Operational Drilling Risk Analysis using Failure Mode and Effect Analysis (FMEA) Method in an Oil and Gas Company

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Abstract*—Drilling operations in the oil and gas industry are among the riskiest activities, with high potential for injury and environmental damage. Therefore, thorough risk analysis and assessment are crucial to minimize these risks. This research aims to reassess and prioritize operational risks, recommending mitigation actions using Failure Modes and Effects Analysis (FMEA) and ISO 31000:2018 standards. The study involves risk identification through expert interviews, resulting in the identification of 364 combined risks, including failure modes, probable causes, and effects. Using the Risk Priority Number (RPN), risks were prioritized, and responses were categorized into mitigate (60%), transfer (25%), accept (11%), and avoid (4%). This approach enables the company to manage risks more effectively, ensuring safety and operational efficiency. The findings indicate that proper risk prioritization and response can significantly reduce potential damage. However, this research highlights the need for a more comprehensive analysis, including financial risk assessments, to maximize the effectiveness of risk management strategies. The results provide valuable insights for improving the company's risk management framework, contributing to the overall safety and sustainability of drilling operations. Future research should focus on integrating financial risk evaluations to enhance the robustness of the risk management process.

***Keywords*—FMEA, Oil and Gas, Risk Identification, Risk Management, Oil and Gas.**

I. INTRODUCTION

THE oil and gas sector remains one of the most prominent industries today, necessitating effective risk management to minimize potential hazards [1]. The industry encompasses extensive processes, from geological exploration to seismic surveying and drilling (Shah et al., 2010). Initially, geologists identify potential reservoirs through geological studies and seismic surveys, which create subsurface images to locate oil and gas traps. The seismic surveying process involves deploying seismic waves from vibratory trucks and interpreting the reflections to identify drilling.

Following exploration, companies must acquire leases to drill, mine, and extract fossil fuels, adhering to legal requirements. Drilling operations, critical to the entire mining process, involve creating a wellbore using specialized equipment. This process includes multiple steps: preparing the site, setting the conductor casing, drilling the surface hole, cementing and testing, and eventually extracting the oil and gas. Production is then supported by processing, treatment, and transportation, with extensive monitoring and optimization to ensure efficiency. Treatment processes such as dehydration, desalting, and stabilization are essential to prepare the extracted resources for transportation.

The oil and gas industry, while essential, is fraught with risks and hazards. High-profile incidents like the 2010 Deepwater Horizon disaster underscore the critical need for robust risk management [2]. Operational risks have been rising, necessitating comprehensive risk management strategies to ensure safety and sustainability [3]. Effective risk management, including methodologies like Failure Mode and Effects Analysis (FMEA), is vital for identifying and mitigating potential failures in oil and gas operations.

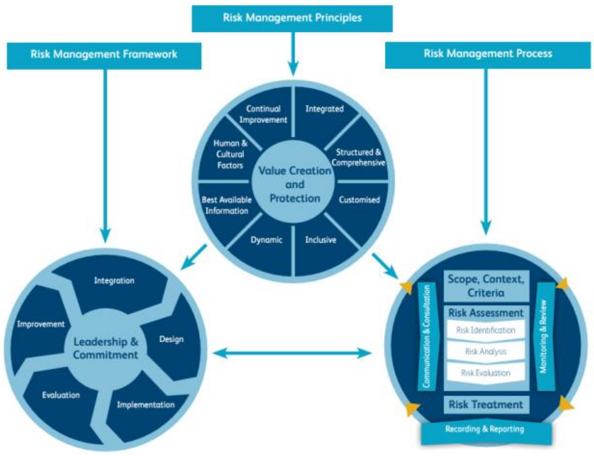

Figure 1. Principles, framework, and risk management process from ISO 31000:2018.

This study focuses on PT X, an oil and gas contractor specializing in drilling operations. The company has faced significant losses due to operational risks, highlighting the necessity for a thorough risk assessment framework. Implementing FMEA could enhance PT X's ability to analyze and mitigate risks, thereby improving operational efficiency, safety, and financial stability.

II. LITERATURE REVIEW

A. *Oil and Gas Industry*

The oil and gas industry operates within a capitalist framework and is inherently exposed to a myriad of risks, including price volatility, political instability, environmental hazards, and technical failures. These risks are heightened by the complexity of the industry's supply chain and the significant capital investment required for exploration, production, and distribution. As a result, effective risk management is paramount to ensuring the industry's sustainability, stability, and safety.

