restricted to hardware. There are gains across the board when the following are also standardized: documentation requirements; data taxonomies; test templates; asset and fault nomenclatures; acceptance parameters; digital handover (information transfer) formats.

This is where CFIHOS becomes relevant. The initiative to handover information for capital assets in the industry works on standardizing data for the delivery of information between suppliers, engineering companies, and operators. The organization itself highlights significant alignment with JIP33 and ISO 14224 in its models, which is extremely useful for the interoperability and maintenance layer (CFIHOS, [n.d.]; ISO, 2016).

In strategic terms, JIP33 and CFIHOS, combined, point to a mature notion of offshore scalability: it is not enough to standardize equipment; it is necessary to standardize the informational and documentary ecosystem that makes it operable and auditable.

Modularity and systems engineering: innovating in blocks, not through complete disruptions

The study by Aristizábal et al. (2021), in proposing a modular hardware architecture for underwater vehicles based on systems engineering, suggests organizing development into functional layers and verifiable interfaces.

The focus of the article is on one type of vehicle, but the principle can be generalized and expanded to offshore submarine systems: modules can change the industry, just as standards have changed metric sys-

tems. This logic reduces the cost of adapting systems and allows for shorter improvement cycles.

This approach allows for: technological upgrades without completely redesigning the arrangement; phased qualification of components; better management of obsolescence ; replacement of suppliers without loss of integration (provided that interfaces and data are common); scaling between fields with different conditions, preserving a "core architecture."

Integrity, reliability, and data throughout the life cycle

Offshore scalability loses value if it is accompanied by a decline in reliability or an increase in operational risk. Therefore, technological standardization needs to be aligned with integrity and reliability management.

ISO 14224, which deals with the collection and exchange of reliability and maintenance data for equipment in the oil, petrochemical, and natural gas industries, provides a conceptual basis for comparable taxonomies and data structures (ISO, 2016). In subsea systems, where maintenance campaigns are complex and expensive, historical data is very important for scheduling inspections in the best possible way.

Tao et al. (2024) propose reliability analysis of subsea control modules based on digital twins and data modeling, showing how operational information and variable conditions can update reliability models over time.

Complementarily, recent studies in Scientific Reports apply FMECA and FFTA to the reliability analysis of submarine manifolds, reinforcing the usefulness of struc-

tured failure analysis methods for critical subsystems (LIU et al., 2024).

The contribution of these approaches to the topic of this article is straightforward: without minimum standardization of nomenclatures, data structures, failure events, maintenance history, and digital twins. In many cases, the barrier to innovation is not the lack of an algorithm, but the heterogeneity of field data.

Functional safety, cybersecurity, and remote operation

The digitization of subsea systems and greater integration between offshore operations, remote centers, and data platforms increase functional safety and cybersecurity requirements. It is not just a matter of avoiding downtime: in control and monitoring systems, failures or compromises can affect operational safety, environmental integrity, and critical decision-making.

IEC 61508 remains the structural reference for the functional safety of safety-related electrical/electronic/programmable electronic systems, providing a conceptual basis for safety lifecycle, requirements, and verification (IEC, 2010).

The ISA/IEC 62443 series organizes cybersecurity requirements and best practices for industrial automation and control systems, an increasingly central topic in connected offshore environments, especially when there is integration of corporate networks, inspection data, remote maintenance, and software-assisted operations (ISA, [n.d.]).

The update of IMCA R 004 Rev. 4, by including remote operations and ROC, reinforces this convergence between operational technology, connectivity, and opera-

tional governance. Based on this reading, technological standardization for scalability must include, from the outset, criteria for: network segregation and architecture; access control and hardening; audit trails; software update requirements; compatibility between functional safety and cybersecurity; and change validation. Without this, digital innovation tends to produce local gains that are fragile or difficult to replicate.

Taxonomy, inspection, and IMR: contribution of the literature on underwater robotics

The literature on ROVs and IMR (inspection, maintenance, and repair) fosters the debate on standardization because it accurately emphasizes how different missions, sensors, and methods depend on clear classifications. The work of Azevedo et al. (2023), in organizing a taxonomy of ROVs and emerging IMR methods, provides a useful conceptual map to avoid excessive generalizations in the specification of robotic capabilities.

In the Brazilian context, dissertations such as those by Sonaglio (2017), Soto Bravo (2020), and Nogueira Junior (2025) show how trajectory planning, sensory integration, pipeline tracking, and instrumentation embedded in ROVs/AUVs depend on well-defined technical requirements, precisely the type of foundation that can be reused in standardized inspection and integrity programs.

