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Underwater Inspection Planning Based on Reliability and Decision-Making Techniques: An FPSO Platform Case Study

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Ensuring the integrity and safety of Floating Production Storage and Offloading (FPSO) platforms is crucial for the oil and gas industry, particularly in offshore environments. A critical component of this is the underwater inspection process, commonly referred to as Underwater Inspection in Lieu of Drydocking (UWILD). Despite its importance, planning such inspections is not trivial and requires a systematic approach that balances risk, reliability, and resource optimization. In this context, this paper proposes a method for planning underwater inspections based on reliability and decision-making techniques. It complies with three main processes: identification of what needs to be inspected, determination of when to inspect, and selection of which inspection method to apply. Each process integrates specific techniques to support the application of the proposed method. First, to prioritize inspection items, potential failure modes are identified, and their effects and criticality are assessed. For determining recommended inspection intervals, life data analysis and degradation analysis are applied to derive reliability functions and data-supported decisions. Finally, for the selection of inspection methods, a Multicriteria Decision-Making (MCDM) approach is used to prioritize inspection techniques based on the specific requirements of each maintenance scope. The proposed method is demonstrated through a case study based on an operational context of a Brazilian FPSO platform. The results obtained show the proposed method can support maintenance planning as it provides structured guidance to systematically define and review the scope of underwater inspections, contributing to the reliability and integrity ensuring. Accordingly, this study is expected to contribute the integration of reliability and decision-making techniques in the field of physical asset management research and the oil and gas industry.

Keywords: Underwater inspection, UWILD, maintenance planning, reliability techniques, FPSO.

1. Introduction

Underwater inspections are critical activities within the scope of physical asset management, particularly for ensuring the integrity and reliability of offshore systems operating in harsh environments. These inspections play a vital role in detecting degradation, preventing failures, and extending the operational life of subsea assets. Floating Production Storage and Offloading (FPSO) platforms, widely used in offshore oil and gas exploration, are one example of such engineering systems that demand rigorous inspection and maintenance strategies to secure safe and efficient operation throughout their service life.

The International Maritime Organization (IMO) is the body responsible for issuing codes and conventions applicable to various types of vessels (IMO, 1974, 2021). In the case of FPSOs, maintenance and inspection activities are typically scheduled based on predefined operating intervals. However, this time-based approach has been widely criticized for its rigidity and limitation to account for the actual condition and performance of the unit (Veruz et al., 2025).

In this context, this paper proposes a method to support the maintenance planning of underwater inspections. The method integrates qualitative and quantitative reliability and decision-making techniques to facilitate data-driven maintenance management of physical assets such as FPSO platforms and other offshore systems. Furthermore, to demonstrate its applicability, the proposed approach is applied to a case study based on the operational context and data from a Brazilian FPSO platform.

This paper is organized as follows: Section 2 presents a brief background on the quantitative reliability techniques, including Life Data Analysis and Degradation analysis. Section 3 presents the proposed method to support the planning of underwater inspections based on reliability and decision-making techniques. Next, Section 4 demonstrates the application of the method to a FPSO platform case study under a real operational context. Finally, Section 5 presents the conclusions about the proposed method and its application in the case study.

2. Fundamentals of Life Data Analysis and Degradation Analysis

This section provides a brief overview of the two quantitative reliability techniques integrated in the proposed method. Other techniques are not addressed for brevity and ease of comprehension in the proposed method and case study.

2.1. *Life Data Analysis*

Life Data Analysis (LDA) is a statistical technique used to evaluate and model time-to-failure data for physical assets, such as machinery, infrastructure, and equipment. Within the context of maintenance management, LDA enables the analysis of asset performance by fitting a probability distribution to time-to-failure data collected from a representative sample of units (HBK, 2024).

By applying LDA, practitioners can make predictions about the expected lifespan and failure behavior of an entire population of assets. This method facilitates the estimation of key reliability metrics, including Mean Time to Failure (MTTF), failure rates, and survival probabilities, providing valuable insights for maintenance planning and decision-making.

