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Evaluation of Asset Reliability and Occupational Safety in Offshore Drilling Projects Using the FMECA Approach

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ABSTRACT

Integrated and reliable occupational safety. This study aims to evaluate the implementation of Asset Management Integrity in offshore oil drilling projects using the Failure Mode Effects and Criticality Analysis (FMECA) method. The research was conducted through a quantitative approach with surveys and secondary data analysis to identify asset failure modes, evaluate the severity and frequency of failures, as well as detection capability. The analysis results were used to calculate the Risk Priority Number (RPN) and to map risk priorities based on a criticality matrix. The findings indicate that the application of FMECA can accurately identify weak points in mechanical systems, support risk-based decision-making, and provide strategic recommendations for improving occupational safety (OSH) and operational reliability. This research provides practical contributions in building a resilient asset management system oriented towards sustainability and risk mitigation in extreme offshore environments.

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1. INTRODUCTION

Supporting national energy resilience, but on the other hand, it is also classified as a sector with a very high level of risk. Extreme working environments, the complexity of mechanical equipment, and limited access during emergencies make this sector prone to system failures and workplace accidents. In this context, Asset Integrity Management (AIM) becomes crucial to ensure occupational safety, operational reliability, and the sustainability of drilling projects. AIM aims to ensure that all assets and mechanical systems in drilling operations function according to performance standards, are safe to use, and can operate within the designed time frame without posing additional risks to workers or the surrounding environment (ISO, 2014; Bousdekis et al., 2018; Teixeira et al., 2020).

However, in practice, there are still a number of issues that hinder the effectiveness of asset management systems in offshore drilling projects, especially in tropical regions such as Indonesia. First, there is no data-based and quantitatively measurable asset reliability evaluation system to detect potential critical failures. Second, there is still a lack of integration between asset management and occupational safety systems (K3), resulting in risk mitigation strategies that are reactive rather than preventive. Third, decision-making related to risk management is often not based on numerically measured risk mapping, leading to less accurate prioritisation in the allocation of maintenance resources. Ultimately, this situation can increase downtime, reduce productivity, and add to the risk of workplace accidents or environmental damage (Reason, 2016; Chakhrit & Chennoufi, 2023).

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To address these issues, the Failure Mode Effects and Criticality Analysis (FMECA) method is one of the most widely used approaches in technical risk analysis and system reliability management. This method enables the identification of potential failure modes, assessment of severity, frequency of occurrence, and detection capability, which are then summarised as the Risk Priority Number (RPN). The results of the RPN analysis can be used to develop a criticality matrix, prioritise failures, and design more targeted risk mitigation strategies (Liu et al., 2017; IEC, 2018). In various regions such as the Gulf of Mexico and the North Sea, the application of FMECA has proven to reduce system failure rates and improve maintenance efficiency and workplace safety (Amaechi et al., 2022; Alma & Sodikun, 2022; Houiri & Sadeghi, 2022; Mustofa et al., 2023).

The novelty of this research lies in the integrated application of the FMECA method within the asset management system of offshore drilling projects in Indonesia's tropical waters. This study offers a quantitative approach through RPN calculations that are directly linked to strategies for improving occupational safety (OSH) and operational reliability. Additionally, this research develops a risk criticality matrix based on local characteristics, such as reliance on satellite communications, fluctuating tropical sea conditions, and limited remote maintenance infrastructure. In the Indonesian context, such studies remain very limited and are mostly focused on partial technical aspects without full integration with safety management systems (Gultom et al., 2025; Ginza & Sukwika, 2024; Melchers & Tan, 2023; Ukato et al., 2022).

Based on this background, the research is designed to answer several key questions: (1) How can the main failure modes of mechanical assets in offshore drilling projects be identified using the FMECA approach? (2) How can the calculation of the Risk Priority Number be used to evaluate the criticality level of asset risks? (3) What risk mitigation strategies are most appropriate to support improvements in occupational safety (K3) and system reliability based on the results of the FMECA analysis?

The purpose of this research is to evaluate the implementation of the Asset Management Integrity system in offshore oil drilling projects using the FMECA approach. The research aims to identify the main failure modes of mechanical assets, calculate the RPN values for each failure mode, and develop strategic risk mitigation recommendations based on the generated data. The expected outcome is the establishment of a more robust and adaptive asset management system to support workplace safety and operational sustainability in extreme offshore environments (Feng, Liu, & Chen, 2025; Zhang, Liu, & Wu, 2023).

2. RESEARCH METHOD

This research utilises a quantitative approach with the objective of evaluating asset management integrity in offshore oil drilling projects through the application of the Failure Mode Effects and Criticality Analysis (FMECA) method. This approach was chosen because it can provide an objective and systematic overview of the reliability of mechanical assets, while also identifying potential failures that could impact workplace safety and project operations. The FMECA method allows researchers to assess the impact of each failure mode through three main parameters: severity, occurrence frequency, and detection capability, which are then calculated in the form of a Risk Priority Number (RPN) as a quantitative risk indicator (IEC, 2018; Liu et al., 2017).

