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Failure Mode Effect Analysis for the Evaluation of BOP Major Offshore Oil and Gas Accidents

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Abstract

The Blowout Preventer (BOP) plays a vital role in preventing the uncontrolled release of oil and gas during drilling and exploration, ensuring operational safety. To evaluate accidents related to BOPs in Europe, a study was conducted using Failure Modes and Effects Analysis (FMEA) on the BOP stack. The study identified and analyzed six critical components in the BOP stack: annular, Blind Ram Shear (BRS), Casing Ram Shear (CRS), pipe and test ram, choke and kill valves, and connectors. These tightly connected components form a unified and fully functional BOP stack. The BOP stack controls downhole pressure by sealing the drill pipe to prevent uncontrolled fluid release and regulating fluid flow during operations. Additionally, it provides an additional layer of safety by quickly and effectively cutting the drill pipe or well casing to contain and control an explosion emergency. Each component has ten (10) failure mechanisms that can cause accidents in the industry. The study found mechanical, clogging, vibration, and hydrogen embrittlement failures were the most common reasons for failure mode codes (F1 to F10). Most of the outages were due to offshore oil and gas drilling systems. Corrosion and erosion, thermal fatigue, wear, performance, and internal and external failures were other critical failure mechanisms that significantly affected the system's operation. The analysis of Risk Priority Numbers (RPNs) before and after the intervention for the assessment of the effectiveness of safety measures for the BOP stack will provide valuable insights to empower industry experts in making informed decisions to mitigate the risk of well blowouts and releases in exploration, development, and production

Keywords: Annular, Blind ram shear, Pipe and test ram, Risk priority number, Failure mechanism.

1 | Introduction

The offshore oil and gas industry faces significant safety challenges. Incidents like fire, explosions, and blowouts threaten personnel, equipment, and the environment [1]. Statistics highlight the severity of these

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risks, with a 27% increase in the oil and gas sector's fatal injury rate from 2013 to 2014 [2]. The Deepwater Horizon disaster of 2010 exemplifies the catastrophic consequences of such accidents [3]. The complexity of offshore operations and the limited availability of comprehensive Blowout Preventers (BOPs) equipment data [4] challenge risk reduction analysis. Traditional methods may not adequately capture the potential for catastrophic failures. Failure Mode and Effect Analysis (FMEA) offers a systematic approach to identifying potential failure mechanisms within BOP systems [5]. By analyzing these failure modes, their causes, and their consequences, FMEA helps assess associated risks [6]. The Risk Priority Number (RPN), derived from severity, occurrence, and detection ratings, provides a comprehensive understanding of potential failure impact [7]. This study leverages FMEA to address the limitations of traditional risk analysis methods in the oil and gas industry. By applying FMEA to BOP systems, this research aims to enhance understanding of potential failure modes and their impact, ultimately contributing to improved safety practices.

Subsea BOPs ensure safe subsea drilling operations by managing extreme well pressure and potential uncontrolled flow [8]. The Deepwater Horizon incident in ʾ2010 tragically exemplified the catastrophic consequences of BOP failure, resulting in loss of life, explosions, and a prolonged oil spill [3], [9]. It highlights the critical role of BOPs and the need for comprehensive studies on their operational risks. The rapid escalation of BOP barrier failures at Macondo emphasizes the urgency of addressing these issues. The accident investigation revealed a combination of technical shortcomings, human error, environmental factors, and management failures contributing to the uncontrolled well blowout (refer to the original text for citations). Challenges in BOP maintenance practices and inadequate standards for drilling operations further underscore the need for improved risk analysis. Despite the vital role of BOPs, risk reduction analysis remains challenging due to the Deepwater Horizon incident. This study seeks to address knowledge gaps in utilizing FMEA, such as process failure mechanisms within BOP systems, RPNs associated with these failures, potential methods for failure detection and corrective actions to mitigate identified failure mechanisms. Through this the understanding of BOP failure modes and contribute to the development of more effective preventative measures and improved safety practices in the oil and gas industry will be enhanced.

Recognizing the importance of identifying critical BOP components for maintenance and testing to ensure functionality, this work aims to contribute to a comprehensive understanding of factors contributing to accidents in the oil and gas industry. This study seeks to leverage FMEA to investigate a major European BOP accident. By identifying process failure mechanisms, potential detection methods, and corrective actions, this research aims to enhance understanding of broader BOP equipment failures and contribute to improved prevention and safety measures in the oil and gas industry.

2 | Methodology

Methods of data collection and analysis are presented in this section.

2.1 | Data Collection

This study collected validated secondary data from reputable sources to ensure a comprehensive and well-informed analysis. These sources included open industry databases like the World Offshore Accident Database (WOAD) and the International Oil and Gas Producers (IOGP) safety zone [10], [11]. Additionally, relevant insights were extracted from peer-reviewed journal articles retrieved through academic databases such as ScienceDirect, Projects, Google Scholar, and ResearchGate [12]. The chosen sources represent established contributors to academic research, fostering the depth and reliability of the study's findings.

