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Assessing the Reliability and Availability of Offshore Subsea Production Systems: A Comparative Analysis Using ESDs and FTA

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As the demand for oil and gas production from offshore fields grows, the complexity and scale of subsea systems continue to increase. Ensuring the reliability and availability of these systems is critical to minimizing operational risks and maximizing productivity. The layout of subsea production systems plays an important role in achieving these goals, but determining the most efficient configuration remains challenging. This paper discusses four distinct subsea production systems: Satellite, Manifold, Trunkline, and Production loop. To assess the reliability of these configurations, we modeled the systems using a combination of Event Sequence Diagrams (ESDs) and Fault Tree Analysis (FTA), allowing us to capture both the dynamic sequences of events and the potential failure modes within each system. We also considered repair and mobility times for the equipment and pipes, treating these times as exponentially distributed random variables to model downtime and repair logistics uncertainties realistically. By comparing the reliability and availability of each system, we provide a comprehensive evaluation of the trade-offs between design complexity and system performance. The insights gained are expected to guide engineers and decision-makers in selecting subsea production system designs.

Keywords: Subsea Reliability Analysis, Availability Modeling, Subsea Production Layouts. Oil and Gas Industry.

1. Introduction

Due to the depletion of shallow-water reserves and growing energy demands, the oil and gas industry is advancing into deep and ultra-deep waters for hydrocarbon exploration and production (Wu et al. 2023). Subsea processing systems offer potential advantages, including enhanced production efficiency and the minimization of surface infrastructure. However, such systems demand exceptional reliability, as operational interventions during production phases result in extended downtimes and significant financial losses (Bhattacharyya and Cheliyan 2019).

Developing offshore production systems requires comprehensive decision-making regarding subsea infrastructure, including optimal well placement, pipeline network configurations, and subsea layout designs (Silva and Guedes Soares 2021). Offshore operations are capital-intensive, reflecting the demanding marine environment, intricate infrastructure, and ongoing maintenance requirements (Maior et al. 2022). Strategic planning of subsea production systems focuses on evaluating operational performance and optimizing layouts to achieve economically viable solutions while adhering to stringent safety requirements (Bhardwaj, Teixeira, and Guedes Soares 2022).

A critical objective in developing subsea oil and gas production systems is ensuring high production regularity. Production regularity, defined as the ability of a system to maintain consistent output, directly impacts profitability by minimizing downtime and maximizing asset utilization (Hokstad 1988). Evaluating production system configurations, such as Satellite, Manifold, Trunkline, and Production Loop designs, is essential to identify optimal layouts that balance economic and operational criteria.

This study investigates the reliability and availability of four subsea production system layouts.

This methodology models component failures as stochastic exponential events and Monte Carlo simulations are performed to compute reliability and availability metrics over a 20-year operational horizon. Using Event Sequence Diagrams (ESDs), the study evaluates the operational consequences of unavailability, quantifying the expected downtime impact for each architecture.

Through this approach, the study aims to contribute to the optimization of subsea system designs, ensuring reliable operations in increasingly challenging offshore environments.

2. RAM Analysis of subsea layouts

Reliability, Availability, and Maintainability (RAM) analysis of subsea systems provides critical insights into offshore production systems' design, operation, and optimization. Prior studies have laid a strong foundation for understanding subsea system reliability using different methodologies and frameworks. Duell and Fleming (2001) identified essential tools and processes to advance BP's deepwater reliability vision, emphasizing the importance of systematic reliability approaches in reducing downtime and optimizing performance.

Brandt and Eriksen (2001) highlighted the economic implications of subsea interventions, while Brandt (2003) extended this work by integrating risk and reliability to address technical uncertainties in subsea designs.

Romer (2023) and Alhanati and Trevisan (2012) further addressed reliability gaps in electrical submersible pump systems, identifying challenges specific to deepwater operations.

Yasseri and Bahai (2018) proposed a novel framework for assessing the availability of subsea distribution systems during the functional design phase. Their approach provides a decision-support tool for selecting the most suitable subsea distribution system based on availability advantages. By employing the Design Structure Matrix (DSM) mapping method, the framework represents system components and their interdependencies, enriched with reliability data for availability calculations.