Regulatory frameworks play a crucial role in shaping the operational landscape of the oil and gas industry. These regulations encompass a broad range of requirements, including stringent environmental regulations aimed at

Table 1.
Regulations in an Oil and Gas Industries

Regulations	Information
Environmental Regulations	Strict environmental regulations govern oil and gas exploration, production, and processing activities. For example, regulations on handling hazardous waste, wastewater management, controlling greenhouse gas emissions, and managing oil well residues can present challenges for companies because they require large investments in technology and sophisticated environmental monitoring.
Occupational Safety and Health	The oil and gas industry has a high risk of work accidents and injuries. Strict K3 regulations, such as work equipment protection requirements, safety training, worksite safety monitoring, and emergency response procedures, require significant commitment and investment from companies to ensure compliance and employee safety.
Taxes and Royalties	Many countries regulate the tax rates and royalties that oil and gas companies must pay for the exploitation of their natural resources. These regulations can be a challenge in managing financial risks as they affect a company's profit margins and investments, especially if tax and royalty rates change suddenly or unexpectedly.
Licensing and Operating Permits	Before undertaking exploration or production activities, oil and gas companies must obtain various permits and permits from the local government. This permitting process can be complex and time-consuming, with the risk of delays or denials that can impact project schedules and company investments.
Sanctions and Penalties	Violations of regulations in the oil and gas industry can result in serious legal and administrative sanctions. For example, violations of environmental regulations can result in large fines, operational bans, or even lawsuits that harm a company's reputation.

minimizing ecological impact, occupational safety and health standards designed to protect workers, and economic policies such as taxation, royalties, and subsidies that affect financial performance. Additionally, companies must navigate the complexities of obtaining licenses and operating permits and face potential sanctions for non-compliance (see Table 1 for a detailed overview of key regulatory frameworks).

B. *Risk and Risk Management*

Risk is defined as any circumstance that can have a favourable or unfavourable impact on corporate goals, encompassing a wide spectrum of potential events or conditions. Risks in the oil and gas industry can be classified into two main categories: internal and external. Internal risks are those arising from within the organization, such as operational risks like equipment failure, process inefficiencies, and human errors. External risks originate from outside the organization and include regulatory changes, market fluctuations, geopolitical tensions, and natural disasters.

Risks can further be categorized into financial risks (e.g., commodity price fluctuations, exchange rate variations), strategic risks (e.g., changes in market demand, technological advancements), operational risks (e.g., supply chain disruptions, project delays), and hazard risks (e.g., fires, explosions, environmental spills). Effective risk management involves a systematic process of identifying, evaluating, and prioritizing risks, followed by implementing actions to minimize their impact. This process operates at three levels:

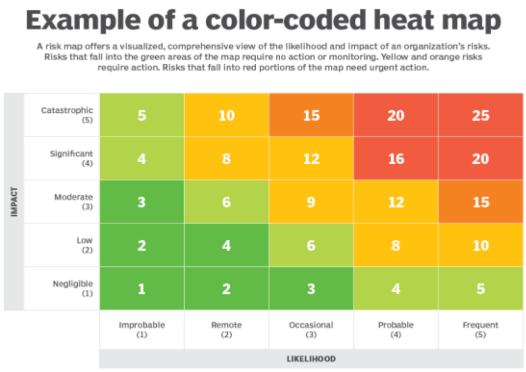

Figure 2. Heat risk mapping.

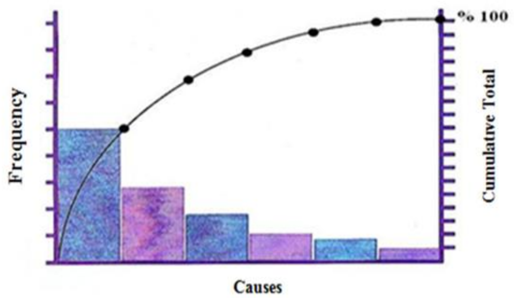

Figure 3. Pareto chart.

corporate, strategic business, and project levels, adhering to established standards such as ISO 31000:2018, the COSO ERM Framework, PMI's PMBOK Guide, NIST SP800-30, and BS31100:2011 [4].

