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Enhancing Safety in Nigeria's Oil and Gas Sector: A Fault Tree Analysis Approach

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Mgbowaji Zacchaeus
ORCID: https://orcid.org/0000-0001-8921-1135
World Bank African Centre for Excellence for Oil Field Chemicals Research, University of Port Harcourt, Choba, Rivers State, Nigeria.
E-mail: mgbowaji@gmail.com
John Nwenearizi Ugbebor
ORCID: https://orcid.org/0009-0007-4122-1861
Centre for Occupational Health, Safety and Environment (COHSE), University of Port Harcourt, Choba, Rivers State, Nigeria.
E-mail: john.ugbebor@uniport.edu.ng
Ikechukwu Ozoemenam Agbagwa
ORCID: https://orcid.org/0000-0001-6425-6273
World Bank African Centre for Excellence for Oil Field Chemicals Research, University of Port Harcourt, Choba, Rivers State, Nigeria.
E-mail: ikechukwu.agbagwa@uniport.edu.ng
Ochuko Felix Orikpete
ORCID: https://orcid.org/0000-0001-8020-2195
Centre for Occupational Health, Safety and Environment (COHSE), University of Port Harcourt, Choba, Rivers State, Nigeria.
E-mail: orikpeteochuko@gmail.com

Abstract
The oil and gas industry, a cornerstone of the global energy supply, faces multifaceted challenges that threaten its operational integrity, environmental sustainability, and socio-economic contributions, particularly in regions like Nigeria where the sector's growth is pivotal to national development. This study embarks on a critical examination of safety and risk management in Nigeria's oil and gas sector, employing Fault Tree Analysis (FTA) to navigate the intricate web of operational hazards that compromise its safety and efficiency. By dissecting incidents ranging from structural failures to security threats, the research illuminates the multifaceted risks entrenched within the sector's activities. Through the lens of FTA, we not only identify specific vulnerabilities but also propose targeted mitigation strategies, thereby contributing valuable insights towards enhancing safety protocols. This investigation, rooted in the Nigerian oil and gas industry, underscores the broader applicability of FTA in addressing complex safety challenges in similar operational contexts globally. Furthermore, the study's emphasis on the sector's exposure to security risks and natural calamities calls for an integrated safety and risk management strategy. By proposing targeted mitigation strategies, this research not only aims to bolster technical and operational safety but also addresses the socio-economic and environmental factors that heighten the sector's susceptibility. The conclusion advocates for the ongoing refinement of safety measures, underlining the importance of vigilance, evaluation, and adaptability in overcoming the complexities of the risk landscape in Nigeria's oil and gas sector.

Keywords: Fault Tree Analysis (FTA), Nigeria's oil and gas sector, Safety and risk management, Environmental and socio-economic impacts, Mitigation measures.

1. Introduction

In Nigeria's oil and gas sector, ensuring operational safety is not just a regulatory requirement but a critical necessity to mitigate the inherent risks associated with exploration, production, and processing activities (Mbanugo *et al*., 2011). This sector, being a cornerstone of the Nigerian economy, faces a myriad of challenges ranging from operational hazards to environmental concerns, necessitating a paradigm shift towards more robust safety management practices (Benson *et al*., 2021).

Fault Tree Analysis (FTA) is a method that employs a top-down deductive approach to evaluate system reliability through the application of Boolean logic (Ferdous *et al*., 2007). Within FTA, a primary event of interest is identified and subsequently decomposed into both intermediate and basic events. These events are linked by logical operators (Cheliyan and Bhattacharyya, 2018). The analysis of the fault tree leverages Boolean algebra principles, translating the tree into a corresponding collection of Boolean equations (Yang, 2017). In traditional Fault Tree Analysis (FTA), the failure probabilities of basic events are assumed to be precise. Yet, accurately determining these probabilities for basic events is often unfeasible due to the lack of sufficient data. Therefore, it becomes essential to rely on estimated probabilities when exact data is unavailable (Purba *et al*., 2014).

