Papel dos FPSOs na exploração em águas profundas e ultra profundas: uma revisão de literatura sobre sistemas de manufatura social na Indústria 5.0

Role of FPSOs in deepwater and ultra-deepwater exploration: a literature review on social manufacturing systems in industry 5.0

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Resumo

Este artigo explora a exploração de petróleo e gás em águas profundas, com ênfase nas Unidades Flutuantes de Produção, Armazenamento e Transferência (FPSOs) e sua integração com sistemas de manufatura social na Indústria 5.0. Revisa métodos comuns de exploração offshore, destaca o potencial dos FPSOs modernos como catalisadores para a Indústria 5.0 e aborda desafios na exploração em águas profundas. O estudo enfatiza a importância contínua da inovação para enfrentar desafios futuros, ressaltando o papel vital dos FPSOs na otimização e sustentabilidade.

Palavras-chave: FPSO; Águas Profundas e Ultra Profundas; Indústria 4.0; Indústria 5.0; Óleo e Gás

Abstract

This article delves into oil and gas exploration in deep waters, particularly focusing on Floating Production Storage and Offloading (FPSOs) and their integration with social manufacturing systems in Industry 5.0. It reviews common offshore exploration methods, highlights the potential of modern FPSOs as catalysts for Industry 5.0 integration, and explores challenges in deep-water exploration. The study emphasizes the ongoing importance of innovation for addressing future challenges, underscoring FPSOs' vital role in optimization and sustainability.

Keywords: *FPSO; Deep and Ultra Deep Waters; Industry 4.0; Industry 5.0; Oil and Gas*

1. Introduction

Offshore oil and gas exploration, crucial for global energy supply, faces challenges in deep waters. This study explores the integration of Floating Production Storage and Offloading (FPSOs) systems with Industry 5.0 to enhance efficiency, safety, and cost reduction. Focusing on FPSOs, the research question is: How can Industry 5.0 integration optimize FPSOs, contributing to advancements in deep-water exploration? The article, structured into Introduction, Methods, Industry 5.0 Integration, Related Studies, and Final Thoughts, aims to address this question and drive progress in the offshore energy industry.

2. Methods

This research involves a literature review utilizing the SCOPUS online database as the primary information source. A comprehensive search was conducted on knowledge production related to offshore exploration in deep waters. The aim was to support the article's content and present the state of the art on the subject, as illustrated in Figure 1.

The search considered titles, abstracts, and keywords for the broad selection of potentially relevant works. The inclusion criteria included texts published between 2019 and 2023, conference papers, articles, and reviews. Using terms like ("oil" OR "oil industry") AND ("offshore") AND ("exploration and production") AND ("deep waters"), 22 articles were initially identified and classified based on citation numbers.

Ultimately, 15 articles were selected and organized into forms containing identification data and a synthesis to capture relevant concepts for offshore exploration in deep waters, with a specific focus on FPSOs and their integration with social manufacturing systems in Industry 5.0.

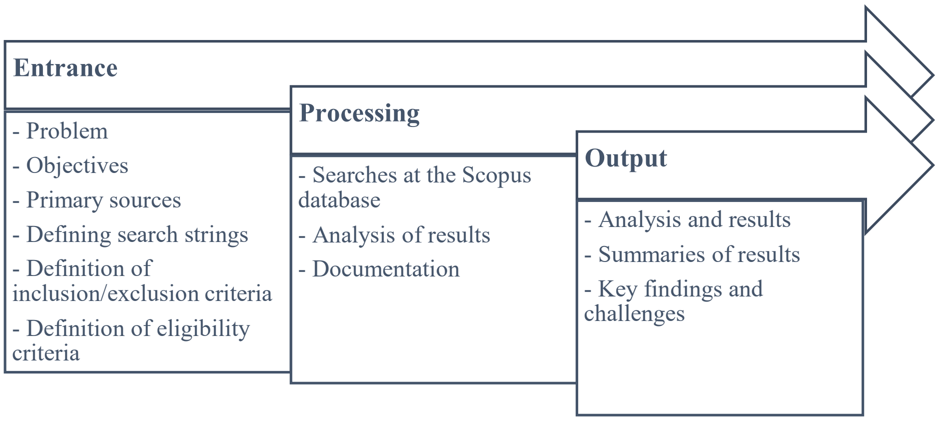

Figure 1: Research method. Source: Prepared by the authors.

