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Reliability Assessment of Fairleads in FPSO Units Based on Expert Elicitation

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Fairleads are critical components of the mooring systems in Floating Production Storage and Offloading (FPSO) vessels, designed to guide anchor lines and withstand significant operational stresses. The reliability of these components is essential to ensure the safety and integrity of offshore operations, particularly given the harsh environments and extended service lives of FPSO units. However, the lack of historical failure data for fairleads poses significant challenges to reliability assessments, as their robust designs and high safety factors result in minimally recorded failures. Traditional inspection intervals, dictated by classification society rules, may not fully account for the specific operational conditions and reliability requirements of fairleads. Additionally, the application of rigorous theoretical models is often impractical due to the absence of sufficient data and the complexity of these offshore systems. In this context, expert elicitation emerges as a practical solution to address these limitations and to support reliability assessments and inspection planning. This paper presents a structured methodology for eliciting expert judgments, including the selection of experts, questionnaire design, and the integration of elicited data into reliability models. The proposed approach is demonstrated through its application to fairleads in a Brazilian FPSO fleet, showcasing its effectiveness in deriving probabilistic reliability estimates and determining optimal inspection intervals. The results highlight the potential of expert elicitation to enhance maintenance strategies, ensuring the long-term operational soundness of critical offshore equipment.

Keywords: Expert Elicitation, Expert Judgement, Fairlead, FPSO, Inspection Interval Selection, Reliability Assessment.

1. Introduction

Floating Production Storage and Offloading (FPSO) units plays a fundamental role in offshore oil and gas exploration, serving as ship-shaped platforms for processing and storing oil. These units rely on robust mooring systems, composed of anchors, chains, mooring lines, and structural components, to maintain their position during extended operations. Among these components, fairleads are critical devices that guide anchor lines, cables, or chains, ensuring structural integrity by absorbing horizontal stresses and mitigating their impact on the mooring system. The fairlead system includes elements such as pulleys that enable controlled rotation between chain links, as adapted de Andrade e Nishimoto (2017) in Fig. 1.

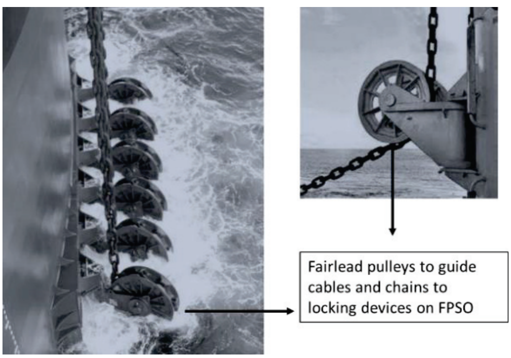

Fig. 1. Fairleads of FPSO platform.

The design and positioning of fairleads play a crucial role in optimizing the performance and reliability of FPSO mooring systems. A widely adopted solution to minimize out-of-plane bending fatigue on chains in permanent mooring systems is the use of articulated fairlead chain stoppers (Kai-Tung et al., 2018). These devices, incorporating gimbals or universal joints, enhance structural integrity by reducing stress concentrations. Furthermore, using thick plates in the welded foundations of fairleads is essential to guarantee robustness under extreme operational conditions (Martins, 2019).

Careful specification of various parameters, including the positioning of anchors and fairleads, is critical during the design of mooring systems, as these significantly influence the forces acting on mooring lines (Amaral, 2020). Fairlead positioning, in particular, significantly impacts structural fatigue, providing valuable guidance for safe and efficient operations in deep-water environments (Naga and Assidiq, 2024).

Although fairleads are designed with high safety factors to ensure reliability, inspection requirements from classification societies mandate periodic evaluations of fairleads and other mooring system components to maintain structural integrity. Typically, inspections are scheduled twice every five years, based on predefined intervals that do not necessarily reflect the actual operational conditions or potential degradation of the equipment. Thus, since FPSO mooring systems include numerous lines, inspection costs are considerable.

To optimize inspection intervals while maintaining safety standards, classification societies allow the adoption of Risk-Based Inspection (RBI) strategies. These strategies aim to balance maintenance costs and operational safety by selecting inspection intervals based on the estimated reliability of critical components.