2.2 | Data Analysis

Data analysis from SINTEF, WOAD, and IOGP was carried out to reveal FMEA and its extension. Failure Mode Effect and Criticality Analysis (FMECA) is an established method for risk reduction in the oil and gas industry [10], [11]. These techniques, grounded in reliability, sustainability, and durability engineering principles, enable systematic identification and mitigation of potential failure mechanisms. The employed methodologies utilized a bottom-up approach to identify failure modes during operations, followed by a logical sequence analysis to determine the ultimate consequences of each failure. FMEA then assessed the risks and hazards associated with these identified failure modes. The analysis considered three key factors: Severity (S), Occurrence (O), and Detection (D) of each failure mode, resulting in a RPN. This process resulted in a Critical Items List (CIL) containing all valid failure modes and their impacts at the component and system levels. The analysis then evaluated potential configuration changes to eliminate items from the CIL. Irremovable items were documented with justifications for accepting the associated hazards. The investigation process itself followed a seven-step approach, considering 1) item or function, 2) failure mode, 3) failure effects, 4) root causes, 5) detectability, 6) corrective or preventive actions, and 7) basis for acceptance. It highlights the structured approach of FMEA/FMECA in identifying, analyzing, and mitigating risks within the oil and gas industry.

2.3 | Instrumentation

The RPN, which is calculated by multiplying the Severity (S), Occurrence frequency (O), and Detection (D) parameters, is a key indicator of the need for addressing a potential failure mode. *Fig. 1* illustrates the representation of this concept. To determine the RPN, the hazard need number, the severity rating, event likelihood rating, and identification likelihood rating are multiplied together as per [13], [14]. *Fig. 2* shows the FMEA structure and process steps for determining the RPN of a system in an oil and gas process industry.

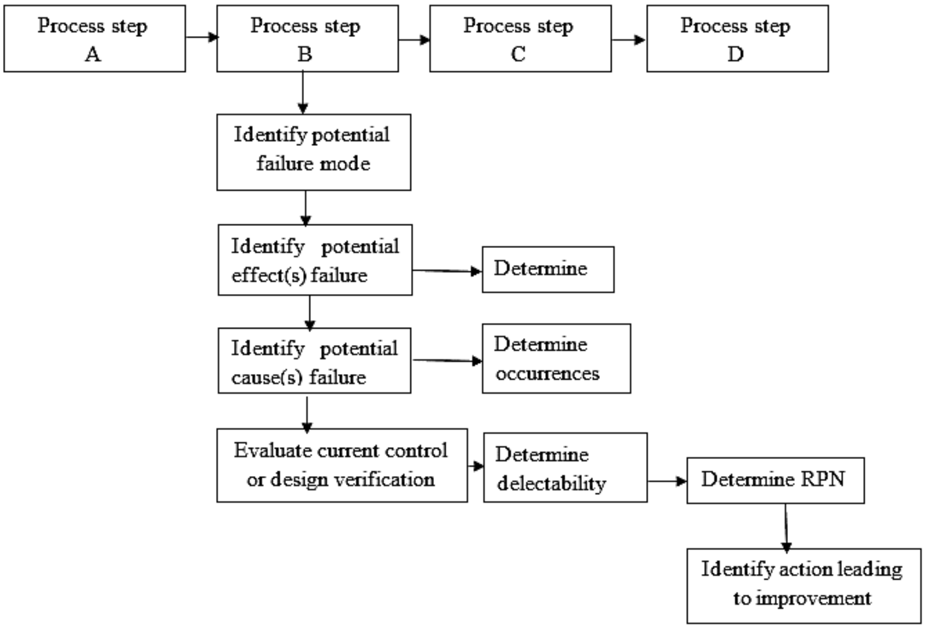

Fig.1. The FMEA structure and process steps for determining the RPN of a system in an oil and gas process industry.

2.4 | Method of Accident Analysis

A process-level technique was employed to investigate a specific process within the BOP system. This technique involved examining the process's steps, components, interactions, and potential failure modes to gain more detailed information on its efficiency, reliability, or safety. The safety nature of the BOP system was segmented for all practical conditions and recognized failure modes were assessed using weights given three factors: severity, occurrence, and detectability. Each component of the BOP was analyzed using FMEA/FMECA criteria and their corresponding rating scales. *Table 1* to *Table 3* were used for this analysis, and the same process was repeated for each component of the BOP until the whole system was analyzed. Pre-planned tables were used to evaluate the occurrence and consequent severity. *Table 1* suggested the criteria to assess the incident's consequent severity using the FMEA technique [15–18].

Table 1. Criteria to evaluate the incident severity in the FMEA method.