The research design is descriptive and inferential, with a survey strategy as the main technique for collecting primary data. The survey was conducted on the operational and maintenance workforce in one of the offshore drilling projects in the waters of Indonesia. In addition to primary data, this research also utilises secondary data in the form of asset inspection documents, maintenance records, and work accident reports. The instrument used is a structured questionnaire developed based on API RP 580 and ISO 55001 standards, and has been validated through expert consultation. To ensure instrument reliability, a Cronbach's Alpha test was conducted with a minimum value of 0.80 as the threshold for internal consistency (Taber, 2021).

The data obtained from the survey and field documents are analysed through three main stages. Firstly, descriptive analysis is used to understand the characteristics of assets and operational environmental conditions. Secondly, multiple linear regression analysis is applied to test the influence of independent variables on asset integrity, particularly in terms of asset age, maintenance frequency, and failure history.

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Thirdly, the FMECA method is applied to identify the most critical failure modes, calculate the RPN values for each mode, and develop a criticality matrix as the basis for prioritising risk mitigation actions.

The implementation of FMECA is carried out systematically, starting with the identification of the main processes in drilling operations. These processes are then evaluated with the technical team to formulate a list of potential failure modes classified based on the stages of operational activities. Each failure mode is analysed based on its causes, symptoms, impacts, and detection mechanisms. The severity, occurrence, and detection parameters are then converted into an ordinal scale of 1–10 for the calculation of the Risk Priority Number (RPN). A high RPN value indicates a critical failure mode that requires immediate action, while a low value suggests a relatively acceptable risk (Chakhrit & Chennoufi, 2023).

After calculating the RPN values, a risk priority matrix is developed to establish appropriate control strategies. The recommended mitigation actions are formulated based on ISO 55000 standards and ISO 31000 risk management principles, focusing on improving asset reliability and strengthening workplace safety systems. This stage concludes with an evaluation of the effectiveness of mitigation actions through a recalculation of post-intervention RPN. A comparison between the RPN values before and after mitigation is used to assess the quantitative reduction in risk levels.

This methodology aligns with approaches applied in various previous studies. For example, Liu et al. (2024) integrated FMECA with digital twin technology to conduct real-time evaluations of drilling system reliability and found that this approach could reduce downtime by up to 40%. Similarly, Ukato, Williams, and Obi (2022) demonstrated that combining FMECA with Monte Carlo simulation can lead to more efficient maintenance strategies for offshore assets. This research adopts these principles for the local context in Indonesia, considering its geographical characteristics, marine environment, and infrastructure limitations, aiming to provide practical contributions to the development of robust and risk-adaptive asset management systems.

3. RESULTS AND DISCUSSIONS

3.1. Result

3.1.1. Failure Mode Analysis

This study reveals that there are several critical failure modes occurring in the information systems and equipment of offshore oil drilling projects. Through direct observation and data collection, the researchers successfully identified several main failure modes, including system inaccessibility, system unavailability, hardware and software failures, network failures, as well as inaccurate or delayed ship location information. The determination of these failure modes was carried out using the Failure Mode Effects and Criticality Analysis (FMECA) approach, where each mode was analysed based on the severity, occurrence, and detection.

Table 1. RPN Calculation

Failure Mode	Occ.	Sev.	Det	RPN
The system cannot be accessed	1	9	7	63
System unavailable	5	10	6	300
Hardware Failure	2	9	7	128
Software Failure	2	8	6	96
Network Failure	6	8	6	288
Power Failure	1	9	3	27
Inaccurate weather information	7	4	7	196
Inaccurate/delayed ship location	9	6	7	378
Ship/map not displayed	3	8	6	144
Loading time is too long	6	4	5	120
Reporting not displayed	1	5	7	35
Ship past tracking information is not shown	3	5	6	90
Notification not appearing	7	4	3	84

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As shown in Table 1, the analysis identified critical failure modes in the offshore drilling system, notably ‘inaccurate or delayed ship location’ (RPN = 378), ‘system unavailability’ (RPN = 300), and ‘network failure’ (RPN = 288). These modes scored high due to the combination of significant operational impact (severity), likelihood of occurrence, and limited detectability. Consistent with Houiri & Sadeghi (2022), these modes highlight the vulnerability of offshore systems to delays and network disruptions. However, unlike their study, which focused on hardware-centric causes, our findings emphasise digital infrastructure and real-time data latency as key contributors.