Liu et al. (2024) introduced a hybrid approach combining Failure Mode and Effects Analysis and the Fuzzy Fault Tree Approach to assess subsea control systems' reliability. Their method provides qualitative and quantitative insights into system vulnerabilities by systematically identifying failure modes and using a risk matrix to assess their severity.

Our methodology emphasizes modeling reliability and availability in a manner directly aligned with industry priorities—specifically, the impact of unavailability on operations by integrating ESD and FTA.

3. Methodology

This study employs a framework centered on ESDs to evaluate system reliability, availability, and the operational impact of downtime. The methodology integrates stochastic modeling, Monte Carlo simulations, and subsystem-level analysis to provide actionable insights for optimizing subsea production layouts.

3.1. *Modeling Reliability and Unavailability*

System reliability was modeled by identifying failure modes at the component level. Each failure was represented as an exponential event, capturing the stochastic nature of component behavior and failure timelines. ESDs were employed to map the progression of events following component failures, providing a dynamic visualization of failure propagation and recovery actions. This method effectively captures sequential dependencies and system behavior under failure scenarios, critical for understanding operational impacts.

Monte Carlo simulations were used to compute reliability and availability metrics over 20 years. By simulating 10,000 iterations, the methodology accounts for stochastic variations in failure and repair events. The simulation results offer a detailed understanding of system behavior over time, including the expected duration of unavailability for different configurations.

Building upon these reliability and availability analyses, productive efficiency was calculated to assess the impact of failures and recovery actions on system performance. This metric represents the ratio between the effective production achieved and the expected production under ideal conditions, serving as a key criterion for evaluating different architectural configurations.

To determine productive efficiency, the effective operational time of each well was computed by subtracting downtime from the total operational period. The effective production was then estimated by considering this operational time, weighted by the well's contribution to total production, along with any reductions caused by failure events. The overall efficiency of an architecture was obtained by summing the effective production of all wells and dividing it by the expected total production. This approach provides a quantitative measure of how system reliability and failure recovery influence long-term production, offering a comprehensive basis for comparing different configurations.

3.2. *Estimating the Impact of Unavailability*

A specific ESD for each architecture was defined by identifying all failure modes and their consequences. To complement the ESD analysis, FTA was utilized to identify the root causes of failures and calculate the probabilities of system-level failures based on component-level reliability data. This approach enables decision-makers to evaluate the layouts based on their ability to minimize downtime and mitigate production losses, aligning closely with industry priorities.

4. Case Study

Four distinct subsea production layouts were analyzed, each characterized by unique connectivity, redundancy, and flow control mechanisms. These layouts are briefly described in the following subsections.

4.1. *Satellite Layout*

In this configuration, each well is directly connected to the Floating Production, Storage, and Offloading (FPSO) via individual flowlines and risers. This decentralized design minimizes shared components, which may avoid possible common-cause failures. However, it incurs higher installation and maintenance costs due to its extensive infrastructure.

4.2. *Manifold Layout*

This configuration consolidates multiple wells to a shared manifold, reducing the number of flowlines and risers required to reach the host facility. Advantages include early production capability, flexibility for tie-backs, and cost reductions in installation. However, challenges arise with larger manifolds for deepwater reservoirs, as their size and weight increase installation complexity and risk.

4.3. *Trunkline Layout*

Similar to the manifold layout, this design connects wells via a series of flowlines to a central riser base but utilizes Pipeline End Manifolds (PLEMs) instead of traditional manifolds. While reducing flowline redundancy, it introduces potential vulnerabilities to single-point failures.

4.4. *Production Loop Layout*

In this configuration, wells and flowlines are arranged in a circular pattern, offering redundancy in production paths. While this design may enhance reliability, it demands complex flowline arrangements and increases system design and operational complexity.

4.5. *Components*

Each layout consists of shared components such as flowlines, risers, and connectors, with specific variations:

- Satellite Layout: Rigid/flexible flowlines, risers, vertical connection modules, and hydraulic connectors.
- Manifold Layout: Subsea manifolds, choke valves, remote operation valves, and rigid spools.
- Trunkline Layout: PLEMs, rigid spools, and hydraulic connectors.
- Production Loop: In-line Tee (ILT), Production Skids, PLEMs, Rigid Spools.