However, applying RBI concepts to fairleads presents a significant challenge due to the scarcity of historical failure data. The limited occurrence of failures in fairleads, attributed to their robust design and the preventive maintenance measures implemented, makes it difficult to establish probabilistic models based solely on life data analysis. Bhardwaj et al. (2018) identified anchor system failures as accounting for 4.19% of offshore incidents between 1980 and 2005, but specific fairlead failures were not distinguished. Similarly, McKeow et al. (2011) described fairlead failures related to missing axle retaining bolts, discovered during remote inspections, which placed additional strain on remaining components and required extensive maintenance. These examples highlight the lack of failure data required for traditional reliability modeling.

In the absence of sufficient data, expert elicitation becomes a valuable approach to support reliability assessments and inspection planning. By leveraging the knowledge of professionals with extensive experience in FPSO operations, expert elicitation enables the estimation of failure probabilities and the modelling of equipment reliability. This approach is particularly useful when traditional life data models are insufficient due to limited recorded failure events.

In this context, this paper presents a structured methodology for eliciting expert opinions to assess the reliability of fairleads in FPSOs and support inspection planning. The methodology encompasses expert selection, questionnaire design, and the integration of elicited data into probabilistic reliability models. A case study involving a Brazilian FPSO fleet demonstrates the proposed approach, providing valuable insights into the application of expert elicitation to evaluate reliability and ensure the operational integrity of critical offshore assets.

This paper is organized as follows: Section 2 provides a literature review on expert elicitation techniques and their application in reliability assessment. Section 3 presents the proposed method to assess reliability based on expert elicitation. Next, Section 4 demonstrates method to an FPSO platform case study in a real operational context. Finally, Section 5 concludes by discussing the proposed method and its application to the case study.

2. Literature Review

Expert elicitation has become an essential tool in reliability assessment, particularly for complex systems like FPSO units, where historical failure data are often scarce. Ayyub (2001) defined the expert-opinion elicitation process as a formal heuristic method to gather information or answers to specific questions about uncertain parameters, such as failure rates, consequences of failures, and service life estimates. This process provides a structured framework to quantify uncertainties and support decision-making, making it highly relevant for evaluating the reliability of offshore equipment.

Bedford et al. (2006) emphasized the importance of addressing potential judgmental biases in expert elicitation processes. Their work advocates for methodologies that generate rational consensus about uncertainties, ensuring that reliability assessments remain objective throughout the engineering design process. Babuscia and Cheung (2014) also highlighted the challenges of integrating multiple and often conflicting expert opinions, proposing a methodology based on probabilistic thinking, calibration, elicitation, and expert aggregation to address these issues effectively.

Colson and Cooke (2018) recognized that existing data and modelling tools often fail to provide decision-makers with all the necessary information to optimize reliability and maintenance strategies. To bridge this gap, expert judgment is frequently used to quantify uncertainties about unknown parameters, such as component failure probabilities, through formalized elicitation procedures.

Fuzzy Set Theory (FST) has also been applied to enhance the expert elicitation process. Suh et al. (2021) proposed a methodology that uses FST to combine expert opinions, assigning weights to individual judgments rather than relying on a collective deliberation process. This approach ensures that all perspectives are considered, providing a robust framework for reliability assessments under conditions of significant uncertainty.

Practical applications of expert elicitation have demonstrated its versatility across various industries. Jenkins et al. (2022) applied structured expert elicitation to determine failure rates of offshore wind turbine components. By asking experts to estimate percentiles of theoretical reliability distributions, the study successfully derived probabilistic models for maintenance planning. Similarly, Leite et al. (2022) addressed the challenges of reliability assessment and inspection planning for railway assets, proposing a structured expert judgment method to quantify uncertainties in long-service-life components, a scenario analogous to offshore systems.

This body of work underscores the critical role of expert elicitation in overcoming the limitations of traditional reliability modelling techniques, particularly in contexts where data are sparse or incomplete. By synthesizing insights from these studies, this paper builds on established methodologies to propose a tailored approach for assessing the reliability of fairleads in FPSO units.

3. Methodology

Traditionally, reliability assessment relies on historical failure data collected over the life cycle of the item under analysis. This process involves five key steps: (1) Gather failure data; (2) Structure failure data; (3) Calculate the times to failure; (4) Estimate the parameters of statistical distribution for failure occurrence and (5) Predict the reliability of the item. Accordingly, Fig. 2 illustrates this traditional method for reliability analysis using historical life data.