3.1.2. Failure Cause Analysis

The Fishbone Diagram (Figure 1) categorises root causes into human error, hardware/software malfunctions, and environmental factors. Particularly, unstable satellite connectivity and misconfigured servers were frequent sources of failure. This aligns with Melchers and Tan (2023), who emphasised cyber-physical system fragility in remote marine operations. Nevertheless, this study extends the discussion by incorporating localised tropical environmental constraints—an often underrepresented risk factor in the global literature.

To explore the root causes of failure, an analysis was conducted using a Fishbone Diagram (Ishikawa) as shown in Figure 1. This diagram groups the factors causing failure into several main categories: human (human error), machine (hardware and software), method (non-standard procedures), and environment (sea weather and satellite connectivity). For example, system access failures are mostly caused by suboptimal server configuration and weak network security. Meanwhile, delays in ship location reporting are caused by limited access to satellite data from third parties. These findings are consistent with the study by Melchers & Tan (2023), which states that real-time data integration in offshore environments is highly dependent on reliable network infrastructure and monitoring systems.

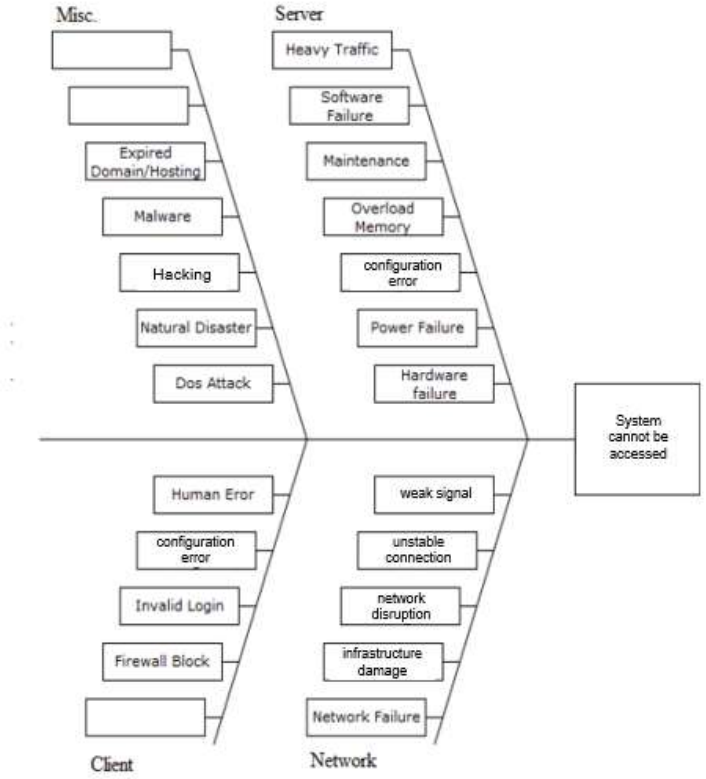


Fig 1. Fishbone Diagram: System Cannot Be Accessed

3.1.3. Interpretation of the Pareto Diagram Image

Furthermore, the results of the failure mode priority mapping are presented in Figure 2, the Pareto Diagram, which shows that 80% of operational impacts are caused by less than 20 per cent of the identified failure

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modes. In this context, the three main failure modes at the top of the Pareto curve are: (1) delays in ship location information, (2) system inaccessibility, and (3) inaccurate ship location information. This pattern confirms the Pareto principle, namely that a small number of causes can lead to the majority of impacts. Therefore, risk control efforts should focus on these modes to achieve optimal mitigation results (Liu et al., 2017; Chakhrit & Chennoufi, 2023).

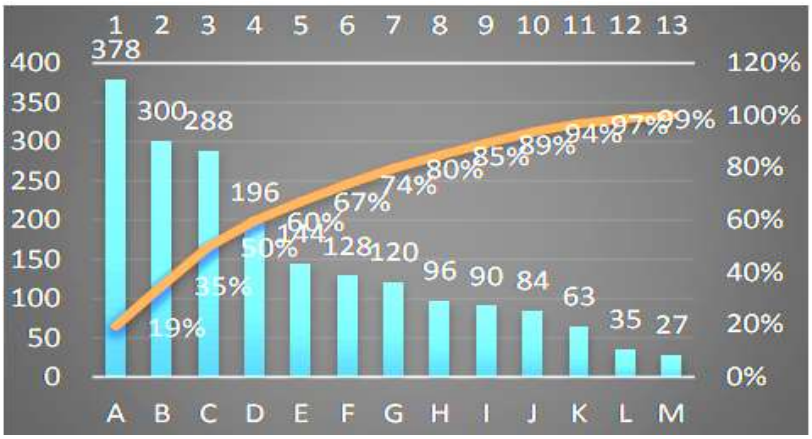


Fig 2. Pareto Diagram of Failure Modes

3.1.4. Evaluation of RPN Values Before and After Mitigation

The RPN reduction in 'system unavailability' (300 → 120) and 'inaccurate ship location' (378 → 210) suggests the interventions were partially effective. The adoption of AES 256 encryption, for instance, directly improved data security, thereby reducing unauthorized access risk. However, the switch to OpenStreetMap—though lighter on system memory—led to an RPN increase in 'loading time' (120 → 300), exposing trade-offs between data richness and access speed. A hybrid approach integrating both offline caching and dynamic cloud updates could be explored in future implementations.