Severity Ranking (S)	Effect	Description
1	None	No effect/damage on the component
2	Very minor	Very low damage to the component
3	Minor	Minor deterioration to the system
4	Very low	Damage to the component is very low
5	Low	System damage is low
6	Moderate	Damage to the system is moderate
7	High	Damage to the BOP component is high
8	Very high	Very high damage to the BOP component
9	Hazardous	Serious damage to the BOP component
10	Hazardous without warning	Complete failure of the BOP component

Incident Occurrence probability (O) refers to the chance that indicates the possibility of an incident occurring during a particular period. The factors used to determine how likely an accident will happen using the FMEA method can be found in *Table 2* [16], [17].

Table 2. Criteria to evaluate the incident probability in the FMEA method.

Occurrence Ranking (O)	Failure Rates	Description
1	Once every 10+ years	Unlikely/impossible failure occurrence
2	Once in 5 – 10 years	Very low failure occurrence
3	Once in 2 – 5 years	Low failure occurrence
4	Once in 1 – 2 year	Relatively low failure occurrence
5	Once a year	Moderate failure occurrence
6	Once in 6 months	Moderately high failure occurrence
7	Once in 3 months	Frequent failure occurrence
8	Once every month	High failure occurrence
9	Once a week	Very high failure occurrence
10	More than once per day	BOP failure occurrence is Inevitable

The incident Detection probability (D) method is a technique that determines the likelihood of an incident or failure occurring at a specific time. To evaluate the potential of failure or incident detection using the FMEA method, a list of criteria has been provided in *Table 3* that was used as a guide in this study [16], [19].

Table 3. Criteria to estimate the failure or incident detection in the FMEA method.

Detection Ranking (D)	Likelihood of Detection	Description
1	Certain	System failure will certainly be detected with over 95% probability through monitoring or annunciation system.
2	Very high	Detection of System control devices is very high.
3	High	Failure detection is 50% through specific monitoring.
4	Moderately high	Failure detection by the device is moderately high.
5	Moderately	Failure may be detected through weekly testing.
6	Low	BOP system failure detection is low.
7	Very low	Very low chance of detecting system failure.
8	Remote	Detection of failure is remote; it can only be detected during general preventive maintenance.
9	Very remote	Very remote failure detection of BOP device.
10	No detection	Certainly, no failure detection.

2.5 | RPN and Criticality Analysis

A normal failure modes and impacts investigation include some techniques to assess and evaluate the hazard related to the potential causes identified during the investigation. There are two techniques: RPNs and criticality analysis; these are depicted below [20], [21].

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D}. \quad (1)$$

$$\mathrm{CA} = \mathrm{S} \times \mathrm{D}, \quad (2)$$

where S equal to severity represents the seriousness of the potential consequence of a failure mode, it is usually rated on a scale from 1 to 10, with 1 being the least severe and 10 being the most severe.

O equal to occurrence represents the failure mode's likelihood or frequency of occurrence. It is also typically rated on a scale from 1 to 10, with 1 indicating the lowest occurrence likelihood and 10 indicating the highest.

D equal to detection represents the likelihood of detecting the failure mode before it reaches the end-user or causes harm. like severity and occurrence, it is usually rated on a scale from 1 to 10, with 1 indicating the highest detection capability and 10 indicating the lowest.

The higher the RPN, the higher the priority for addressing that particular failure mode and the most critical issues that could impact the process in terms of risk mitigation or corrective action.

The RPN was also useful when comparing different failure modes within the same analysis.

3 | Results and Discussion

The results are presented and discussed in this section.

3.1 | Determination of the Process Failure Mode that Leads to Accident and the Failure Mechanism of Equipment

In this study, the FMEA method criteria table (*Table 1* to *Table 3*) was used to examine the probability of equipment failure, the severity of the failure, and the equipment failure detection system or signs. Multiplying error severity, probability, and detection yielded the RPN.

The following failure mechanisms were determined to be the cause of most BOP accidents in the oil and gas industry; as such, experts should look into it during the process for Monitoring, Inspection and Testing (MIT):

I. Mechanical damage failure (fracture, galling, etc.).
II. Corrosion and erosion failure.
III. Thermal fatigue failure.
IV. Wear failure (vibration failure, poor lubrication).
V. Internal failure (leakage, rapture or burst).
VI. External failure (leak, collapse).
VII. Plugged failure.
VIII. Vibration failure.
IX. Hydrogen embrittlement failure.
X. Power outage failure.

The BOP stack has six parts of its system that may fail due to the above-mentioned causes. The six parts are:

I. Annular.
II. BSR.

III. CSR.

IV. PTR.

V. Choke and Kill Valves (CKLV).

VI. Connectors.

The FMEA/FMECA is an inductive reasoning approach that consider in what way the failure mechanisms of every component part could bring about system performance complicationsm and assesses the safety measures set up (counting built-in protection and checking systems, human activities, and support exercises) to anticipate, reduce, or moderate such complications. The principle center of an FMEA/FMECA is to 1) set up the conditions and end results connection between potential failure, practical failure, and the end effect (s) of those failures, and 2) evaluate the criticality of the proposed useful failure/failure mode [22].