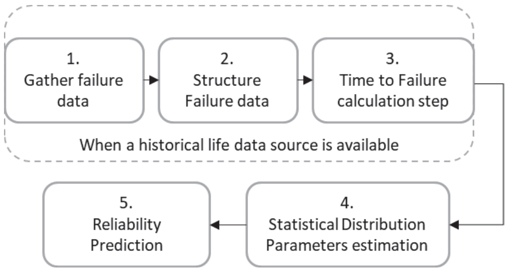

Fig. 2. Traditional reliability prediction method based on historical life data.

However, for items or systems designed with high safety factors, failure events may not occur during their entire operational life. In such cases, even when historical data are available, they are often recorded with low accuracy, making their treatment time-consuming and resource-intensive. These limitations underscore the need for alternative methods to assess reliability when historical data are incomplete or unreliable.

To address these challenges, the proposed methodology in this paper combines the principles of reliability theory, based on Life Data Analysis (LDA), with the time-proven expert elicitation process. This hybrid approach is particularly useful for evaluating the reliability of items such as components, equipment, or systems where historical failure data are sparse or unavailable.

The proposed methodology consists of the following steps, as shown in Fig. 3:

- Questionnaire Elaboration: A structured questionnaire is developed to elicit expert judgments on reliability-related parameters. The questionnaire is carefully designed to ensure that the experts can provide relevant and actionable insights.
- Expert Recruitment: Professionals with substantial expertise in the design, supply, logistics, installation, operation, or maintenance of the analysed item are selected. Their diverse expertise ensures that the elicited data comprehensively reflects operational realities.
- Questionnaire Submission: The questionnaire is submitted to the selected experts, whose responses provide the primary input for the reliability analysis. These responses reflect their beliefs about failure intervals and reliability parameters.
- Statistical Distribution Parameter Estimation: The data collected from the experts are used to estimate the parameters of statistical reliability distributions, such as Weibull or exponential distributions. This step translates expert judgments into a probabilistic framework.
- Reliability Prediction: Using the estimated distribution parameters, the reliability of the item is predicted for specific points in time. This step supports the definition of inspection intervals based on reliability targets.

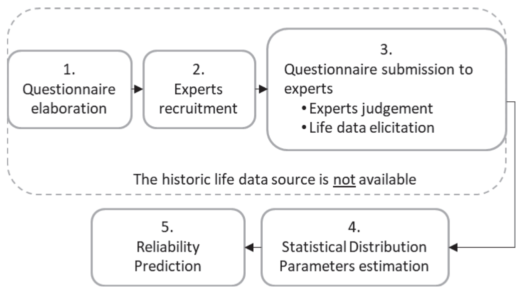

Fig. 3. Proposed reliability prediction method based on expert elicitation

The expert elicitation process plays a pivotal role in this methodology. By submitting a carefully structured questionnaire to professionals with relevant expertise, it is possible to gather quantitative data, such as the estimated number of failures over the item's lifecycle. These data provide the necessary input for developing a probabilistic model capable of predicting the reliability of the item under analysis.

The proposed methodology enables the creation of a reliability model that establishes the probability of failure at different phases of the item's operational campaign. Based on the experts' input and the statistical models, reliability predictions can be made for specific time intervals. In this paper, a reliability threshold of 85% is considered good practice for defining inspection intervals, ensuring a balance between operational safety and inspection efficiency.

4. Case Study

A fairlead system was selected as the focus of this case study to implement the proposed methodology. Fairleads are manufactured using high-resistance materials and are subjected to operational stresses significantly below their maximum capacity, which explains the absence of severe failures during their operational life. Historical documents, covering inspection reports from an FPSO fleet between 2006 and 2024, were analysed, and no high-severity failure events were identified. Consequently, expert opinion was explored to gather reliable information and support inspection plan development.

4.1. *Experts' elicitation process through reliability interviews*

The expert elicitation process consisted of five interview sessions. The selected experts had over 20 years of experience in FPSO mooring systems and had worked with a fleet of five vessels for 11 years, involving a total of approximately 130 fairleads. The elicitation sessions were guided by a structured reliability questionnaire containing 20 questions that covered aspects of operational performance and failure events specific to FPSO fairleads, as summarized in Table 1.

Experts expressed that, due to the robust design of fairleads and the absence of observed failures, they could not estimate the percentiles of the failure probability distribution, as described by Jenkins et al. (2022). Instead, it was proposed an alternative approach by considering failures in the fairlead's subsystems, such as cathodic and mechanical protection systems, which could be modelled as a series system of components. Table 2 presents the abnormalities identified during inspections and their occurrence frequencies.