In LDA, data is typically collected from testing scenarios or operational environments, reflecting the lifespan of assets under specific conditions. These datasets often include complete failure times, right-censored data (representing items that have not failed by the end of the observation period), and/or left-censored data (representing failures that occurred before the observation period began). Statistical models are then applied to this data to estimate reliability parameters (Modarres et al., 2016).

To obtain the Probability Density Function (PDF) of failure, the collected data must be organized, ensuring that failure times and any censoring information are accurately recorded. Next, a suitable probability distribution model is selected based on the characteristics of the dataset through adherence tests, with common choices being the Weibull, exponential, or lognormal distributions. Then, the parameters of the chosen distribution are then estimated using statistical methods such as Maximum Likelihood Estimation (MLE) (Modarres et al., 2016).

Once the parameters of the PDF of failure are determined, the reliability function R(t), the cumulative failure function F(t), and the failure rate function h(t) can be derived using the equations specific to the selected probability distribution. These functions enable engineers to assess the likelihood of failure over time, providing insights for maintenance planning and decision-making.

2.2. *Degradation Analysis*

Degradation analysis is a statistical technique used to evaluate the gradual deterioration of a system or component over time, allowing for the estimation of its Remaining Useful Life (RUL) (Gorjian et al., 2010). It involves measuring performance data directly related to the presumed failure of an item, allowing analysts to link failure mechanisms to asset degradation and extrapolate an assumed failure time based on degradation measurements over time (HBK, 2024).

Unlike LDA, which relies on discrete failure times, degradation analysis utilizes measurement data of a system's condition, such as corrosion, wear, or performance decline. By monitoring degradation over time, this technique provides a more detailed understanding of how an item approaches its failure threshold, enabling more precise predictions regarding the timing of maintenance or replacement interventions.

The degradation analysis typically begins by collecting historical monitoring data. This dataset is the basis for modeling the degradation process. Then it is necessary to determine the failure threshold, a predefined level of degradation beyond which the component is considered to have failed (Gorjian et al., 2010). By fitting a model to the degradation trajectory and projecting it forward, analysts can estimate the time at which the degradation level will reach the failure threshold.

A key aspect of degradation analysis is the extrapolation of degradation trajectories to predict when each item will reach the failure threshold. By plotting the degradation data for multiple items or historical degradation records, each trajectory is extended to estimate the time at which the degradation level crosses the predefined threshold. For example, if degradation data for seven items are analyzed, seven distinct failure times can be extrapolated. These failure times form the basis for estimating the parameters of the PDF through methods such as MLE.

Finally, the extrapolation process can be performed using various regression models such as linear, exponential, power, logarithmic, Gompertz, and Lloyd-Lipow (HBK, 2024), depending on the nature of the degradation data. The choice of model should be guided by its ability to adequately represent the observed degradation behavior, ensuring accurate projections of failure times and robust reliability analysis.

3. Proposed Method

This paper proposes a novel method to support the planning of underwater inspections based on reliability and decision-making techniques. This method includes three main processes: Identification of what needs to be inspected (I), Determination of when to inspect (II), and Selection of which inspection method to apply (III). It is detailed and illustrated in Fig. 1.

3.1. *Identification of what needs to be inspected*

The proposed method begins with the process to identify the items that require underwater inspection. The first activity involves accessing the portfolio of items, which is usually available in a Computerized Maintenance Management System (CMMS) such as IBM MAXIMO or SAP. However, if the organization does not utilize such systems, the portfolio should be manually compiled.

It is important to note that not all items within the portfolio are relevant for UWILD. For instance, FPSO topside systems and other components located above the waterline are physically excluded from underwater inspection planning, as they are better suited for alternative inspection approaches. Thus, an applicability assessment is conducted in the second activity of this process to identify the items applicable for underwater inspection.

Once the items eligible for underwater inspection have been identified, a systematic study is required to understand their functions, potential failure modes, and potential failure effects. This analysis is carried out through the three subsequent activities of the process, which are typically performed in qualitative reliability techniques such as Failure Mode and Effects Analysis (FMEA) and Reliability-Centered Maintenance (RCM).