Fault Tree Analysis (FTA) offers a promising avenue to enhance safety protocols by identifying potential failure points and analyzing the probabilities of safety incidents (Nassaj and Barabady, 2016). The application of Fault Tree Analysis (FTA) in the oil and gas industry has been widely explored in various studies. FTA has been utilized for risk evaluation of oil and natural gas pipelines, particularly in assessing the impact of natural hazards and leakage in abandoned wells (Badida *et al*., 2019; Lavasani *et al*., 2015).

Additionally, FTA has been applied in the petrochemical process industry, extending to the quantified risk analysis of fire and explosion in crude oil tanks, emphasizing its relevance in addressing safety concerns in the industry (Lavasani *et al*., 2015; Wang *et al*., 2013). Furthermore, the development and implementation of direct evaluation solutions for FTA have been highlighted, showcasing the continuous advancement of FTA methodologies in addressing complex engineering systems' reliability and safety (Cortes *et al*., 2023; Kaushik and Kumar, 2022; Purba *et al*., 2022).

Moreover, the FTA techniques has been employed for risk assessment of specific accidents, such as methanol storage tank fires, demonstrating the versatility of FTA in addressing diverse risk scenarios in the oil and gas sector (Ramezanifar *et al*., 2023). Additionally, FTA has been reviewed as a reliable method for analyzing the reliability of systems in the oil and gas industry, particularly in determining the probability of failure in oil and gas transmission pipelines (Baig *et al*., 2013; Dong & Yu, 2005).

Zhao-mei (2011) utilized Fault Tree Analysis (FTA) on a crude oil gathering-transport station to identify and establish a fault tree for fire and explosion risks, simplified using Boolean algebra to find minimum path sets and calculate the top event's probability, analyzed the basic event's importance degrees, and proposed improvement measures, offering theoretical guidance for the station's design, construction, management, and maintenance.

Yuan *et al*. (2018) employed Fault Tree Analysis (FTA) to examine the cause factors and safety of emergency processes in oil-gas storage and transportation fire accidents, summarized 19 cause factors, calculated 44 minimal cut sets and eight minimal path sets to explore secondary accident causes and preventions, and analyzed the probability importance of each event to propose countermeasures, demonstrating the method's scientific and practical value in understanding and improving system safety.

Unlike other methods like Hazard and Operability Study (HAZOP), Quantitative Risk Assessment (QRA), Layer of Protection Analysis (LOPA), Bow-Tie Analysis, and Event Tree Analysis (ETA), which either focus on qualitative analysis, require extensive data, or analyze consequences rather than causes, FTA combines the ability to identify root causes with quantitative risk evaluation, making it invaluable for developing preventative strategies (Yousfi Steiner *et al*., 2012). Its compatibility with stringent safety and regulatory standards, along with its integration potential with other risk assessment tools, renders FTA a comprehensive and versatile choice for addressing the multifaceted risk landscape of the oil and gas sector, where failures can have significant consequences (Tian *et al*., 2013).

The Nigerian oil and gas sector, a linchpin of the national economy, is beset by a myriad of safety and operational challenges that not only threaten its productivity but also have profound environmental and socio-economic ramifications. From recurrent incidents of oil spills to the looming spectre of industrial accidents, the sector's vulnerabilities call for an urgent re-evaluation of its safety and risk management practices. This study responds to this imperative by adopting a Fault Tree Analysis (FTA) approach, a method renowned for its efficacy in identifying and quantifying risks in complex systems.

Unlike previous studies that have predominantly conceptualized FTA's methodology and applications, our research delves into the practical application of FTA within the specific context of Nigeria's oil and gas operations. By analyzing data on incidents, failures, and operational hazards, we aim to not only map out the sector's risk landscape but also to spotlight the effectiveness of FTA in crafting robust safety measures.

Addressing the gap in literature, this study situates itself at the intersection of safety analysis and operational reality, focusing explicitly on the Nigerian oil and gas sector—its processes, challenges, and the critical need for enhanced risk management strategies. Through this targeted exploration, the research endeavours to present a model for problem-solving that holds relevance not just for Nigeria but for similar industries grappling with the complex dynamics of safety and risk.