3. Industry 5.0 integration and challenges in offshore exploration with FPSOS

Industry 5.0 integration in offshore exploration with FPSOs offers chances to improve efficiency and sustainability, focusing on human-intelligent system collaboration and technologies like AI and robotics. However, the harsh environments and safety concerns require innovative multidisciplinary solutions. Thorough analysis and effective strategies are necessary for successful adoption and ensuring competitiveness in facing these challenges.

3.1. Integration of Social Systems in Industry 5.0 and Offshore Challenges

In the Industry 4.0 era, digital transformation has revolutionized production, impacting industries and daily lives. The integration of manufacturing processes with information and communication technologies, particularly the Internet of Things, forms Cyber-Physical Systems (CPS). [1]

This integration offers technological opportunities, transforming configuration times, labor, input costs, and processing times, leading to productivity gains. Business leaders increasingly demand integrated industrial processes and strategies to meet market demands. Industry 4.0 utilizes cloud-stored data for incremental gains in production autonomy and cybersecurity. The paradigm shift highlights the importance of humans in operating systems, with concerns about the underrepresentation of human factors in research flows.[2]

González *et al*. [3] emphasize the importance of educational proposals aligned with Industry 4.0 (I4.0) to foster skills and inclusive opportunities. However, a gap exists between educational needs and structures, hindering effective integration of new skills. Process optimization in I4.0 raises concerns about social impact, including job reduction and resistance from unions and politicians.

In offshore exploration with FPSOs, digitalization is crucial for addressing challenges and reducing the CO2 footprint. Industry 5.0 (I5.0) emerges as a response to I4.0 challenges, promoting smart factories with reduced human labor. FPSOs are adopting I5.0 principles for improved processes and quality. I5.0 emphasizes collaboration between machines and humans, focusing on creativity, decision-making, and empathy, aiming to drive environmental sustainability and social responsibility while maintaining efficiency.

3.2. Offshore oil exploration

Oil drilling dates to 256 B.C., with significant progress made in 1853 with George Bisell's oil sample and Colonel Edwin Drake's large-scale onshore exploration in 1859 [4][5]. Offshore oil exploration began in the late 1940s in the Gulf of Mexico and Caspian Sea. Petrobras, authorized in 1953, faced challenges in Brazil, such as a lack of qualified professionals.

Brazil's first successful oil discoveries occurred in 1939, followed by offshore discoveries in 1968-73 in the Campos Basin. Water depths of 0-300m, 300-1,500m, and above 1,500m define shallow, deep, and ultra-deep waters [6]. Deepwater and ultra-deepwater exploration access untapped hydrocarbon reserves but present high pressures, extreme temperatures, and harsh environments. Technology innovations are needed for the Brazilian oil industry to address such challenges.

PETROBRAS holds a 22% share in global deepwater and ultra-deepwater production, despite uncertainties and dependence on imports [6]. Exploration starts with marine seismic imaging and exploratory drilling, using fixed or floating platforms.

Offshore production systems include fixed or floating platforms, subsea systems, or FPSOs [6] depending on factors like water depth, climate, and resource quantity. FPSOs excel in deep and ultra-deep waters, being the definitive production system, less carbon intensive, in the process of exploring and producing.

After production system installation, development drilling and well completion take place to control oil/gas flow. Transportation involves pipelines or tankers for FPSO systems. Decommissioning includes equipment and structure removal and well abandonment when production becomes unviable [7].

3.3. The Importance of FPSOs in Offshore Exploration

FPSOs are crucial in offshore exploration, offering mobility, deepwater operation, flexibility, and cost savings over fixed platforms. It is essential to highlight the advantages and disadvantages between the chosen production systems, as shown in Table 1.