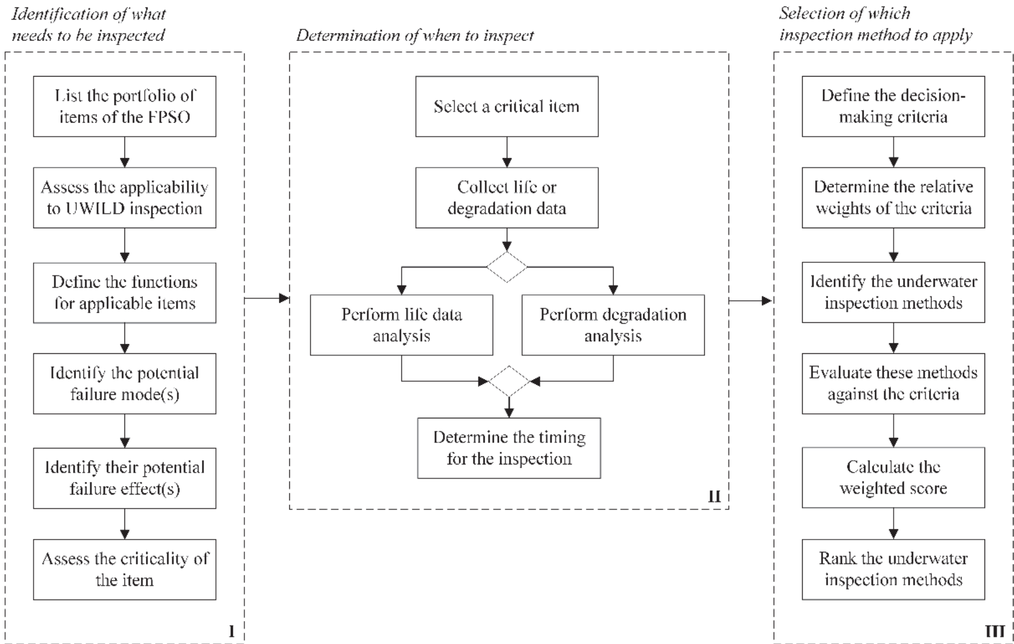

Fig. 1. The proposed method to support the planning of underwater inspection based on reliability and decision-making techniques

Finally, based on the results of the item study, a criticality assessment is conducted to identify whether it is a critical item. A critical asset is one having potential to significantly impact on the achievement of the organization's objectives and it can be critical in safety, environment, or performance and can relate to legal, regulatory, or statutory requirements (ISO, 2014). Thus, critical items are recommended to be considered to underwater inspection and input for the following processes as criticality is an important property of physical assets that influences maintenance planning decisions (Silva et al., 2021).

3.2. *Determination of when to inspect*

The second process was designed to support the determination of inspection intervals using quantitative reliability techniques. The sequence of activities is performed for each critical item, which is why this process begins with the selection of a critical item.

For determining when to inspect an item, the proposed method relies on data-driven decision. Depending on the item, this data may include failure history, known as life data, or measurements obtained through degradation monitoring. After collecting the relevant data, each item is analyzed using one of the reliability techniques "Life Data Analysis" or "Degradation Analysis", as illustrated in Fig. 1.

Both techniques are applied to determine the parameters of a Probability Density Function (PDF). In reliability analysis, the two-parameter Weibull distribution is commonly used due to its flexibility and applicability across various failure scenarios. For Life Data Analysis, the times of previous failures of the item are used as a sample to estimate the Weibull parameters. On the other hand, in Degradation Analysis, time estimates for reaching the failure threshold are used as a sample for Weibull parameter estimation.

From the PDF, it is possible to derive the Reliability Function (R(t)) in the case of LDA, as well as to calculate the probability of the item reaching the threshold within a specified time t. Both approaches enable data-driven decisions of the timing of the next underwater inspection.