Significant changes are shown in Table 2, which presents the RPN values before and after the implementation of mitigation actions. After system improvements were made, such as strengthening the firewall, implementing AES 256-bit encryption, switching maps to OpenStreetMap, and updating the ship search algorithm, the RPN values for several failure modes showed a considerable decrease. For example, the RPN for system unavailability dropped from 300 to 120, and for inaccurate ship location, it decreased from 378 to 210. This reduction indicates that the mitigation strategies implemented were effective in reducing the risk of failure.

Table 2. Results of Recalculated RPN

Failure Mode	Occ.	Sev.	Det.	ΔRPN	RPN (before)
System cannot be accessed	1	9	7	63	63
System unavailable	2	0	6	120	300
Hardware Failure	1	9	7	63	128
Software Failure	1	8	6	48	96
Network Failure	3	8	6	144	288
Power Failure	1	9	3	27	27
Inaccurate weather information	4	4	7	112	196
Inaccurate/delayed ship location	5	6	7	210	378
Ship/map not displayed	3	8	6	144	144
Loading time is too long	6	5	6	300	120
Reporting not displayed	1	5	7	35	35
Ship past tracking information not shown	3	5	6	90	90
Notification not appearing	1	4	3	12	84
Total				1368	1949

Remark: Occ.: Occurrence, Sev.: Severity, Det.: Detection (scored on a 1–10 ordinal scale where 10 = highest risk)

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However, there is an anomaly in the “loading time too long” mode, which actually experienced an increase in RPN from 120 to 300. This was caused by switching the map provider to OpenStreetMap, which is lighter for the system but has limitations in access speed due to its dependence on user connectivity. This change shows that not all corrective actions result in overall performance improvements, but rather need to be adjusted to the technical context and comprehensive system requirements (Feng et al., 2025).

3.2. Discussion

The research demonstrates that FMECA can support proactive asset reliability and occupational safety planning. Integrating RPN analysis into real-time system monitoring, as suggested by Liu et al. (2024), could further enhance predictive capability. However, this study also reveals a limitation: the lack of stakeholder-level accountability tracing within failure modes. Future work should integrate Responsibility-Accountability-Matrix (RACI) modelling alongside FMECA to assign failure responsibility and improve interdepartmental coordination.

The findings of this research reinforce the understanding that the FMECA approach is an effective tool for identifying critical points in offshore drilling operational systems. By calculating the RPN, companies can determine risk priority scales and develop data-driven control strategies. Furthermore, the implementation of RPN-based mitigation actions has proven to reduce risk values in most failure modes. These results support the findings of Liu, Wang, and Chen (2024), who developed a digital twin-based FMECA system to enhance the accuracy of failure detection in the offshore sector.

In the context of occupational safety (OSH), the FMECA approach also contributes to preventing potential accidents resulting from system failures, particularly by detecting and addressing risks before incidents occur. Studies by Zhang, Liu, and Wu (2023) and Mustofa et al. (2023) show that the use of FMEA and FMECA equipped with machine learning can increase response speed to system threats and proactively mitigate risks. Therefore, the application of FMECA in offshore drilling projects in Indonesia has great potential to strengthen asset management systems and occupational safety that are adaptive to extreme environmental challenges.

4. CONCLUSION

This study shows that the Failure Mode Effects and Criticality Analysis (FMECA) method is an effective approach for identifying, analysing, and prioritising failure risks in mechanical asset systems in offshore oil drilling projects. Through the calculation of the Risk Priority Number (RPN), this research successfully revealed the most critical failure modes that have the potential to disrupt operations and occupational safety, such as delays in ship location information, system unavailability, and network failures. The implementation of mitigation strategies based on FMECA results has proven capable of significantly reducing RPN values in most failure modes, although there are still some technical obstacles that require further evaluation. The results of this study emphasise the importance of integrating asset management systems and occupational safety within a single risk-based framework, especially in complex and dynamic offshore environments. In addition to providing practical contributions to strengthening operational reliability, this research also enriches the theoretical study of FMECA application in Indonesia’s offshore energy sector. Further research is needed to integrate predictive approaches based on digitalisation, such as digital twins and machine learning, to improve early detection accuracy and accelerate responses to potential failures.

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