Fig. 2 outlines the comprehensive FMEA/FEMCA steps in assessing the BOP system. Specifically, this study concentrated on adopting both functional and equipment-level approaches. The FMEA/FMECA technique is consistent with other methods centered on ensuring the reliability and dependability of equipment in the petroleum industry. Ultimately, the main goal is to identify and prevent BOP equipment failures.

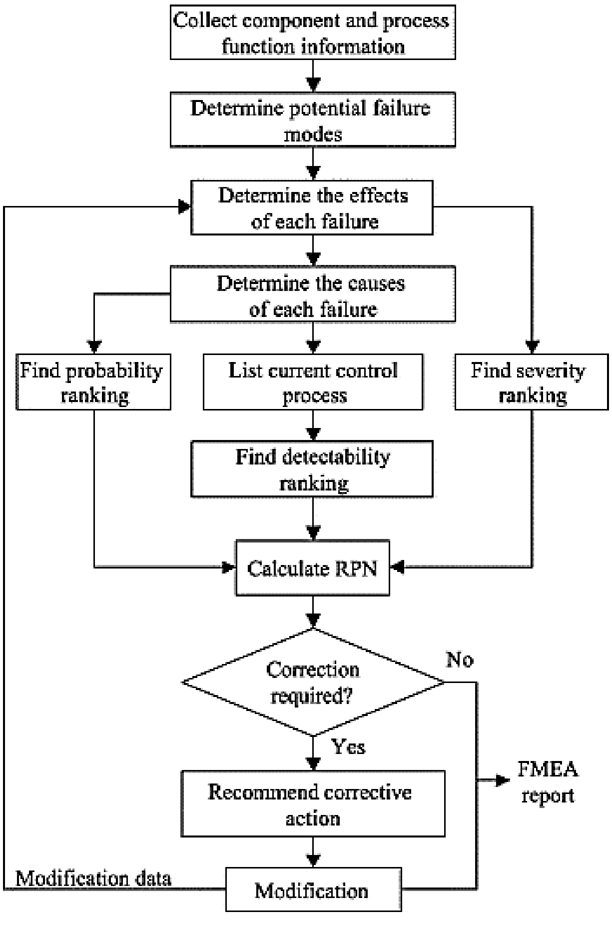

Fig. 2. Overall FMEA flow chart used for this work [22].

3.2 | Critical Analysis of BOP Systems

Analysis of failure mechanisms in BOP systems (*Table 4*) revealed thermal fatigue (17.98%, RPN = 540) and wear and tear (17.98%, RPN = 540) as the most frequent causes of annular preventer failure. These were followed by mechanical damage (13.30%, RPN = 400) and vibration (11.97%, RPN = 360). Other notable failure mechanisms included power outages, internal failures, external failures, corrosion/erosion, plugging, and hydrogen embrittlement, decreasing in frequency. *Fig. 4* visually presents these failure mechanisms, aiding stakeholders in identifying critical areas for risk mitigation. The RPN percentages will further assist decision-makers in comprehending the overall risk landscape and allocating resources effectively for targeted interventions. This approach can significantly enhance safety and reliability within oil and gas operations.

Table 4. Failure mechanisms of BOP annular using failure mode and effect analysis.

Item/ Function	**Potential Failure Mode**	**Failure Mode Code**	**Potential Failure Effects**	**Severity (S)(1-10)**	**Potential Causes**	**Occurrence (O) (1-10)**	**Current Controls**	**Detection (D) (1-10)**	**RPN= (SXOXD)**	**Percentage**	**Actions Taken**	**Severity (1-10)**	**Occurrence (1-10)**	**Detection (1-10)**	**New RPN**
ANNULAR: Its function is to seal the wellbore and allow drill string to up and down via the closed BOP	**In what ways could the step or feature go wrong?**	**How to identify and represent each of the failure modes**	**What is the impact on the customer if this failure is not prevented or corrected?**		**What causes the step or feature to go wrong? (how could it occur?)**		**What controls exist that either prevent or detect the failure?**			**What is the Percentage calculation for the RPN? (%)**	**What actions were completed (and when) concerning the RPN?**				
	Mechanical Damage Failure	F1	Equipment damage, fracture	10	Fracture, creep and inadequate maintenance	5	Dampers installation on equipment and use of sensors.	8	400	13.3	Regular machine part service/ maintenance	10	5	6	300
	Corrosion and Erosion Failure	F2	Material degradation due to chemical reactions with the environment.	10	PH of water, oxygen in water, chemicals and water temperature	2	Electroplating, painting and use of good materials	9	180	5.98	Electroplating, painting and coating.	10	3	3	90
	Thermal Fatigue Failure	F3	Initiation of crack and fracture on equipment	10	Stress and cycling of process in one direction	6	Good temperature material and temperature detection equipment.	9	540	17.96	Use of high-temperature material for equipment design.	8	6	7	336
	Tear and Wear Failure	F4	Material loss and equipment damage	10	Caused as a result of ageing	6	Maintenance testing and inspection of equipment	9	540	17.96	Regular maintenance, testing and inspection	7	7	7	343
	Internal Failure	F5	Internal pressure leading to leakage of equipment	10	Pressure and high velocity (turbulent flow)	3	Internal Pressure detection device	8	240	7.97	Use of high-pressure resistance material	9	3	3	81

Continue Table 4. Failure mechanisms of BOP annular using failure mode and effect analysis.