C. *ISO 31000:2018*

ISO 31000:2018 is a globally recognized standard that provides a comprehensive framework for risk management, applicable across various industries. It integrates systematic risk management principles and processes at all organizational levels, emphasizing a proactive approach to identifying, assessing, and mitigating risks. The standard outlines a simplified procedure that includes core components such as risk management principles, frameworks, and processes. These components are illustrated in Figure 1, highlighting the integration of risk management into organizational processes, decision-making, and culture [5].

D. *Failure Mode and Effect Analysis*

Failure Mode and Effect Analysis (FMEA) is a structured methodology used to analyze potential failure modes within an operational process and assess their impacts. FMEA aims to identify and mitigate risks associated with failures before they occur, thereby enhancing reliability and safety. There are several types of FMEA, including system FMEA, design FMEA, process FMEA, and service delivery FMEA. Each type focuses on different aspects of a system or process, ensuring a comprehensive risk assessment.

The FMEA process involves several steps: defining the system or process, identifying potential failure modes, assessing the severity, occurrence, and detection of each failure mode, calculating the Risk Priority Number (RPN), and developing countermeasures to mitigate high-priority risks [6]. This systematic approach ensures that potential

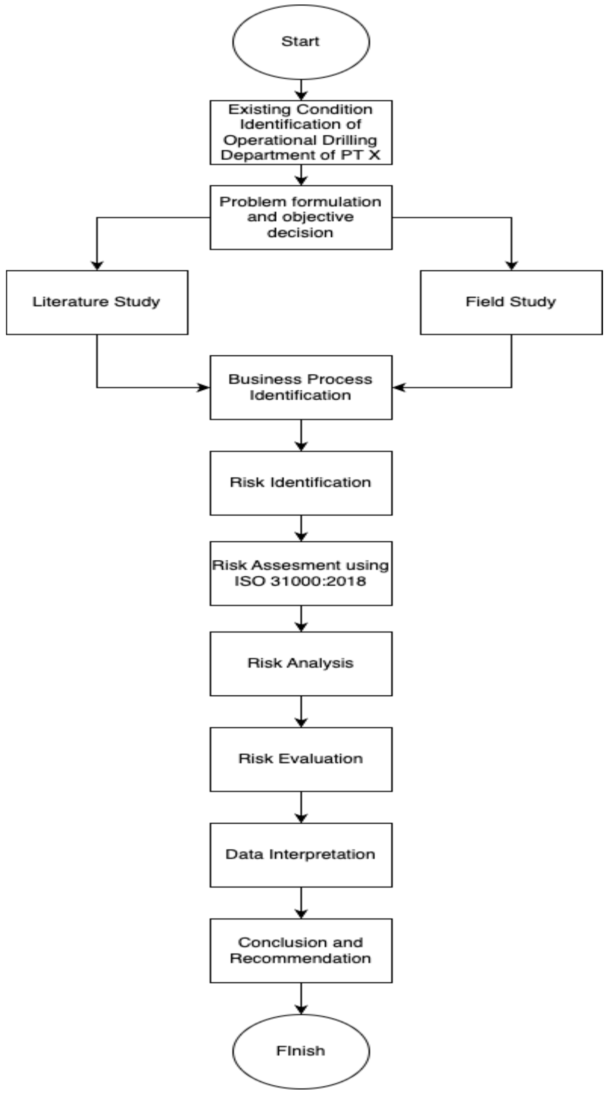

Figure 4. Flowchart of the research methodology.

failures are proactively addressed, reducing the likelihood and impact of adverse events.

E. Risk Analysis

Risk analysis is a critical component of risk management, involving the evaluation of the likelihood and impact of identified risks to prioritize them effectively. Various tools and techniques are used to analyze and visualize risks, facilitating informed decision-making. Risk heat maps, for instance, provide a visual representation of risks based on their severity and likelihood, enabling organizations to focus on high-priority risks [1]. Figure 2 illustrates a typical risk heat map used in risk analysis.

Pareto analysis, another valuable tool, helps organizations identify the most significant risks by categorizing them based on their cumulative impact. This approach is grounded in the Pareto Principle, which posits that a small number of causes often account for the majority of effects. Figure 3 demonstrates Pareto curves used in risk analysis, highlighting the importance of prioritizing high-impact risks [7].