Table 1: Advantages and disadvantages of production systems.

System	Advantage	Disadvantage
Fixed platforms	Stability, robustness, suitable for harsh weather, ideal for long-lasting fields, lower operating cost	Limited to 500 meters depth, higher installation and decommissioning cost, less flexibility, costly decommissioning
Floating platforms (e.g. Tension Leg Platform - TLP, Spar Platform, Semi-submersible Platform)	Suitable for larger depths (3,000 meters+), adaptable, lower installation and decommissioning costs	Higher operating cost, sensitive to weather and sea movements, costly decommissioning
Subsea Production Systems - SPS	Suitable for extremely large depths (3,000 meters+), lower environmental impact, lower installation, and decommissioning costs	Higher operational, maintenance costs, difficulties in monitoring control
FPSO	Flexible, easy to relocate, storage and offloading capabilities, suitable for short-lived/remote fields, simpler, less expensive decommissioning	Higher operating cost, sensitive to weather and sea movements

Source: Authors.

An FPSO, usually converted from tankers (Very Large Crude Carrier, VLCCs) or purpose-built, has processing equipment on top, separating oil, gas, water, and impurities. Crude oil is stored in the ship's tanks for further discharge into tankers or onshore refinement. The lashing, crucial for stability, is adapted to the environment, ensuring continuous operations for 20 years or more [8].

FPSOs use the Differentiated Anchoring and Compliance System (DICAS) for positioning, incorporating scattered mooring in calm waters and disconnectable mooring systems in cyclone- or hurricane-prone environments. This adaptability enables the vessel to be removed and returned to its position during adverse weather events [8].

Subsea pipelines and risers facilitate oil and gas (O&G) extraction, transporting them to the FPSO for separation and treatment. Treated oil is stored, while gas can be reinjected, used as fuel, or exported. Offloading transfers oil to a tanker for further transportation [6].

Ideal for remote or challenging O&G fields, FPSOs offer a solution where fixed infrastructure is impractical. They are suitable for short-term fields or those with uncertain reserves and can be easily relocated or decommissioned efficiently and cost-effectively [6].

3.4. Characteristics of modern FPSOs

Modern FPSOs, exemplified by FPSO Cidade de Campos dos Goytacazes (MV29), leverage technological advancements for enhanced production, efficiency, and safety, recognized by the World Economic Forum in 2020 [9]. Despite the Oil & Gas sector's traditional resistance to innovation, FPSOs emerged as a definitive exploration solution, as declared by Petrobras [9].

These FPSOs employ converted or purpose-designed tanker hulls, providing increased storage capacity and optimized functionality for specific conditions, including extreme weather [10]. Advanced processing systems, such as multi-stage separators and gas compression, contribute to improved product quality reducing environmental impact [11].

Furthermore, modern FPSOs adopt sophisticated mooring systems like the Turret Mooring System, optimizing safety and efficiency during production and unloading operations [12].

Various mooring systems are available, with the choice based on environmental conditions, such as the use of an inner tower in the hull for locations prone to cyclones and severe marine conditions, like off the northwest of Australia and Hong Kong [13].

These modern FPSOs integrate advanced automation and control systems to remotely monitor and control operations, improving efficiency, safety, and reducing the need for manual interventions.

FPSOs employ efficient and sustainable power generation systems like gas turbines or low-emission diesel engines, along with energy-efficient technologies such as waste heat recovery systems, aligning with Net Zero Carbon commitments [14].

Emphasis on safety and environmental protection is evident through features like fire detection and suppression systems, oil spill prevention, and wastewater treatment, adhering to strict standards like MARPOL and SOLAS [15].

FPSOs are customized for specific oil or gas field requirements, following customer guidelines, and varying in features and technologies. This adaptability positions FPSOs as tools for continuous digital transformation.

3.5. **Challenges of deepwater exploration with FPSOs in Industry 5.0**

The implementation of social manufacturing systems (also known as Cyber-Physical Production Systems - CPPS) in FPSOs was not a widespread practice, however, we can list some of the concepts that are already being applied, and others that may soon contribute to optimizing production and maintenance.