For instance, based on a reliability requirement for an item, it is possible to estimate the time at which the item reaches the minimum acceptable reliability level. Using this time frame, inspections can be scheduled within the interval. Similarly, it is possible to estimate the remaining time for the item to reach a specified probability of exceeding a specific degradation threshold. Based on this estimate, inspections can also be planned accordingly.

3.3. *Selection of which inspection method to apply*

After defining which items to inspect and determining the appropriate timing through the previous processes, the third and final process focuses on selecting the most suitable inspection method for maintenance inspection execution. The proposed sequence of activities is grounded in a Multicriteria Decision-Making (MCDM) theory, beginning with the identification of relevant criteria.

The selection criteria should reflect the organization's operational context, alongside the priorities and expectations of the decision-makers. Thus, it is recommended that the list of criteria is reviewed and validated by a panel of experts within the organization. Once the criteria are established, the subsequent activity involves assigning their respective weights to indicate relative importance.

Various techniques are available to assess the preference of criteria, including the swing weighting method, as outlined in the Simple Multi-Attribute Rating Technique (SMART) (Goodwin and Wright, 2014) and pairwise comparison approaches utilized in the Analytic Hierarchy Process (AHP) (Saaty, 1987). In both cases, expert elicitation method plays a crucial role in supporting and accurately reflecting the relative weights for the criteria.

With the relevant set of criteria and their relative weights established, following a value-focused decision-making approach, the next step in the proposed process is to identify underwater inspection methods as alternatives to be assessed against each criterion. This can be done through different means, such as a systematic approach involving a review of literature or service providers, or through expert elicitation using a non-systematic approach.

Next, each applicable inspection method for the item or set of items is evaluated against each criterion. In the final two activities, the scores are aggregated using a weighted sum to rank the most suitable alternatives. Inspection methods with the highest aggregated scores are indicated the most appropriate for underwater maintenance inspection planning.

4. Case Study

In this paper, the proposed method is demonstrated through the maintenance inspection planning of a Brazilian FPSO platform within a real operational context. This case study incorporates collected data on physical assets alongside expert knowledge provided by technical personnel. Accordingly, this section presents the results obtained from applying the three main processes, as illustrated in Fig. 1.

The proposed method demonstration begins with the process of identifying which FPSO items require underwater inspection, following the sequence of seven activities. First, the portfolio of FPSO items was obtained from the organization's CMMS, which identified eight systems, as presented in Table 1.

Table 1. FPSO systems portfolio

Id	System description
1	Hull
2	Water intake system
3	Spread mooring system
4	Towing system
5	Riser system
6	Water discharge system
7	Topside system

A numerical identifier was assigned to each FPSO system to establish a hierarchical structure with its subsystems and components. For instance, the water intake system (2) is divided into two subsystems: the sea chest subsystem (2.1) and the seawater lift subsystem (2.2). Each subsystem can also be further detailed to specify its components.

From the complete list of items derived from the FPSO systems portfolio, the applicability of each item to underwater inspection was assessed. Items located entirely above the waterline were disqualified, while those below the waterline were deemed applicable to UWILD. It is worth noting that some items are situated in the splash zone, a region where the item's position relative to the waterline can vary. These items were considered potentially applicable due to their dependency on the platform's cargo status.

Out of a total of 39 assessed items, 14 FPSO items were classified as applicable for underwater inspection, while 13 were classified as potentially applicable. Consequently, the subsequent four proposed activities of the process were performed for these 27 items. Given the scope and depth of the systematic study conducted on this set of items, this paper presents the obtained results only for a subset of applicable items in Table 2.

Table 2. Example of study of applicable and potentially applicable FPSO items for UWILD