In summary, the literature on risk management in the oil and gas industry underscores the importance of a structured and proactive approach to identifying, evaluating, and mitigating risks. By leveraging established frameworks and methodologies such as ISO 31000:2018 and FMEA, organizations can enhance their resilience and ensure the

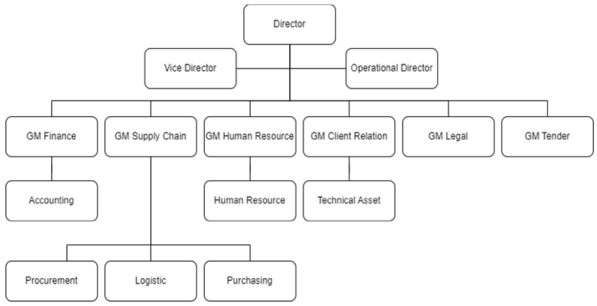

Figure 5. Company structure of PT X.

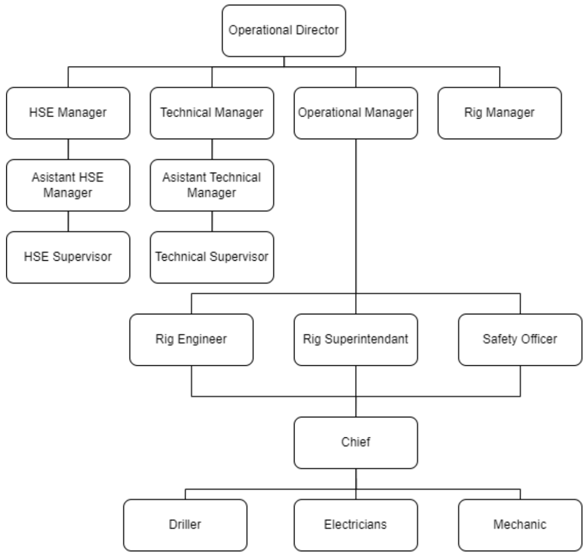

Figure 6. Company operational department structure.

safety, stability, and sustainability of their operations.

III. METHODOLOGY

In doing this research, the author has a methodology to complete the research and clarifying the flow on how the research would solve the problem and answering the objective formulation. Exploring the knowledge trough literature study to as a basis knowledge and collecting the data through company as the resource and analyzing and processing them into a risk assessment and risk management adjustment. Later on, interpreting the evaluation and analysis and providing the solution, conclusion and suggestion. The flowchart of the whole process can be seen in Figure 4.

IV. RESULT AND DISCUSSION

This chapter details the systematic process of data collection and processing, including company business processes, risk registers, RPN calculations, and risk management for sustainable drilling operations.

A. Company Profile

The company is an oil and gas contractor service company that helps the clients obtaining their goals. In order to do so the company has built a management structure regarding the cause and can be seen in Figure 5 of the overall company management structure.

The company focus is the drilling department and will be the objective of the research. The drilling department handles the company core business and the sector that are needed to identify the risk. The company drilling department structure

Table 2.
Methodology Difference

Aspect	FMEA	HIRAC
Scope	Focused on potential failures within a system or process.	Covering all types of hazards in a workplace or operational environment.
Methodology	Uses a structured approach with a focus on failure modes and their effects.	Involves identifying hazards, assessing risks, and implementing control measures.
Outcome	Results in a Risk Priority Number (RPN) to prioritize failures, leading to mitigation actions for the most critical risks.	Leads directly to the implementation of control measures to mitigate identified hazards.
Application Focus	Commonly used in technical and engineering contexts to improve system or process reliability.	Widely used in occupational health and safety to ensure overall workplace safety.

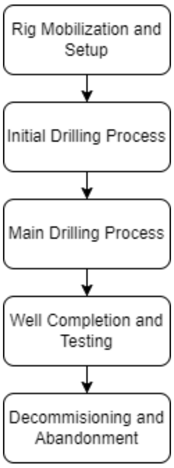

Figure 7. Operational drilling business process of PT X.

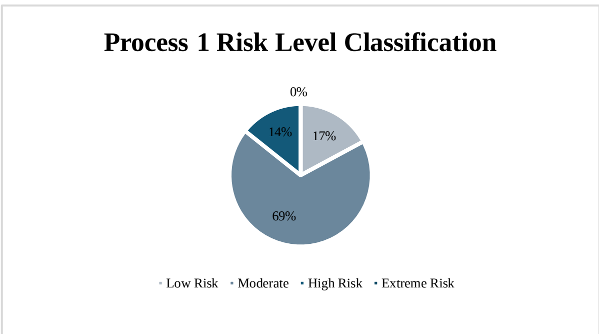

Figure 8. Rig mobilization and setup.

will be provided in Figure 6.