The experts were unable to provide precise information on the moments at which the abnormalities occurred. It is considered in this study that each type of event occurred as data grouped and in different pieces of equipment, i.e., for A1, abnormalities were detected in 2 fairleads while the other 128 fairleads were considered as suspensions during the 11 years of operation. Based on such information and the occurrence frequency for the four types of abnormality events, the analyst estimated the parameters for the construction of the reliability prediction statistical model.

Table 1. Questionnaire content summary

Topic	Objective
Most frequent failure modes	Identify which failure modes can be triggered by abnormalities found during inspections.
Failure modes occurrence frequency	Obtain each failure mode occurrence frequency based on the expert's practical experience.
Failure modes severity	Verify the degree of severity of failure modes triggered by the evolution of identified abnormalities.
FPSOs' operational particularities	Assess if, due to operations in sites subjected to different Ultimate Limit State (ULS) conditions, there might be a meaningful impact on the occurrence frequency of failure events in fairleads.
New failure modes	Add new failure modes not identified during the data-gathering phase.

Table 2. Abnormalities occurrence frequency

Id.	Abnormalities description	Qty. events
A1	Drop of cathodic protection due to poor fixation of anodes	2
A2	Anchor line misalignment and rubbing on fairlead's lateral structure	2
A3	Low electrochemical potential at fairlead pulley	16
A4	Low electrochemical at fairlead structure	1

4.2. *Statistical model*

The statistical Weibull distribution parameters were estimated using the Maximum Likelihood Estimation (MLE) method, a robust and efficient approach for parameter estimation when data adhere to a specific statistical distribution. For this study, the Weibull distribution was chosen due to its versatility and adaptability to various failure patterns.

The shape parameter (β), also referred to as the shape of the Weibull distribution, and the scale parameter (η), which determines the variability of life data, were calculated for each abnormality type and are presented in Table 3.

Table 3. Weibull parameters for abnormality events

Abnormality Id.	β	η
A1	2.6	54.7
A2	2.48	79.4
A3	2.29	37.4
A4	2.76	64.2

For the abnormalities reported during the interviews, the PDF function was determined using Eq. (1), with t in years:

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

Fig. 4 illustrates the Probability Density Function (PDF) curves for each identified abnormality, along with the combined PDF curve representing the overall fairlead system behavior.

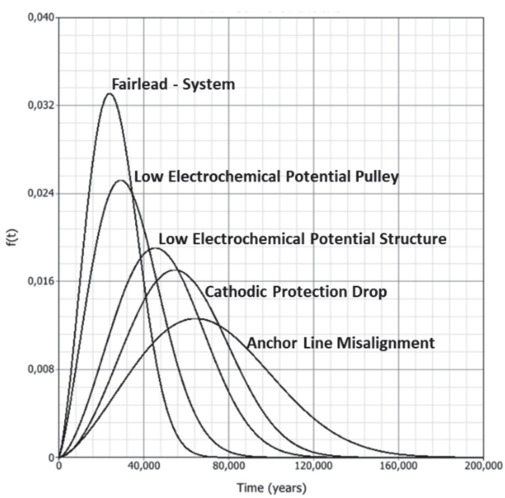

Fig. 4. Abnormalities PDF curves.

This combined curve was derived using the Reliability Block Diagram (RBD) technique, which models the dependencies among the identified abnormalities. The RBD approach calculates the overall system reliability as the product of the reliabilities of its individual components. Both the RBD diagram and the PDF curves were generated using Reliasoft Weibull++ software.

The RBD associating the different fairlead types of abnormalities is shown in Fig. 5. In this configuration, the reliability of the system is calculated as the product of the reliabilities of individual blocks.

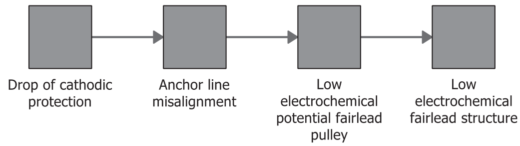

Fig. 5. RBD for fairlead abnormalities

Whenever an abnormality occurs, corrective intervention must be carried out on the fairlead. This necessity explains why the modeled blocks are arranged in series within the reliability system. Considering the PDF curve for the fairlead system, with parameters $\beta = 2.6$ and $\eta = 31.4$ years, the B15 life was determined to be 14 years, corresponding to a reliability value of 85%.