2. Methods

The methodology illustrated in Figure 1, which guides this study's comprehensive Fault Tree Analysis (FTA) of the Nigerian oil and gas sector, integrates principles and procedural frameworks established in the literature on safety analysis and risk management. Notably, this methodology draws upon the works of Ferdous *et al*. (2007) for its structured, systematic approach to FTA, emphasizing a top-down deductive logic to evaluate system reliability and identify potential failure points within complex systems. Additionally, the qualitative and quantitative analysis steps are informed by the practices outlined by Lavasani *et al*. (2015), who applied fuzzy fault tree analysis to assess risks in oil and natural gas pipelines, demonstrating the utility of FTA in extracting actionable insights from data. This study's adaptation of these methodologies is tailored to the unique operational, environmental, and socio-economic contexts of the Nigerian oil and gas sector, ensuring a rigorous, context-sensitive examination of its safety and risk landscapes. This diagram visually articulates the systematic progression from the initial system definition to the final formulation of risk mitigation strategies. Each step is interconnected, demonstrating the logical flow from identifying the top event of interest, through system decomposition and analysis, to the eventual development of targeted safety improvements.

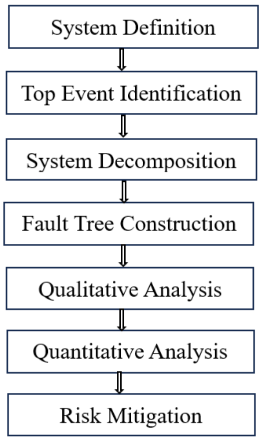

Figure 1 - Research methodology.

Each of the steps outlined in Figure 1 will now be explained further to provide a comprehensive understanding of the methodology employed in the study.

2.1 System definition

The study initially delineated the system's boundaries, focusing on components relevant to safety in the Nigerian oil and gas sector, establishing a clear context and scope for the Fault Tree Analysis (FTA).

2.2 Top event identification

It then pinpointed the top event, representing a critical failure or undesirable outcome within the system, such as a major safety incident.

2.3 System decomposition and probability assignment

Upon identifying and decomposing the system into its constituent elements, probabilities were assigned to each basic event within the fault tree to evaluate their likelihood of occurrence. This quantification process is pivotal for assessing the overall risk associated with the system's identified vulnerabilities. The assignment of probabilities and the subsequent risk quantification were based on a combination of operational data, historical incident records, and expert judgment, adhering to methodologies established in the literature on risk analysis and safety engineering.

Probabilities for basic events were determined using operational data sourced from industry reports, safety incident databases, and direct communications with participating companies in the Nigerian oil and gas sector. This data provided a historical basis for estimating the likelihood of specific failures or errors occurring within the sector's operations. The risk associated with identified vulnerabilities was quantified using the following equation, which integrates the probability of basic events (P) with their potential impact (I): $Risk = \sum(P_i \times I_i)$

where:

P_i represents the probability of occurrence for the *ith* basic event, and

I_i denotes the impact of the *ith* event, assessed based on potential safety, environmental, and economic consequences.

This equation allowed for the aggregation of individual risks to estimate the overall risk associated with the top event in the fault tree, providing a clear metric for prioritizing risk mitigation strategies.

2.4 Fault tree construction and symbolism

The fault tree developed as part of this study employed a standardized set of symbols and notations to represent basic events, intermediate events, and logic gates, adhering to the conventions widely accepted in the field of safety engineering and risk analysis. These symbols facilitate the visualization of complex system interactions and the propagation of failures leading to the top event. The use of symbols in this study followed the recommendations and guidelines set forth by Vesely *et al*. (1981) in their seminal work, "Fault Tree Handbook," which provides a comprehensive overview of fault tree analysis techniques, including detailed descriptions of symbols and their applications.

Basic Events: Represented by circles, denote failures or errors that can occur independently.