External Failure	F6	External loads and condition	9	Ocean current, misalignment and vibration	3	Selection of material with good mechanical strength and load detection device	8	216	7.2	Proper equipment checks and environmental condition	6	3	5	90
Plugged Failure	F7	Blockage of line in the equipment	9	Blockage, high pressure, and temperature	3	Installation of external monitoring device.	6	162	5.39	Installation of relief valve and purging system	7	3	3	63
Vibration Failure	F8	Loss of equipment joints. From vibration stress	10	Misalignment, poor lubrication and inadequate maintenance.	4	Installation of dampers, lubrication of parts and tightening of equipment parts	9	360	11.97	Regular servicing/ maintenance, tightening of all loose parts of equipment.	10	3	3	90
Hydrogen Embrittlement failure	F9	The equipment parts become brittle and fracture.	9	Equipment wall degradation due to hydrogen, sulphide and oxygen	2	Coating of material, selection of material with chromium and detection device.	7	126	4.19	Painting and coating	8	3	3	120
Power Outage Failure	F10	Loss of power or degraded power supply (shut down)	9	Circuit Overload, low current flow. And equipment overload	3	Adequate load for current, step up and down transformer	9	243	8.08	Installation of power sensors and equipment reduces the load	9	3	3	81

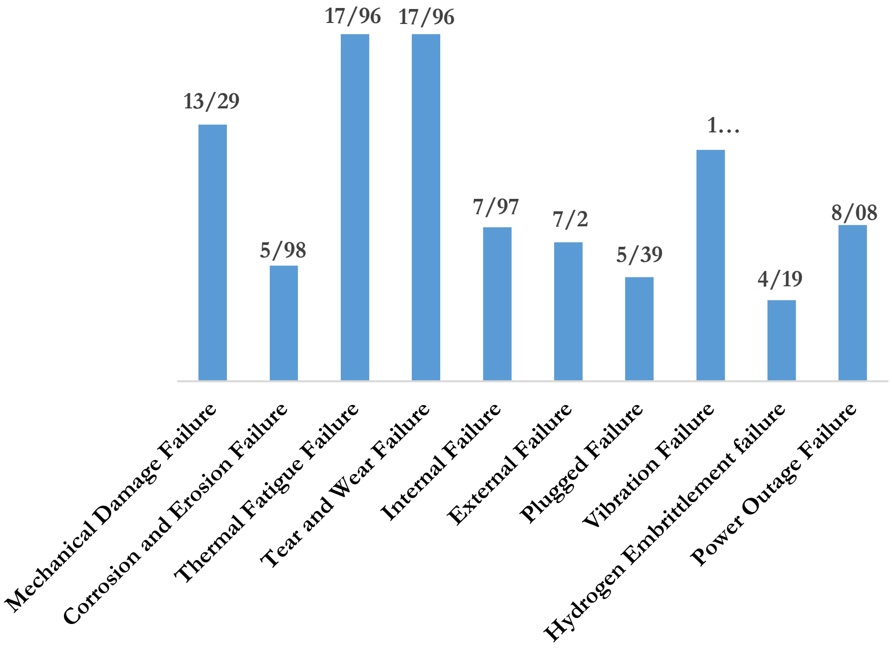

Fig. 3. Percentage failure mechanisms of BOP annular.

An FMEA identified tear and wear (RPN = 126) and thermal fatigue (RPN = 162) as the least critical failure modes for the annular preventer (*Table 5*). Conversely, hydrogen embrittlement plugging (RPN = 540), mechanical damage (RPN = 540), and plugging (RPN = 400) posed the highest pre-intervention risks. Following intervention implementation, RPN scores for these critical failure modes decreased: mechanical damage (RPN to 340), plugging (RPN to 360), and hydrogen embrittlement plugging (RPN to 346). This reduction in RPN scores across the annular section of the BOP (*Table 5* and *Fig. 4*) signifies the effectiveness of the implemented interventions, including equipment upgrades, improved maintenance procedures, training initiatives, and operational protocol enhancements. Stakeholders can leverage this information to assess the success of intervention programs in mitigating risks and enhancing operational safety within the oil and gas industry.

Table 5. RPN before and after the intervention for annular.