Table 2: Social manufacturing systems to optimize the production and maintenance of FPSOs.

Proposals/Concepts	Detailing
Integration of Sensors and Smart Devices	IoT sensors for real-time monitoring, smart devices for data collection
Advanced Data Analytics	Big data analytics, machine learning algorithms, predictive analytics for equipment maintenance
Real-Time Communication and Collaboration	Real-time communication systems, collaborative platforms for information sharing
Additive Manufacturing (3D Printing)	Production of spare parts and custom components, reducing downtime

Augmented Reality (AR) and Virtual Reality (VR)	Operator training, remote problem diagnosis, computer-aided maintenance
Automation and Remote-control	Automated control systems, remote-control capabilities for FPSO operation and monitoring
Cyber Security	Robust cybersecurity measures to protect data and critical systems from threats

Source: Authors.

The use of sensors and data analysis in FPSOs allows for early problem detection, predictive maintenance, and improved sustainability by optimizing production and reducing costs [16]. Companies must address challenges by embracing social manufacturing systems and adopting innovative, cleaner solutions, including digital technologies like AI, machine learning, and IoT, which enhance FPSO operation and maintenance.

Renewable energies, energy-efficient tech cut fossil fuel use, greenhouse gases. Sustainable practices, biodegradable fluids, biodiversity protection lessen environmental impact. Improved monitoring, fire detection, spill containment boost safety in deep waters.

Collaboration between industry stakeholders, technology providers, and research institutions is crucial for accelerating innovation. Public-private partnerships and joint research initiatives facilitate knowledge sharing and resource-driven FPSO evolution [16].

4. Related studies

4.1. Offshore O&G Exploration Technologies

Seyyedattar *et al.* [17] stresses the importance of technological advances in exploring deep and ultra-deep waters, highlighting the need for modern and innovative methods. It identifies a gap in the literature regarding a comprehensive analysis of specific contributing technologies, which this study aims to fill.

Nnabuife *et al*. [18] concentrate on offshore production and flow control, advocating for a comprehensive riser flow control approach in deepwater exploration. They recommend slugging as a robust flow pattern but do not explore its potential integration with Industry 5.0 principles, a key focus of the present research.

4.2. Deepwater Drilling Practices and Challenges

Shann *et al.* [19] assess the Sureste Basin in southern Mexico as a potential super basin for hydrocarbon exploration, emphasizing uncertainties in deepwater exploration. While their study provides insights into challenges, it lacks exploration of the potential benefits of integrating social manufacturing systems in Industry 5.0, a central concern of this research.

Ojeh-oziegbe *et al.* [20] addresses the need for development in various fields, emphasizing cost containment and efficient technologies in the offshore energy industry. They introduce an innovative single-trip well completion technique for economy, safety, and efficiency, covering design evolution, contractor management, equipment interfaces, operational steps, risks, and lessons learned.

Patel *et al.* [21] spotlights the preference for non-harmful non-aqueous fluids (NAF) in reservoir drilling, presenting the innovative Clay Free Invert Drilling Fluid (CFIDF). Developed with a polymeric rheology modifier, CFIDF offers a clay-free system with constant rheology across temperatures, crucial for deepwater drilling. Field tests show positive performance in drilling rate, ECD control, and well cleanliness, reducing the potential for circulation loss.

4.3. Industry 4.0 and Sustainability

Ghobakhloo *et al.* [22] scrutinizes the sustainability functions of Industry 4.0, employing interpretive structural modeling to unveil complex relationships. The study highlights that economic sustainability, emphasizing production efficiency and innovative business models, takes precedence over socio-environmental sustainability functions. By shedding light on Industry 4.0's potential for global sustainability, the research encourages collaborative efforts for effective and equitable implementation.

4.4. Deepwater Infrastructure and Platforms

Hari *et al.* [23] emphasizes the increasing energy demand driving hydrocarbon exploration in deepwater and ultra-deepwater, where Tension Leg Platforms (TLPs) play a critical role. Their study examines the dynamic response of the shelf restriction system in extreme sea conditions, highlighting the significant increase in stress cycle variation and averaging during severe offshore weather events.