<table>
<tr><th>Item</th><th>Function</th><th>Potential failure modes</th><th>Potential failure effects</th><th>Criticality</th></tr>
<tr><td rowspan="2">1.1 Hull plating</td><td>Ensure the watertight integrity of the unit</td><td>Hull breach</td><td>Ingress of water into the unit's internal compartments; Loss of buoyancy; Environmental damage due to hydrocarbon leakage</td><td rowspan="2">Critical</td></tr>
<tr><td>Withstand external loads</td><td>Reduced plate thickness</td><td>Increased stress on hull plates; Hull breach</td></tr>
<tr><td rowspan="5">2.1.1 Sea chest grating</td><td rowspan="3">Prevent large debris from entering the sea chest</td><td>Deformed grating elements</td><td rowspan="3">Obstruction of the seawater intake system, leading to reduced efficiency or complete operational failure of the dependent systems</td><td rowspan="5">Critical</td></tr>
<tr><td>Reduced thickness of grating elements</td></tr>
<tr><td>Fracture of grating elements</td></tr>
<tr><td rowspan="2">Allow seawater intake</td><td>Partially obstructed grating</td><td>Decreased efficiency of systems reliant on seawater intake from the sea chest</td></tr>
<tr><td>Completely obstructed grating</td><td>Operational failure of systems dependent on seawater intake from the sea chest</td></tr>
<tr><td rowspan="5">3.8 Mooring lines</td><td rowspan="5">Keep the FPSO anchored and aligned with environmental conditions</td><td>Fracture of chain link body</td><td rowspan="4">Chain breakage; overloading of the remaining mooring lines, potentially leading to the failure of one or more lines and allowing unintended FPSO movement</td><td rowspan="5">Critical</td></tr>
<tr><td>Fracture of chain link weld</td></tr>
<tr><td>Corroded chain</td></tr>
<tr><td>Steel wire rope rupture</td></tr>
<tr><td>Fractured anchor shackle</td><td>Line detachment; overloading of the remaining mooring lines, potentially causing the failure of one or more lines and resulting in unintended FPSO movement</td></tr>
</table>

From the 27 assessed items, a total of 16 were identified as critical. In addition to the three items presented in Table 2, other examples of critical items include the bilge keel (1.5), seawater lift piping (2.2.1), caisson submersible pump (2.2.2.2), fairleads (3.7), and discharge valve grating (6.4). The set of critical items serves as the input for the second process, which focuses on determining the optimal timing for inspection.

As presented in Fig. 1, the modeled process for determining when to inspect these items involves a sequence of activities based on quantitative reliability techniques. Due to its criticality to the structural integrity of FPSO platforms, in this paper, the item hull plating (1.1) was selected to demonstrate this process. While the other critical items are not addressed in this case study, their inspection schedules should likewise be determined using the same process.

Once the critical item was selected, the hull maintenance data for the hull plating was collected through the periodic measurement maintenance plan reports. Given the structural nature of the hull plating and the characteristics of the available data, a degradation analysis approach was applied to support decision-making. To illustrate this process, a specific plate from the FPSO hull was selected, and the measurement history at five points on this plate is presented in Table 3. Additionally, it also includes the as-built thickness measurement and the thickness threshold that defines substantial material loss.

Table 3. Example of hull plating thickness history

#	As built thickness	After 10 years	After 15 years	Threshold thickness
1	36,5 mm	35.5 mm	35.0 mm	25,2 mm
2	36,5 mm	35.6 mm	35.0 mm	25,2 mm
3	36,5 mm	35.8 mm	34.8 mm	25,2 mm
4	36,5 mm	35.7 mm	35.0 mm	25,2 mm
5	36,5 mm	35.4 mm	35.0 mm	25,2 mm

Based on the degradation data for this hull plating, a degradation analysis was conducted using ReliaSoft Weibull++ software. For each measurement point on the plate, the degradation trend was extrapolated using a linear regression model, which demonstrated the best fit to the data according to the Kolmogorov-Smirnov test. The results of this analysis are shown in Fig. 2.