The primary differences lie in connectivity, redundancy, and flow control. For example, the Satellite layout minimizes shared components, enhancing reliability but at higher costs, whereas the Manifold and Trunkline layouts consolidate connections, reducing installation costs but increasing vulnerability to single-point failures. The Production Loop introduces redundancy but requires more complex flowline arrangements and failure isolation mechanisms.

4.6. Key Assumptions

In order to estimate reliability and availability, we made some assumptions. All subsea production layouts were composed of 12 wells with the same productivity. Also, all layouts included Wet Christmas Trees. However, it was not modeled in this analysis, as the focus was on comparing different components and their arrangements across the layouts.

In addition, component failure data was extracted from the PARLOC (Pipeline and Riser Loss of Containment) and OREDA (Offshore and Onshore Reliability Data) databases. Repair times were modeled as exponentially distributed random variables with a mean of 30 days. Mobilization times followed an exponential distribution with a mean of 90 days.

Monte Carlo simulations were performed with 10,000 iterations to account for stochastic variations in component failure and repair events.

5. Results and Discussion

The reliability and availability analysis over a 20-year operational period revealed distinct performance differences across the four subsea production system layouts. Uncertainties in the modeling process arise from several factors. The failure and repair rates used in the simulations are typically derived from databases such as OREDA or PARLOC, which provide average values based on a broad set of equipment under different operational conditions. These aggregated rates may not fully capture the variability specific to a given system or operational environment. Additionally, assumptions regarding maintenance efficiency and external influences, such as environmental conditions or operational stresses, introduce further uncertainties.

The standard deviation of reliability and availability metrics was calculated to quantify these variations, providing a measure of dispersion around the expected values. This allows for a clearer assessment of the variability in system performance and the degree of confidence in the results obtained. The average availability values and the standard deviation (in parenthesis), considering rigid and flexible flowline options, are illustrated in Figure 1 and summarized below:

- Satellite – rigid flowlines: 99.01% (0.1%)
- Satellite – flexible flowlines: 98.27 (0.7%)
- Trunkline – rigid flowlines: 98.34% (0.6%)
- Trunkline – flexible flowlines: 97.1% (0.8%)
- Manifold – rigid flowlines: 97.66% (0.6%)
- Manifold – flexible flowlines: 96.19% (0.9%)
- Production Loop – rigid flowlines: 98.32% (0.1%)
- Production Loop – flexible flowlines: 97.34% (0.1%).

The Satellite Layout demonstrated the highest availability among all configurations. This outcome can be attributed to its decentralized design, where each well is directly connected to the host facility via individual flowlines and risers. The absence of shared components minimizes the risk of cascading failures, where the failure of one component could propagate through the system. However, this reliability comes at the cost of increased installation and operational expenses, as the system requires multiple flowlines and risers.

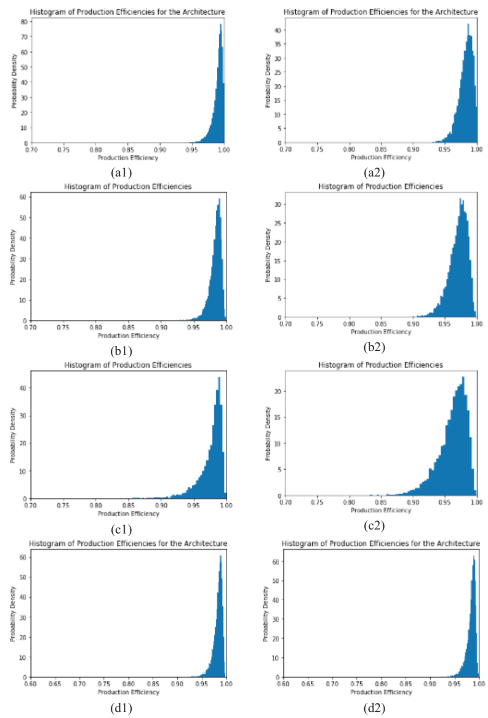

Fig. 1. Productive efficiency of the layout: (a1) Satellite, (b1) Trunkline, (c1) Manifold, and (d1) Production Loop over 20 years with rigid production pipelines; and productive efficiency of the layout: (a2) Satellite, (b2) Trunkline, (c2) Manifold, and (d2) Production Loop over 20 years with flexible production pipelines.