These works suggest an important point: scalable standardization does not mean "always using the same robot," but rather creating standardized inspection programs by mission class, with comparable technical envelopes, minimum mandatory data, quality criteria, and recording protocols.

Analysis and discussion

The false dilemma between standardization and innovation

The literature and documents analyzed indicate that the conflict between standardization and innovation is, to a large extent, a false dilemma. The real problem lies in where to standardize and where to allow variation.

When an organization attempts to standardize the wrong layer (for example, by freezing rapidly evolving analytical tools, software architectures, or sensors), it loses its ability to learn and update. When, on the other hand, it leaves the structural layers (interfaces, data, test criteria, handover, and integrity) unstandardized, innovation becomes a collection of non-scalable pilots and an eternal restart.

The sectoral harmonization experience (JIP33/CFIHOS) and standardized references point to an intermediate solution: basic standardization + innovation in modules. In technology management language, this is equivalent to separating: stable layers (interfaces, taxonomies, minimum requirements, data, security, documentation); evolutionary layers (algorithms, sensors, analytics, advanced automation, replaceable components). This separation reduces rework, facilitates knowledge reuse, and improves the portability of solutions between assets, vessels, and fields.

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Proposed analytical framework: layered standardization for subsea systems

Based on the sources analyzed, a layered standardization framework for offshore subsea systems is proposed:

Layer 1, integrity and safety requirements (unchanging core): Includes minimum criteria for integrity, reliability, functional safety, and cybersecurity, aligned with applicable practices and standards. This layer defines the "floor" of acceptable performance and risk.

Layer 2, Interfaces and interoperability (standardized core): covers mechanical, electrical, communication, and data interfaces; information exchange formats; nomenclatures; metadata; handover templates; and versioning rules. Initiatives such as JIP33 and CFIHOS help structure this layer.

Layer 3, Technology Qualification and Testing (Bridge Between Standard and Novelty): This layer organizes technology qualification criteria, FAT/SIT/SAT, performance evidence, and acceptance criteria for new modules. The presence of DNV recommended practices for technological qualification and integrity indicates that innovation needs to enter through a structured validation door, rather than through improvised contractual exceptions. (DNV, [n.d.-a]).

Layer 4, innovative modules (space for competitive differentiation): Includes sensors, electronic units, analysis software, prediction models, digital twins, predictive maintenance routines, and remote operation applications. In this layer, modularity based on systems engineering (ARISTIZÁBAL et al., 2021) and dynamic reliability approaches (TAO et al., 2024; LIU et al., 2024) enable faster evolution without breaking the system.

Layer 5, Operational and learning governance (organizational layer): comprises change management, lessons learned, failure libraries, indicators, traceability, and technology update policies. It is the layer that transforms standardization into cumulative capacity, preventing each project from "starting from scratch."

This framework is particularly useful for offshore operations because it simultaneously responds to three demands: scalability (replicate with less f r friction); innovation (evolve without total reengineering); reliability (preserve integrity and safety).

Practical implications for operators, EPCs, and suppliers

For operators, the main implication is contractual and governance-related: specifications must explicitly distinguish between core requirements (non-negotiable) and areas of innovation (negotiable, provided they are qualified). This reduces technical conflicts and speeds up integration.

For EPCs and integrators, the opportunity lies in building libraries of interfaces, test templates, and reusable handover models. Engineering scalability comes less from "doing a single project faster" and more from reusing common structures with variant control.

For technology providers, the logic of modularity and layered standardization can be advantageous: instead of competing only for fully proprietary solutions, they can differentiate themselves by the performance of modules compatible with standardized ecosystems, expanding their addressable market.

For the Brazilian context, this approach is especially promising because it allows combining installed offshore expertise (operation, IMR, engineering, integration, testing) with a history of incremental innovation in sensors, software, and robotics. The national technical and academic literature on ROV/AUV and underwater inspection provides a concrete basis for this, especially in mission planning, perception, and instrumentation adapted to critical environments.

Final considerations

Technological standardization in subsea systems should be treated as a scalability strategy, not as an obstacle to innovation. Analysis of standards, industry initiatives, and academic literature suggests that more efficient and resilient offshore operations emerge when standardization is concentrated in the integrity, interface, and data layers, while innovation is encouraged in the modular hardware and software layers.

This arrangement preserves interoperability, security, and traceability, which are indispensable in subsea environments, while accelerating technological upgrades and organizational learning. In short, innovating without losing offshore scalability requires less "total standardization" and more intelligent, architecture-driven standardization.

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