Intermediate Events: Depicted as rectangles, represent conditions that result from one or more basic events but can also lead to further events.

Logic Gates: Including AND gates (indicating that all input events must occur for the output event to happen) and OR gates (where any of the input events can trigger the output event), follow the standard symbols used in logical and reliability engineering.

This alignment with established FTA symbolism ensured that the fault tree analysis presented in this study was accessible and interpretable by practitioners and researchers familiar with the methodology. By adhering to the guidelines proposed by Vesely *et al*., the study upholds the rigor and clarity essential for effective risk assessment and communication within the engineering community.

2.5 Qualitative analysis

A qualitative analysis was conducted to discern the minimum cut sets—the simplest combinations of basic events that could trigger the top event, highlighting critical system vulnerabilities.

2.6 Quantitative analysis

The study proceeded with a quantitative assessment, assigning probabilities to basic events by analyzing data from industry operations and incorporating expert insights to calculate the overall likelihood of the top event's occurrence, quantifying the risk associated with identified vulnerabilities.

2.7 Risk mitigation measures:

Based on the insights from the fault tree analysis, targeted strategies were formulated to mitigate identified risks, enhancing the safety framework within Nigeria's oil and gas sector.

2.8 Data source and scope

This study leveraged a comprehensive database compiled from the Nigerian oil and gas sector operations, encompassing the period from January 2010 to December 2020. The database consists of operational, safety, and incident records for 50 major oil and gas companies actively operating within Nigeria during this timeframe. These companies represent a cross-section of the industry, including upstream exploration and production companies, midstream pipeline operators, and downstream refining and distribution firms. Operations encompassed within the dataset range from offshore deep-water drilling to onshore pipeline maintenance and refinery operations, providing a holistic view of the sector's safety landscape. Operational data critical for the analysis were obtained from a range of sources to ensure a comprehensive understanding of the sector's risk profile. These sources included:

- Annual safety and operation reports from the Nigerian National Petroleum Corporation (NNPC) and the Department of Petroleum Resources (DPR).
- Incident and accident databases maintained by international oil and gas safety organizations.
- Direct submissions and interviews with safety managers from the analyzed companies, ensuring the relevance and accuracy of the data.

The triangulation of data from these varied sources enabled a robust and nuanced assignment of probabilities to the fault tree's basic events, grounding the FTA in the specific operational realities of the Nigerian oil and gas sector. The selection of companies and the corresponding dataset were determined in collaboration with the Nigerian National Petroleum Corporation (NNPC) and the Department of Petroleum Resources (DPR), ensuring a comprehensive representation of the industry. To maintain confidentiality and comply with data sharing agreements, specific company names and sensitive information have been anonymized. The analysis conducted herein focuses on aggregated trends and systemic issues rather than individual company practices. This approach ensures the protection of confidential information while allowing for a thorough examination of the sector's safety performance and risk factors.

2.9 Calculation of risk scores (RS)

Within the Fault Tree Analysis (FTA) framework utilized in this study, each basic and intermediate event associated with a potential failure or hazard was quantitatively assessed to determine its Risk Score (RS). The RS is a numerical value that reflects the relative risk each event poses to the system's integrity and safety, facilitating the prioritization of risk mitigation efforts. The calculation of RS was derived from a combination of the event's probability of occurrence (P), its potential impact on system safety and operations (I), and the detectability of the event before it leads to a system failure (D). The formula used is as follows: $RS = P \times I \times D$

Where $P =$ Probability of Occurrence, which was assessed based on a scale from 1 (least likely) to 10 (most likely), based on historical data, operational statistics, and expert judgment.

$I =$ Impact, which was evaluated based on a scale from 1 (minimal impact) to 10 (catastrophic impact), considering factors such as potential for injury, environmental damage, and economic losses.

And $D =$ Detectability, which was rated based on a scale from 1 (easily detectable) to 10 (hard to detect), reflecting the likelihood that the event could be identified and addressed before resulting in a failure.