While offering significant cost savings through centralized connections, the Manifold Layout exhibited lower availability than the Satellite Layout. This is primarily due to the increased vulnerability to single-point failures in the manifold itself. Centralized systems inherently concentrate risk, and failure in critical components such as choke valves or the manifold structure can lead to extensive downtime.

The Trunkline Layout strikes a balance between cost and reliability by utilizing PLEMs instead of traditional manifolds. This configuration performed better than the Manifold Layout but lagged behind the Satellite Layout in terms of reliability.

Finally, due to its redundancy in production paths, the Production Loop Layout showed competitive availability results, particularly with rigid flowlines. The circular arrangement of wells and flowlines provides alternative flow paths in the event of component failures, enhancing fault tolerance.

Across all configurations, the use of flexible pipes (risers and flowlines) resulted in a substantial reduction in availability compared to rigid pipes. Flexible pipes exhibited a tenfold higher failure rate than rigid pipes. This disparity arises from material properties, such as fatigue resistance and susceptibility to wear, and operational conditions, including temperature fluctuations and external pressures.

Moreover, the standard deviation values provide key insights into the variability of system performance across different subsea production layouts. A higher standard deviation, as observed in configurations with flexible flowlines, indicates greater fluctuations in availability, suggesting that these systems are more susceptible to operational uncertainties and unpredictable failure patterns. This variability challenges long-term planning and maintenance strategies, as higher uncertainty can lead to unexpected downtimes. On the other hand, configurations with lower standard deviations, such as those using rigid flowlines, exhibit more consistent performance.

The results also highlight the correlation between system complexity and availability dispersion. For instance, the Production Loop layout with rigid flowlines maintains a relatively low standard deviation, benefiting from its redundant flow paths that enhance fault tolerance. In contrast, centralized architectures, like the Manifold layout, exhibit greater variability due to their dependence on shared components that can become single points of failure. These findings underscore the importance of considering the mean availability and the dispersion of results when selecting a subsea system layout.

It is worth mentioning that the choice of the exponential distribution for modeling the system's reliability is based on its widespread use in reliability analysis due to its memoryless property, simplifying calculations, and assumptions regarding constant failure rates. However, this assumption may not always hold in real-world applications, where failure rates can change over time. Alternative models, such as the Weibull distribution, could offer a more flexible representation by accounting for aging effects or early-life failures but were not considered in this initial approach. Indeed, the observed variability suggests that alternative failure models, such as the Weibull distribution, could be explored in future studies to capture the time-dependent nature of failure rates and refine the reliability predictions.

Given these results, the choice of pipe material emerges as a critical factor in subsea system layouts. While flexible pipes may offer ease and adaptability to seabed contours, their higher failure rates significantly impact long-term reliability and availability. Rigid pipes are a more reliable choice for projects requiring extended operational lifespans or higher uptime despite their higher initial costs.

5. Conclusion

This study evaluated the availability of Satellite, Manifold, Trunkline, and Production loop subsea production layouts, providing insights into their respective strengths and vulnerabilities.

The Satellite Layout demonstrated the highest availability, attributed to its decentralized design. However, this reliability comes at the cost of higher installation and operational expenses due to the extensive infrastructure required. In contrast, the Manifold and Trunkline Layouts offer opportunities for cost optimization through centralized connections but exhibit slightly lower availability due to their susceptibility to single-point and cumulative failures. The Production Loop Layout, with its redundant flow paths, provides a balance of fault tolerance and complexity, making it an attractive option.

In addition, the significantly higher failure rates of flexible pipes highlight the need for careful consideration of material selection in subsea layouts, particularly for long-term operations or projects prioritizing high uptime.

To build on these findings, future research will focus on (1) incorporating artificial lift systems into the reliability model to account for their critical role in subsea production, (2) creating a streamlined tool for availability and reliability assessments, enabling rapid and comprehensive evaluation of system configurations and (3) including the components of the control system, which were not modeled in this initial phase.

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