Failure Mechanisms	OLD RPN	New RPN
Mechanical damage failure	400	340
Corrosion and erosion failure	180	90
Thermal fatigue failure	162	64
Tear and wear failure	126	72
Internal failure	240	81
External failure	216	90
Plugged failure	540	360
Vibration failure	360	180
Hydrogen embrittlement failure	540	346
Power outage failure	243	120

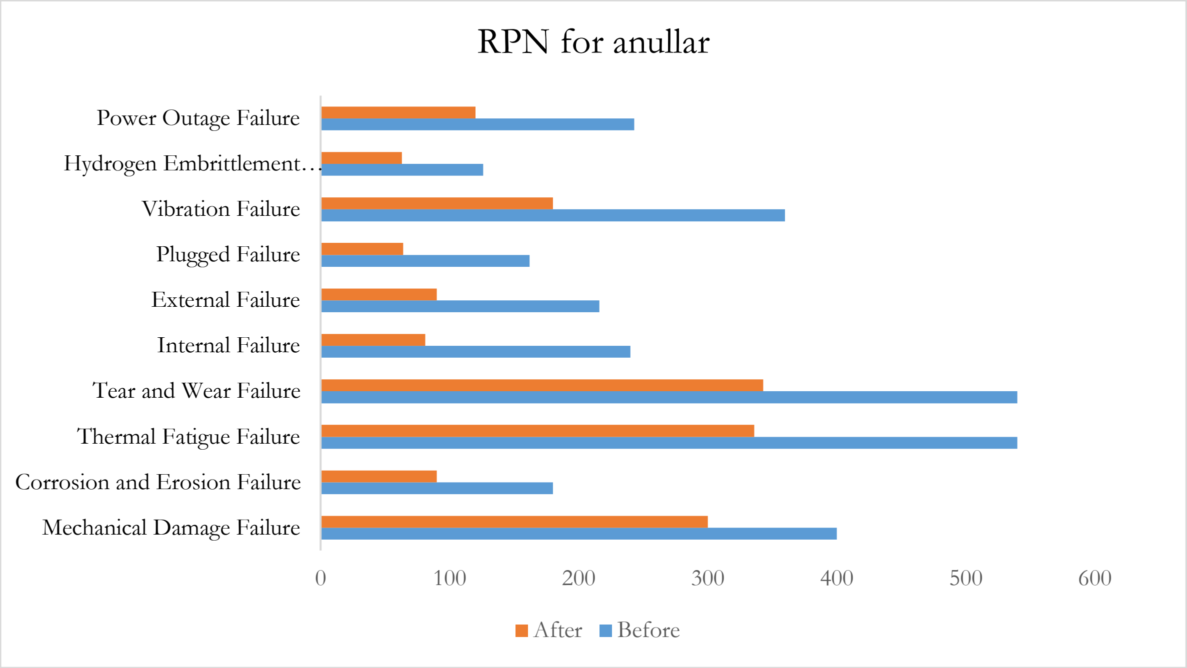

Fig. 4. Comparison of RPN Before and after intervention for annular.

This study analyzed the failure mechanisms of Blind Shear Rams (BSRs) and BOP systems. BSR failures were primarily caused by plugged failures (21.14%, RPN = 450), mechanical damage (16.92%, RPN = 360), and power outages (16.45%, RPN = 350). Contributing factors included vibration (11.42%, RPN = 243), wear and tear (10.15%, RPN = 216), and thermal fatigue (8.88%, RPN = 189). Other potential failures included hydrogen embrittlement (4.51%, RPN = 96) and corrosion/erosion (3.95%, RPN = 84). Analysis of BOP collapses identified external failures (16.61%, RPN = 405) as the leading cause, followed by internal failures (14.77%, RPN = 360), mechanical damage (13.29%, RPN = 324), and wear and tear (11.08%, RPN = 270). Corrosion/erosion (4.59%, RPN = 112) and hydrogen embrittlement (4.59%, RPN = 112) were also significant contributors (*Table 6*).

Multiple failure mechanisms compromised the sealing ability of BOP pipes and test rams, potentially leading to uncontrolled wellbore fluid releases. Researchers identified four critical failure modes: corrosion [23] thermal fatigue [24], plugging, and hydrogen embrittlement [25]. Additionally, operational factors (vibration, power outages) and degradation factors (wear and tear, external impacts) accelerated BOP deterioration [26], American Petroleum Institute (API) [27] [28], a reported range of contribution percentages (1.3% to 25.77%) highlighted the variable impact of different factors on BOP failures. Factors like thermal fatigue or mechanical damage likely contributed a higher percentage, while power outages might have a lower contribution. Understanding these failure mechanisms is crucial for prioritizing preventative measures and ensuring BOP integrity in the oil and gas industry. The results are presented in *Table 6*. Among the different types of failures considered, thermal fatigue failure, plugged failure, internal failure, and power outage failure have the lowest percentages of failure contribution, which are 5.11% (RPN = 100), 4.60% (RPN = 90), 4.09% (RPN = 80), 3.68% (RPN = 72), and 2.45% (RPN = 48), respectively.