PT X uses a risk prioritization method to ensure effective management and safety in their operations. They implement Hazard Identification, Risk Assessment, and Control (HIRAC) as part of their Health, Safety, and Environment (HSE) evaluation. Table 2 compares HIRAC with Failure Mode and Effects Analysis (FMEA), the latter being the focus of this research to enhance risk management practices.

B. *Operational Drilling Business Process*

The operational drilling has a few business processes that will be stated in Figure 7.

Table 3.
Process 1 Risk Identification

Sub-sub Process	Risk Code	Risk
Rig Mobilization and Setup		
Journey Management Planning	R1	Incorrect route planning
	R2	Delays due to unforeseen events
	R3	Accidents during transportation
Logistic Planning	R4	Inadequate supply chain management
	R5	Delays in material delivery
	R6	Poor inventory control
Relations (Stakeholder Management)	R7	Poor communication with stakeholders
	R8	Conflicts with local communities or regulatory bodies
	R9	Non-compliance with regulations

Table 4.
Process 1 Risk Analysis

Risk ID	Failure Mode	Probable Cause	Effect Risk Register	Effect
Rig Mobilization and Setup				
R1	Incorrect route planning	Inaccurate data or outdated maps	R1.1	Increased transportation time and costs
R2	Delays due to unforeseen events	Poor weather conditions or road construction	R2.1	Project delays
R3	Accidents during transportation	Driver error or vehicle malfunction	R3.1	Injuries or fatalities, damage to equipment
R4	Inadequate supply chain management	Inefficient supplier coordination	R4.1	Shortages or surpluses of materials
R5	Delays in material delivery	Transportation issues or customs delays	R5.1	Project delays

C. *Risk Identification*

The risk identification is the part in which the author proceeds to gather information regarding the risk process that are identified in the previous chapter, the risk that are identified will be gathered from doing an interview from one of the operational managers of PT X and will be considered as sufficient and adequate for this research. The process that will be included in these chapter would just be the first process as the example of the research purposes. Table 3 show process 1 risk identification.

D. *Risk Analysis*

The risk analysis is the part in which the risk that are identified being analyzed by seeing the bigger picture of probable cause and the effect that the risk might've produced. The analysis is created and are identified by both authors and the operation manager of PT X, and by doing so, the data are validated and considered as adequate and sufficient. The process that will be included in these chapter would just be the first process as the example of the research purposes. Table 4 show process 1 risk analysis.

Table 5.
Process 1 Risk Scoring Analysis

Rig Mobilization and Setup						
Failure Mode	Probable Cause	Effect Risk Register	Effect	Severity	Occurrence	Detection
Incorrect route planning	Inaccurate data or outdated maps	R1.1	Increased transportation time and costs	7	5	3
Delays due to unforeseen events	Poor weather conditions or road construction	R2.1	Project delays	4	6	3
Accidents during transportation	Driver error or vehicle malfunction	R3.1	Injuries or fatalities, damage to equipment	6	5	4
Inadequate supply chain management	Inefficient supplier coordination	R4.1	Shortages or surpluses of materials	5	5	4
Delays in material delivery	Transportation issues or customs delays	R5.1	Project delays	5	6	4
Poor inventory control	Lack of proper inventory tracking systems	R6.1	Increased costs due to expedited shipping or stockouts	4	5	3

Table 6.
Risk RPN Calculations

Rig Mobilization and Setup					
Effect Risk Register	Effect	Severity	Occurrence	Detection	RPN
R1.1	Increased transportation time and costs	7	5	3	105
R2.1	Project delays	4	6	3	72
R3.1	Injuries or fatalities, damage to equipment	6	5	4	120
R4.1	Shortages or surpluses of materials	5	5	4	100
R5.1	Project delays	5	6	4	120

Table 7.
Risk Appetite Range

Risk Level				
Scale	Low Risk	Moderate	High Risk	Extreme
Severity	Severity Scale ≤ 2	Severity Scale = 3-4	Severity Scale = 5-7	Severity Scale > 7
Occurrence	Occurrence Scale ≤ 2	Occurrence Scale = 3-4	Occurrence Scale = 5-7	Occurrence Scale > 7
Detection	Detection Scale ≤ 2	Detection Scale = 3-4	Detection Scale = 5-7	Detection Scale > 7
Risk Appetite Range	RPN ≤ 75	76 ≤ RPN ≤ 130	131 ≤ RPN ≤ 249	250 ≤ RPN ≤ 1000