4.3. *Inspection interval indication*

The decision regarding the initial inspection interval was based on the Cost Per Unit of Time (CPUT) which is common for determining optimal intervals for preventive maintenance activities such as restoration or replacement. Thus, it was applied to determine the optimal inspection interval for the fairlead system. The CPUT analysis incorporates both the reliability curve, R(*t*), defined for the fairlead, and the associated costs of planned inspections, relative to the costs of corrective maintenance.

For the calculation of the CPUT curve, Eq. (2) was applied, where C_{insp} represents the cost associated with inspection activities, C_{corr} corresponds to the cost of corrective maintenance tasks, and R(*t*) is the reliability at time *t*:

$$CPUT = \frac{C_{insp} \cdot R(t) + C_{corr} \cdot (1 - R(t))}{\int_0^t R(t)dt} \quad (2)$$

According to expert assessments, the cost of corrective maintenance was estimated to be 25 times greater than the cost of planned inspections. Based on this assumption, the optimal inspection interval for the fairlead system was determined to be 11.5 years. This result is illustrated in Fig. 6, which presents the CPUT curve generated using Reliasoft Weibull++ software. It is noteworthy that the optimal inspection interval of 11.5 years, as indicated in the CPUT graph, is shorter than the

14 years derived from the PDF curve, where the reliability value equals 85%. However, the reliability curve also shows that at the 11.5-year mark, the fairlead system retains a reliability level of approximately 91%.

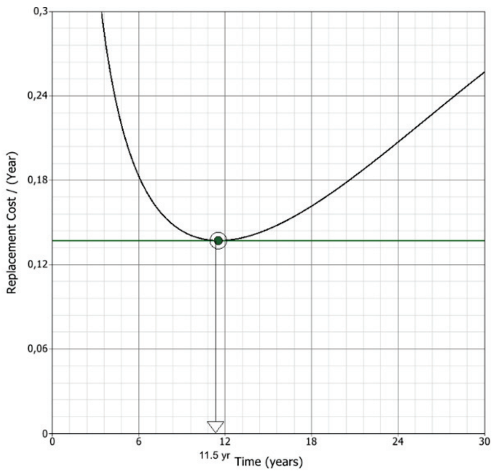

Fig. 6. Graph of fairlead CPUT curve.

The discrepancy between the inspection interval suggested by the PDF curve (14 years) and the interval optimized by the CPUT analysis (11.5 years) highlights an important distinction between reliability-focused and cost-driven decision-making criteria. While the PDF establishes a threshold of 85% reliability for determining the fairlead's operational life, the CPUT analysis integrates economic considerations, prioritizing a balance between planned maintenance costs and the higher costs associated with corrective actions. This discrepancy is not a contradiction but rather a reflection of the complementary nature of the two approaches.

It is essential to acknowledge the inherent uncertainties in both analyses. The parameters of the Weibull distribution (β and η) are derived from expert-elicited data and observed abnormalities, which, while valuable, may not fully capture all operational variables or future conditions. Similarly, the CPUT analysis relies on cost estimates for planned and corrective maintenance, which are subject to change over time due to market fluctuations or operational adjustments. As such, the 11.5-year interval should be interpreted as a pragmatic recommendation that optimizes economic efficiency while maintaining a safety margin, as indicated by the 91% reliability at this point. Continuous monitoring and updating of the models are recommended to account for operational changes and reduce uncertainties, ensuring that the intervals remain both safe and cost-effective.

This reflection underscores the importance of integrating both reliability and economic perspectives in maintenance planning. While the PDF-based approach provides a technical benchmark for operational safety, the CPUT-based interval offers actionable guidance that aligns maintenance schedules with economic constraints. The combination of these analyses equips decision-makers with a robust framework for optimizing inspection strategies in complex systems such as FPSO fairleads.

5. Conclusions

This paper presented a structured methodology for eliciting expert opinions to assess the reliability of fairleads in FPSOs and support inspection planning. The methodology, encompassing expert selection, questionnaire design, and the integration of elicited data into probabilistic reliability models, was successfully demonstrated through a case study involving a Brazilian FPSO fleet.

The proposed method is inherently ad-hoc, tailored to address the specific challenges associated with fairleads, such as the absence of historical failure data and the influence of adjacent protective systems. By leveraging expert knowledge and integrating it into a probabilistic framework, the method allowed for the construction of Weibull-based PDF and CPUT curves. These outputs provided complementary insights for defining inspection intervals, balancing safety and economic considerations. While the PDF suggested a reliability threshold-based interval of 14 years, the CPUT analysis optimized this to 11.5 years, offering a more cost-effective approach while maintaining a reliability level of 91%.