This study employed RPNs to prioritize critical BOP failure mechanisms. Initially, high RPN values identified mechanical damage, obstructions (plugged failures), and power outages as significant risks to the BSR component. These values considered the severity, likelihood, and detectability of each failure. Following the implementation of corrective actions and intervention programs (*Table 7*), RPN values for these critical failure mechanisms decreased substantially. This decrease reflects the success of the interventions in mitigating risks and enhancing BSR reliability. The revised risk assessments are crucial for informed decision-making and risk management during BOP operations. Intervention programs demonstrably reduced the likelihood and severity of high-risk failures like plugging, mechanical damage, and power outages. It translates to improved operational efficiency and safety for offshore oil and gas activities. Lower RPN ratings indicate a lower overall risk profile for the BOP system due to a decreased likelihood of BSR component failures. It empowers operators and decision-makers with greater confidence to manage maintenance tasks, allocate resources, and conduct operational procedures, ultimately leading to safer and more reliable offshore oil and gas operations across Europe. Understanding how intervention programs impact critical BSR failure mechanisms is essential for effective risk management. This knowledge ensures BOP systems' continuous safe and efficient operation, ultimately enhancing overall operational safety.

High- RPN scores indicate a significant risk of equipment failure in BOP systems. This can lead to blowouts or uncontrolled well fluid releases, posing serious safety and environmental threats (*Table 7*). This study implemented an intervention program to address critical risks associated with the Casing Shear Ram (CSR). Following the program, the RPN score for the CSR decreased to 100, demonstrating the effectiveness of the intervention in reducing the risk of system failure. By comparing RPN scores before and after interventions, stakeholders gain valuable insights into the effectiveness of risk mitigation measures. This information informs decision-making regarding maintenance priorities, resource allocation, and operational procedures. Ideally, a graphical representation of the CSR's RPN score over time would show a clear downward trend following the intervention. This trend signifies a reduction in the likelihood and severity of potential CSR failures.

The positive impact of the intervention program would be further evident through reduced maintenance costs and enhanced safety and operational integrity of the BOP system. Monitoring RPN scores facilitates assessing intervention program success through key performance indicators. Identifying areas for improvement contributes to safer and more reliable offshore oil and gas operations. This information empowers stakeholders to make informed decisions regarding maintenance, resource allocation, and operational procedures, ultimately ensuring the safety and reliability of their equipment and operations.

This study assessed the effectiveness of intervention measures for CKLV within a BOP system using RPN scores. Before the intervention, alarmingly high RPN scores (336, 288, and 240) were identified for mechanical, vibration, and plugged failures, respectively. These scores indicated a significant risk of malfunctions, operational disruptions, or even blowouts, jeopardizing personnel safety, environmental protection, and operational continuity. RPN scores were compared after corrective actions to assess the intervention's effectiveness.

This pre-and post-intervention analysis allowed decision-makers to evaluate the impact on risk reduction and operational safety. A decrease in RPN scores after the intervention signifies the success of the measures in mitigating failure mechanisms and enhancing BOP integrity. The comparative analysis demonstrates the value of RPN scores in assessing risk mitigation strategies and informing decision-making for safe and reliable BOP operations. This study emphasizes the importance of proactive maintenance, continuous monitoring, and targeted interventions to minimize operational risks and ensure the safety of personnel, assets, and the environment. The effectiveness of the implemented measures highlights the need for continuous assessment and improvement of BOP systems for safer and more reliable oil and gas operations. An analysis of RPN scores revealed concerningly high pre-intervention risk levels for the BOP connector. Vibration (RPN = 504), wear and tear (RPN = 360), hydrogen embrittlement (RPN = 288), and mechanical damage (RPN = 270) all exhibited significant RPN scores. These scores indicate a substantial risk to the BOP connector's integrity and reliability (*Table 7*).

After implementing intervention measures, there was a significant drop in RPN scores in the Pipe and Test Rams (PTR) for each failure mechanism (*Table 7*). Vibration has reduced to 336, wear and tear to 150, hydrogen embrittlement to 126, and mechanical damage to 105. The reduction in RPN scores signifies that the level of risk associated with each failure mechanism has been considerably reduced. This decline indicates the effectiveness of the implemented corrective actions in mitigating risks and enhancing PTR reliability. A separate analysis highlighted concerningly high pre-intervention RPN scores for the BOP connector, suggesting significant risk. A FMEA identified thermal fatigue, wear and tear, mechanical damage, and vibration as the most frequent causes of annular failure. The annular seals the wellbore while allowing drill string movement. The hydraulic system, particularly the accumulator poppet and string assembly, is susceptible to thermal fatigue from excessive pre-charge, potentially leading to bladder displacement [29], [30]. Mechanical failures encompass fracture, deformation, misalignment, collapse, high friction, and inadequate material yield.

A FMEA identified F1, F7, F8, and F9 of the annular preventer (*Table 4*) as having the highest RPNs exceeding 300. This signifies a critical risk zone for the ring preventer, a vital BOP component during well closure. While F6 and F10 have slightly elevated RPNs, their criticality is lower than the identified root causes. Regardless of criticality level, quality assurance measures like maintenance, inspections, and monitoring are crucial [31].