Table 8.
Risk Level Categorization

Rig Mobilization and Setup			
Effect Risk Register	Effect	RPN	Risk Category
R1.1	Increased transportation time and costs	105	Moderate Risk
R2.1	Project delays	72	Low Risk
R3.1	Injuries or fatalities, damage to equipment	120	Moderate Risk
R4.1	Shortages or surpluses of materials	100	Moderate Risk
R5.1	Project delays	120	Moderate Risk

E. Risk Scoring Analysis

Risk scoring analysis is the process in which the risk identification and analysis, the severity and occurrence and detection are determined by doing an identification by both parties of the authors and operational manager, so the analysis could be considered as adequate and sufficient. The data that are shown will be their representation of all the process as an example of this whole research. Process 1 risk scoring analysis at Table 5.

F. Risk Profiling

The risk profiling section will include the RPN calculation where the severity, occurrence and detection will be categorized multiplied to acquire the RPN and adjusting them to the risk appetite range as the risk level categorization and risk mitigation method. The table of both can be seen in table 6.

Table 6 is the RPN Calculation for the 1 process and will be used as an example of the whole research RPN calculations. The Risk Appetite Range will be stated as the classification determination of the risk category.

Table 7 is the risk appetite range for classifying the risk that are identified and calculated based on the RPN, the data that are used will be the 1 process as an example of the research.

The risk level categorization is stated in Table 8, as the category of each risk are different, in this process, the risk that are identified are categorized into 3 risk level which are low risk, medium risk and high risk.

The risk mitigation plan that are stated in Table 9, is the process of analyzing the risk and the probable cause with adjusting to the effect, and determining whether to transfer, mitigate, accept, or avoid risk of each risk that are identified.

V. ANALYSIS

A. Risk Analysis of Operational Drilling Activity at PT X

PT X prioritizes risk management due to the inherently high-risk nature of its operational drilling activities. The company adheres to several ISO standards and employs robust risk mitigation measures to ensure the effectiveness and efficiency of its operations. The operational drilling department is pivotal, comprising five main business processes: rig mobilization and setup, initial drilling process, main drilling operations, well completion and testing, and

Table 9.
Process 1 Mitigation Plan

Rig Mobilization and Setup				
Effect Risk Register	Effect	RPN	Risk Response	Mitigation Plan
R1.1	Increased transportation time and costs	105	Mitigate	Use updated maps and GPS, verify routes before departure
R2.1	Project delays	72	Mitigate	Develop contingency plans, monitor weather and road conditions
R3.1	Injuries or fatalities, damage to equipment	120	Mitigate	Provide driver training, regular vehicle maintenance, enforce safety protocols
R4.1	Shortages or surpluses of materials	100	Mitigate	Establish reliable supplier relationships, implement supply chain management software
R5.1	Project delays	120	Mitigate	Schedule deliveries with buffer time, use multiple suppliers where possible
R6.1	Increased costs due to expedited shipping or stockouts	60	Mitigate	Implement robust inventory management systems, conduct regular audits