For instance, in Figure 2, an RS of 13.14 for a structural failure due to poor design or construction indicates a relatively high combination of occurrence probability, impact severity, and detection difficulty, underlining the critical nature of this risk factor. Conversely, a lower RS value suggests a less critical risk, either due to lower probability, lesser impact, or higher detectability. This systematic, quantitative approach ensures that mitigation strategies are focused on the most significant risks to system safety and operational integrity.

3. Results

3.1 Structural failure fault tree

The fault tree analysis outcomes are depicted in Figure 2, providing a visual representation of the factors contributing to the structural failure hazardous event. Table 1 presents the root causes associated with each hazard, offering a detailed breakdown of the identified issues.

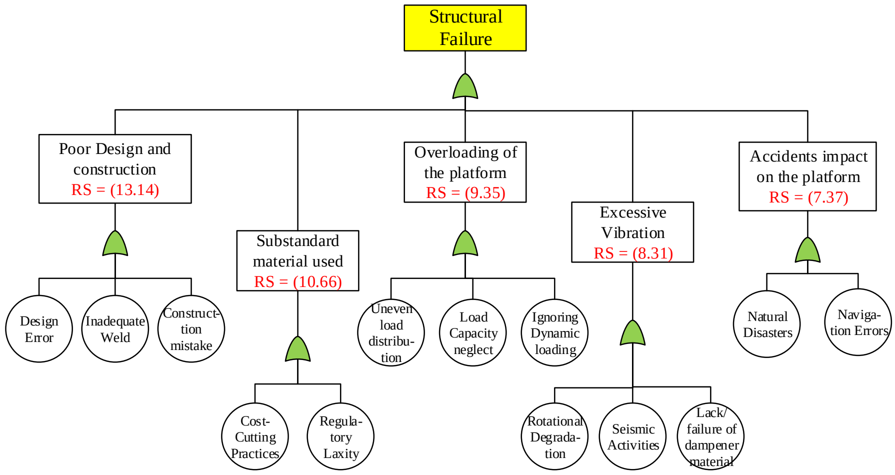

Figure 2 - Fault tree for structural failure.

Table 1 - Root causes for structural failure hazards.

Hazardous events	**Hazards**	**Root causes**
Structural Failure	Poor design or construction	Design errors during the planning phase caused by lack of expertise or rushed decision-making
		Inadequate welds or joints in structural elements influenced by shortcuts to save time and resources.
		Construction mistakes during the implementation phase due to inadequate supervision and training of workers
	Excessive vibration	Wear and tear in rotating components
		High wind or seismic activities causing vibrations beyond the design limits
		Lack or failure to install dampener material
	Accidents impact on the platform	Natural disasters, such as storms, earthquakes, or floods
		Errors in navigation leading to accidental collisions caused by inadequate training and awareness
	Substandard material used	Contractors taking advantage of high profit margins by sourcing the cheapest materials available, compromising quality
		Lack of regulatory enforcement and supervision allowing contractors to cut corners without consequences.
	Overloading of the platform	Failing to distribute the weight evenly
		Ignoring load limits specified in the design due to a lack of awareness or accountability.
		Not taking into account the dynamic loading of the platform

3.2 Gas leak fault tree

The outcomes of the fault tree analysis are visually represented in Figure 3, providing a comprehensive overview of the root factors contributing to the gas leak hazardous event. Table 2 offers a detailed breakdown of the root causes associated with each hazard, shedding light on the critical issues contributing to gas leaks.