Based on RPN scores in *Table 4*, mechanical damage, plugging, and power outages were identified as the top three critical failures for the BSR within the BOP system. The BSR seals the wellbore entirely during blowouts, but the FMEA analysis reveals these failure mechanisms have RPNs exceeding 300, indicating high-risk criticality. Such failures necessitate immediate corrective actions, such as replacement or design changes, to prevent endangering personnel and equipment on the platform [30], [32].

Table 6. Percentage failure mechanism of BOP Stack parts.

Potential Failure Mode	BSR RPN	Percentage	CSR RPN	Percentage	PTR RPN	Percentage	CKLV RPN	Percentage	Connector RPN	Percentage
Mechanical damage failure	360	16.92	324	13.29	196	6.87	336	18.26	270	13.8
Corrosion and erosion failure	84	3.95	112	4.59	405	14.2	108	5.87	144	7.36
Thermal Fatigue failure	189	8.88	240	9.84	360	12.62	189	10.27	90	4.6
Tear and wear Failure	216	10.15	270	11.08	96	3.36	144	7.83	360	18.41
Internal failure	70	3.29	360	14.77	600	21.03	160	8.7	80	4.09
External failure	70	3.29	405	16.61	450	15.77	216	11.74	100	5.11
Plugged failure	450	21.14	243	9.97	270	9.46	240	13.04	72	3.68
Vibration failure	243	11.42	192	7.88	128	4.49	288	15.65	504	25.77
Hydrogen embrittlement failure	96	4.51	112	4.59	240	8.41	135	7.34	288	14.72
Power outage failure	350	16.45	180	7.38	108	3.79	24	1.3	48	2.45

Note: BSR = Blind Shear Ram; CSR = Casing Shear Ram; PTR = Pipe and Test Rams; CKLV = Choke and Kil Line Valve

Table 7. RPN before and after the intervention.

	BSR		CSR		PTR		CKLV		Connectors	
Failure Mechanisms	Old RPN	New RPN	Old RPN	New RPN	Old RPN	New RPN	Old RPN	New RPN	Old RPN	New RPN
Mechanical damage failure	360	135	324	120	196	105	336	216	270	105
Corrosion and erosion failure	84	42	112	24	405	256	108	84	144	98
Thermal fatigue failure	189	81	240	108	360	256	189	96	90	60
Tear and wear failure	216	63	270	144	96	54	144	120	360	150
Internal failure	70	42	360	140	600	350	160	84	80	45
External failure	70	42	405	240	450	280	216	120	100	80
Plugged failure	450	270	243	144	270	168	240	140	72	45
Vibration failure	243	135	192	120	128	80	288	120	504	336
Hydrogen embrittlement failure	96	72	112	56	240	162	135	81	288	126
Power outage failure	350	150	180	108	108	72	24	16	48	36

5 | Conclusion

This study proposed a risk evaluation and assessment technique using FMEA for BOP accidents in the European offshore oil and gas industry. The approach focuses on analyzing the reliability and dependability of critical BOP components. FMEA prioritizes criticality and dependability during the design phase to ensure optimal performance and safety. This approach helps define system requirements and guide component design for redundancy in case of failure. Standards like considering failure consequences, likelihood, and frequency within the system inform this process. BOP systems consist of interconnected parts. FMEA analysis identifies these components and potential failure points, allowing for a nuanced understanding of subsystem criticality within the larger BOP system.

The successful application of FMEA in Europe's oil and gas industry will help identify failure-prone BOP components, pinpoint their specific failure mechanisms, and calculate RPNs for both components and failure modes. This analysis provided valuable insights into potential system failures, aiding risk mitigation strategies for improved safety and reliability in offshore oil and gas operations.

Author Contribution

The authors' contributions are: "The Conceptualization, Amani David Haruna. and Y.Y.; Methodology, Amani David Haruna. and Adinife Patrick Azodo.; Software, Amani David Haruna.; Validation, Okwuchi Smith Onyekwere., Amani David Haruna. and Adinife Patrick Azodo.; formal analysis, Okwuchi Smith Onyekwere., Amani David Haruna.; Investigation, Amani David Haruna.; resources, Okwuchi Smith Onyekwere., Amani David Haruna. and Adinife Patrick Azodo.; data maintenance, Amani David Haruna.; writing-creating the initial design, Amani David Haruna.; writing-reviewing and editing, Adinife Patrick Azodo. And Okwuchi Smith Onyekwere.; visualization, Amani David Haruna.; monitoring Amani David Haruna.; project management, Amani David Haruna.; funding procurement, Okwuchi Smith Onyekwere., Amani David Haruna. and Adinife Patrick Azodo. All authors have read and agreed to the published version of the manuscript. All Authors have made a significant contribution to the work reported.

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Data Availability

Some data were obtained from literature, which has been included in the references. No special permission was required for the obtained and used data.

Conflicts of Interest

The authors declare no conflict of interest. No Funders, other than the authors, played a role in the study's design, in the collection, analysis, or interpretation of the data, in the writing of the manuscript, or in the decision to publish the results.

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