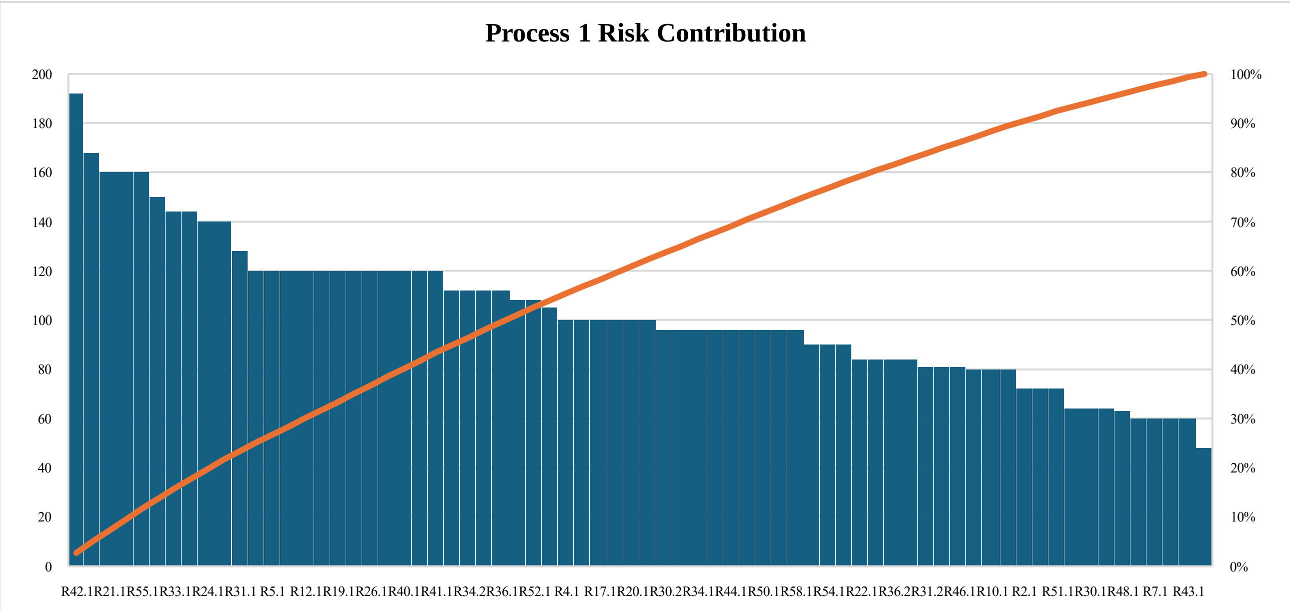

Figure 9. Process 1.

decommissioning and abandonment. Each of these processes involves various risks that can impact the company's overall business process, leading to financial, strategic, and hazard risks. Comprehensive risk profiling and analysis, validated by experts, are essential for the company's operational success.

B. Risk Analysis Scoring and Risk Contribution

This section evaluates the risks identified in the drilling operations, calculating the Risk Priority Number (RPN) based on severity, occurrence, and detection. PT X identified 321 risks across its operations, categorized into four risk levels: low, moderate, high, and extreme. The categorization is based on RPN values, with low risk having RPN < 75, moderate risk between 75 and 131, high risk between 130 and 250, and extreme risk above 250. The analysis aids in prioritizing critical risks that need immediate attention to mitigate potential damage to the company, clients, and the environment. Risk level classification showed in Figure 8 and Figure 9 show graph of risk contribution.

In the rig mobilization and setup process, 58 risks were identified. The highest RPN of 192 was associated with the risk of missed defects in equipment inspection due to human error, which poses significant safety hazards and operational delays.

The lowest RPN of 14 was linked to site preparation mismatches, considered low risk due to the company's adequate site planning and control measures. The risk level analysis indicated that 14% of risks were high, 17% low, and 69% moderate. The risk prioritization graph highlighted that R42.1 had the highest contribution to overall risk, emphasizing the need for targeted risk mitigation strategies in this process.

The risk response analysis for the operational drilling processes at PT X highlights several key mitigation strategies. The graph indicates that mitigation is the most recommended response, emphasizing the importance of having backup plans to ensure the well-being of operations amidst various uncertainties. Mitigation strategies include implementing safety protocols, improving procedures, and investing in additional training for personnel. Risk response show at Figure 10.

A significant portion of risks, 25%, are managed through transfer strategies, which involve using insurance, outsourcing, or risk-sharing arrangements with specialized companies. Accepting risks, at 11%, is considered when the risk is tolerable and presents a cost-benefit advantage to the company. Finally, risk avoidance accounts for 4%, as it is

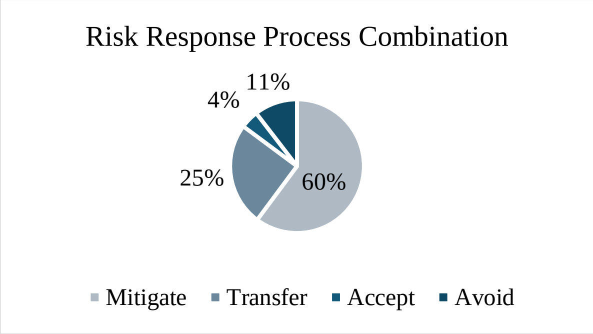

Figure 10. Risk response.

challenging to avoid risks entirely in the high-stakes environment of operational drilling. Hence, mitigation is prioritized over avoidance to ensure successful and sustainable operations.