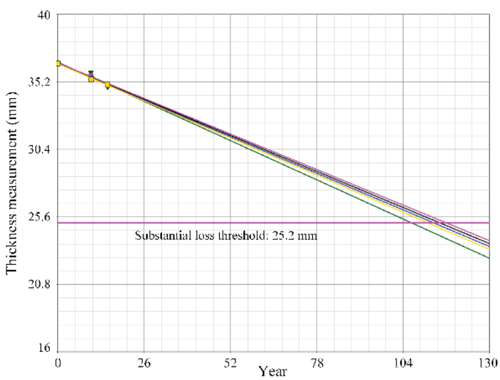

Fig. 2. Degradation analysis of the thickness hull plating through linear regression

From the linear regression models applied to the five measurement points, one time-to-threshold estimates were obtained for each degradation trend, corresponding to the moment when the hull plating reaches the predefined substantial loss thickness threshold. Then, these five time estimates were used to fit a 2-parameter Weibull distribution through MLE. The obtained shape parameter β was 29.17 while the scale parameter η was 114.28. The PDF for this Weibull distribution is presented in Fig. 3.

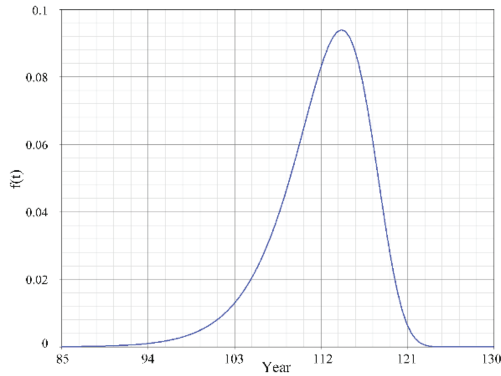

Fig. 3. PDF of the 2-parameter Weibull distribution fitted to threshold time estimates.

For the 2-parameter Weibull distribution, with the estimated parameters, the reliability function R(t) is given by Eq. (1).

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} = e^{-\left(\frac{t}{114.28}\right)^{29.17}} \quad (1)$$

This equation can be applied to determine the timing for the next underwater inspection based on predefined reliability requirement such as 90% or 95%. These reliability requirements correspond to t values of approximately 106.28 years and 103.69 years, respectively. In practical terms, this analysis suggests cumulative failure probabilities of 10% and 5% at these intervals.

The inspections were conducted with a five-year interval and the degradation analysis indicates it could be extended. However, the analysis was based on only two thickness measurements besides the as-built thickness, highlighting the need for additional data to improve the model and enhance understanding of the degradation process. As recommendation, extending the five-year interval but aligning it with the maximum interval allowed by the classification society would enable incorporating new measurements into the analysis, updating the PDF, verifying reliability requirements, and guiding future inspection planning while considering the degradation analysis results.

Finally, the third and final process of the proposed method focuses on selecting the appropriate underwater inspection method. The details of this process are beyond the scope of this paper, as they have been thoroughly addressed in previous work (Veruz et al., 2024).

Therefore, only an overview of the activities and results will be discussed here.

Seven criteria were established to support the decision-making process regarding the selection of an appropriate UWILD method, considering both the operational context of the organization and the specific characteristics of the FPSO. The cost-related criteria included "Initial investment" and "Operational cost", while the benefit-related criteria comprised "Detection ability", "Mean Time to Failure", "Operational maturity level", "Robustness to environmental aspects", and "Automation level".

The relative weights of the criteria were determined using the swing weighting approach (Goodwin and Wright, 2014) with expert support. For each criterion, a scale was developed to assess the performance of the underwater inspection methods. The list of methods was compiled based on a literature review, which aimed to identify UWILD methods employed in FPSOs and their specific inspection focus, such as detecting corrosion and cracks (Veruz et al., 2024). The methods were ranked based on their global scores, calculated as the weighted sum of performance across all criteria, guiding the recommendation of the most suitable method.

5. Conclusion

Maintenance management of underwater physical assets is critical for structural integrity, safety, and operational availability of offshore oil and gas operations. In this context, the present work proposed a method to support the planning of underwater inspections based on reliability and decision-making techniques. Although designed to be applicable to various physical assets of asset-intensive industries, the proposed method is recommended and demonstrated to the offshore installations such as FPSO platforms.

As a result, the proposed method showed its potential to systematically address three key aspects of underwater inspection planning: determining what to inspect, when to inspect, and how to inspect. Thus, it is expected this study contributes to the integration of reliability analysis and decision-making techniques in the field of physical asset management research and the oil and gas industry.

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