The flexibility of the proposed methodology lies in its adaptability to other critical offshore equipment beyond fairleads. By tailoring the elicitation process to the operational and design specifics of different systems, the method can provide robust reliability assessments and support inspection planning in varied contexts. This adaptability makes the approach a valuable tool for addressing reliability challenges across a wide range of applications in offshore operations.

Despite potential biases inherent to expert elicitation, the structured nature of the process mitigates inconsistencies and provides reliable data for analysis. The integration of expert judgment with probabilistic modelling ensures that the method remains both practical and effective, particularly in scenarios where conventional failure data are unavailable or insufficient.

Future work includes opportunities to expand the application of the method to other FPSO systems, such as sea chests, and testing it on a broader range of vessels and experts. These efforts aim to further validate the method's versatility and enhance its applicability to diverse operational environments, ultimately contributing to the advancement of reliability assessment and maintenance planning in offshore engineering.

Additionally, the authors intend to extend their approach to scenarios where failure records exist but are either unreliable or insufficient for estimating the reliability function (e.g. only one past failure record). In such cases, expert knowledge must be integrated, enabling the combination of historical data with domain expertise.

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References

Amaral, G. A. (2020). Analytical Assessment of the Mooring System Stiffness (Master thesis). Escola Politécnica, Universidade de São Paulo (USP).

Andrade, B. and K. Nishimoto. (2017). Design of a Floating Offshore Structure. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability*, 471-481.

Ayyub, B. M. (2001). *A Practical Guide on Conducting Expert-Opinion Elicitation of Probabilities and Consequences for Corps Facilities*. U.S. Army Corps of Engineers Institute for Water Resources Alexandria, VA, USA.

Babuscia, A. and K. M. Cheung. (2014). An approach to perform expert elicitation for engineering design risk analysis methodology and experimental results. *Journal of the Royal Statistical Society Series A: Statistics in Society 177 (2)*, 475–497.

Bhardwaj, U., A. P. Teixeira and C. G. Soares. (2017). Analysis of FPSO accident and incident data. In *Progress in the Analysis and Design of Marine Structures*, eds. Guedes Soares, C. & Teixeira A. P., CRC Press.

Bedford, T., J. Quigley and L. Walls. (2006). Expert Elicitation for Reliable System Design. *Statistical Science 21 (4)*, 428–450.

Colson, A. R. and R. M. Cooke. (2018). Expert Elicitation: Using the Classical Model to Validate Experts' Judgments. *Review of Environmental Economics and Policy 12 (1)*, 113–132.

Jenkins, B., I. Belton, J. Carroll and D. McMillan. (2022). Estimating the major replacement rates in next-generation offshore wind turbines using structured expert elicitation. *Journal of Physics: Conference Series 2362 (1)*, 012020.

Kai-Tung M., J. Zou and P. Vargas. (2018). Guidance for Assessing OPB Fatigue on Chain for permanent mooring systems. *Proceedings of the 23rd Offshore Symposium, February 14th 2018, Texas Section of the Society of Naval Architects and Marine Engineers*.

Leite, M., V. Infante and A. R. Andrade. (2022). Using expert judgement techniques to assess reliability for long service-life components: An application to railway wheelsets. *Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability 236(5)*, 879-892.

Martins, K. L. (2019). Análise do comportamento mecânico de brackets da fundação de fairleads de uma plataforma FPSO através de simulação numérica (Master thesis). Escola de Engenharia da Universidade Federal do Rio Grande (FURG).

McKeown, R., A. Bisset and M. Stephen. (2011). Offshore Replacement of a Damaged FPSO Fairlead. Paper presented at the SPE Offshore Europe Oil and Gas Conference and Exhibition, Aberdeen, UK.

Naga, H. B. and F. M. Assidiq. (2024). Mooring Design and Fatigue Damage on Variant Fairlead Positions During FPSO Operation – Case Study. *Maritime Technology and Society 3(1)*, 43-51.

Suh, Y. A., K. Song and J. Cho. (2021). Fuzzy-technique-based expert elicitation on the occurrence probability of severe accident phenomena in nuclear power plants. *Nuclear Engineering and Technology 53 (10)*, 3298-3313.