VI. CONCLUSION

A. Conclusions

Based on the comprehensive data collection, processing, analysis, and interpretation, the research on the operational drilling activities of PT X has led to several key conclusions. The identification of risks within the operational drilling department revealed a total of 321 risks, encompassing all five main chapter processes. These risks were documented and evaluated by strategic and hazard risk management teams, referencing potential operational risks and failures that might occur during the drilling expeditions.

Risk scoring was conducted using the Failure Modes and Effects Analysis (FMEA) method, aligned with ISO 31000:2018 standards. The Risk Priority Number (RPN) was calculated based on scales for severity, occurrence, and detection from 1 to 10. This approach facilitated the prioritization and identification of critical risks. The risk level categories for the various chapter processes were as follows: the Rig Mobilization and Setup process had 17% low risk, 69% moderate risk, 14% high risk, and 0% extreme risk; the Initial Drilling Operation had 35% low risk, 46% moderate risk, 18% high risk, and 1% extreme risk; the Main Drilling Operation had 14.9% low risk, 29.7% moderate risk, 52.7% high risk, and 2.7% extreme risk; the Well Completion and Testing process had 3% low risk, 93% moderate risk, 3% high risk, and 0% extreme risk; and the Decommissioning and Abandonment process had 9% low risk, 34% moderate risk, 57% high risk, and 0% extreme risk.

B. Suggestions

From the research conducted, several suggestions for improvement and further refinement are evident. The operational process should be identified during actual voyages and operations to ensure a broader and more unbiased identification of risks and probable causes. This real-time approach will provide a more comprehensive understanding of the risks involved. Additionally, providing a thorough analysis of mitigation strategies and risk responses will offer the best possible outcomes and comprehensive suggestions for the company.

Utilizing simulations and involving external experts to review the risks during operational voyages and expeditions is also recommended. This external perspective can provide valuable insights and enhance the risk management process, ensuring that PT X can effectively address and mitigate any risks that arise during their drilling operations.

Further risk prioritization was achieved through Pareto analysis to identify the critical 20% of risks that contribute to 80% of the risk pool. This analysis revealed the highest and lowest RPN values for each process. For Rig Mobilization and Setup, the highest RPN was 192 for R42 and the lowest was 48 for R14. The Initial Drilling Operation had a highest RPN of 252 for R142 and a lowest of 36 for R87. The Main Drilling Operation's highest RPN was 280 for R156 and the lowest was 30 for R177. The Well Completion and Testing process had a highest RPN of 216 for R214 and a lowest of 72 for R261. The Decommissioning and Abandonment process had a highest RPN of 216 for R318 and a lowest of 64 for R268. This detailed prioritization allowed PT X to identify the most critical risks and develop appropriate mitigation actions and risk responses, ensuring the smooth operation of their drilling activities. The classification of risk responses resulted in 60% mitigation, 25% transfer, 11% acceptance, and 4% avoidance of risks.

BIBLIOGRAPHY

[1] M. Albu, “Considerations regarding environmental aspects of risk management,” *Adv. Eng. Forum*, vol. 27, 2018.

[2] L. T. Ostrom and C. A. Wilhelmsen, *Risk Assessment : Tools, Techniques, and Their Applications*. Hoboken: John Wiley & Sons, 2019. ISBN: 9781119483465.

[3] Z. Wu, W. Liu, and W. Nie, “Literature review and prospect of the development and application of FMEA in manufacturing industry,” *Int. J. Adv. Manuf. Technol.*, vol. 112, pp. 1409--1436, 2021.

[4] T. Merna and F. F. Al-Thani, *Corporate Risk Management*, 2nd ed. Cornwall: John Wiley & Sons, 2008. ISBN: 978-0-470-51833-5.

[5] H. Argadinata, B. B. Wiyono, A. Imron, and M. F. Pramudya, “Identifying risks based on ISO 31000:2018 using risk factors at public universities of legal entities,” in *2ND International Conference on Educational Management and Technology (ICEMT 2023)*, 2023, pp. 43--60.

[6] K. Onodera, “Effective techniques of FMEA at each life-cycle stage,” in *Annual Reliability and Maintainability Symposium*, 1997, pp. 50--56.

[7] A. Gorener and K. Toker, “Quality improvement in manufacturing processes to defective products using pareto analysis and FMEA,” *Beykent Üniversitesi Sos. Bilim. Derg.*, vol. 6, no. 2, 2013.