Chandrasekaran *et al.* [24] explore semi-submersible floating structures in deepwater oil exploration, focusing on a restricted positioning system. By evaluating CNOOC's HYSY-981 platform with a sixteen-point catenary mooring system (case 1) and comparing it with a conventional system using a submerged buoy (case 2), numerical analyses reveal the dynamic behavior at different depths. The addition of the buoy improves mooring service life, but failures in adjacent lines adversely affect service life due to load transfer.

4.5. Optimization and Efficiency in Deepwater Operations

Yang & Xiao [25] optimizes ultra-deepwater drilling's operational performance and reduce riser system weight, employing a multi-objective approach with NSGA-II and an RBF metamodel. Objectives include minimizing riser system weight and maximizing operability envelope area, addressing computation and convergence challenges.

De Freitas *et al.* [26] propose a gas-lift optimization workflow for oil wells, crucial for 30% of monthly oil production in Brazil. The method enhances reservoir recovery and gas efficiency, achieving a 0.5% increase in cumulative production, reducing gas consumption, and improving project financials within platform limitations.

Ng *et al*. [27] emphasize preparation for deepwater and offshore hydrocarbon exploration, highlighting Shell Malaysia's Real-Time Operation Centre's role in optimizing well operations. They cover hydraulic management, pressure-controlled drilling, vibration mitigation, well cleanliness, and cost savings through minimized wasted time, underscoring the growing importance of Real-Time Operation Centers.

4.6. Risk Management and Safety in Offshore O&G Projects

Agbadiba & Maduagwu [28] examines deepwater O&G exploration challenges, emphasizing floating platforms and FPSOs in Nigeria's Gulf of Guinea. Use mixed methods (literature review, interviews, online research) to stress safety culture, incident reporting. Propose incident reporting model for better risk management, accident prevention, operational sustainability, profitability in offshore O&G projects.

4.7. Innovative Solutions and Techniques in Deepwater Exploration

Karacali *et al.* [29] introduced a dynamic deepwater well testing solution for multiple and varying reservoirs. The test program involved a rig with a surface well test package to optimize operations, reduce costs, and support the operator's growth plans.

Tjåland *et al*. [30] discussed mineral extraction in deep waters and the similarities in challenges between the mineral and O&G industries. They suggested that oil industry technologies, such as FPSO vessels, can be adapted for deepwater mineral extraction, emphasizing the need for innovation to minimize environmental impact.

Panayirci *et al.* [31] analyzed the structural robustness of a slimmer well design for the FortunaCo project in Equatorial Guinea using a static nonlinear finite element motor. The numerical model proved suitable for estimating critical buckling loads and optimizing the design efficiently during the conceptual phase.

Nardy *et al.* [32] explored developing methods for underwater inspection of subsea equipment, vital for deepwater O&G exploration. They proposed an innovative computational system for generating accurate 3D models of underwater structures, beneficial for planning and executing monitoring and maintenance in the offshore oil exploration and production industry. Feasibility tests confirmed the system's potential usefulness.

5. Final thoughts

This article focuses on offshore O&G exploration, particularly on FPSO systems, and their advantages and disadvantages compared to other systems. It emphasizes the potential of FPSOs to integrate with social manufacturing systems in Industry 5.0, driving industrial development and connecting horizontal and vertical manufacturing processes.

Challenges of using FPSOs in deep and ultra-deep waters are addressed, as well as the benefits of integrating social manufacturing systems, including increased efficiency, safety, and cost reduction. FPSOs play a crucial role in deepwater exploration, and their integration with Industry 5.0 offers new opportunities for optimization and sustainability.

Future research should investigate innovative strategies and solutions for challenges like cybersecurity, industry resistance, and the environmental and social impacts of implementing social manufacturing systems in FPSOs. Other areas of interest include developing simulation and modeling methodologies, such as Digital Twins, for optimizing integration and improving efficiency, safety, and cost reduction in offshore exploration.

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