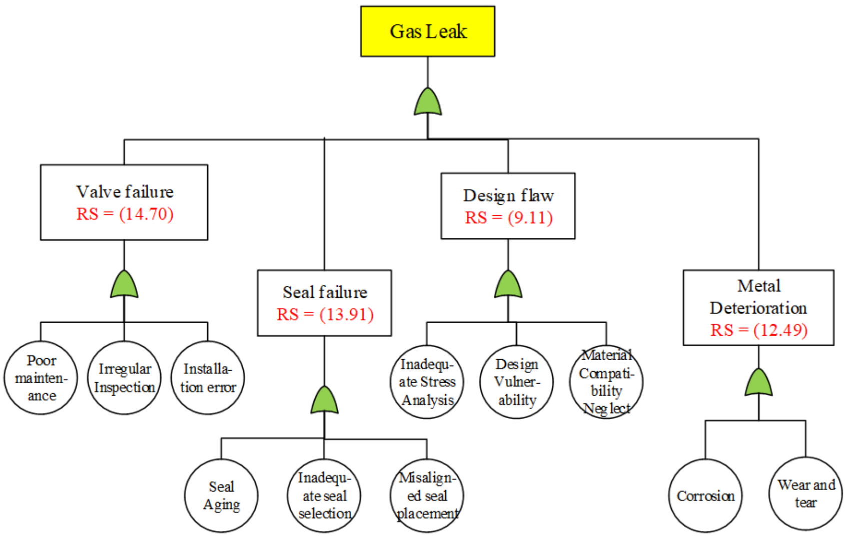

Figure 3 - Fault tree for gas leak.

Table 2 - Root causes for gas leak hazards.

Hazardous events	**Hazards**	**Root causes**
Gas leak	Valve failure	Inadequate maintenance leading to wear and tear in valve components
		Lack of regular inspection causing undetected faults in valve mechanisms.
		Improper installation resulting in faulty valve performance.
	Seal failure	Deterioration of seals due to prolonged usage without replacements.
		Seal misalignment during installation causing leakage points.
		Improper selection of seal materials
	Design flaws	Insufficient consideration of potential stress points in the system's design.
		Inadequate evaluation of material compatibility, leading to corrosion and seal degradation.
		Use of inappropriate materials
	Metal deterioration	Corrosion due to exposure to corrosive substances in the transported gas
		Mechanical wear and tear

3.3 Security threat fault tree

The fault tree analysis results are visually represented in Figure 4, offering a comprehensive overview of the factors contributing to security threats in the region. Table 3 provides a breakdown of the root causes associated with each hazard, shedding light on critical issues leading to security concerns.

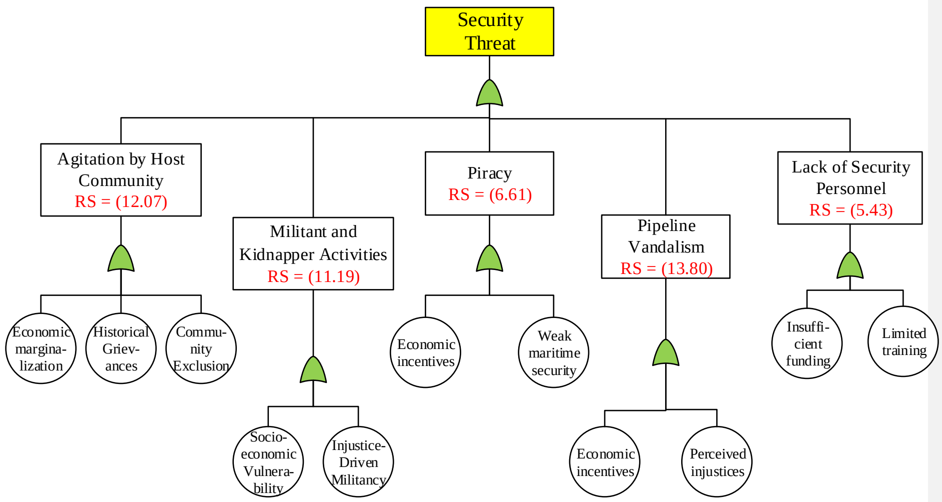

Figure 4 - Fault tree for security threat.

Table 3 - Root causes for security threat hazards.

Hazardous events	**Hazards**	**Root causes**
Security threat	Agitation by host community	Economic disparities and lack of development initiatives leading to community dissatisfaction
		Historical grievances and unresolved conflicts fuelling community agitation.
		Lack of community engagement in oil and gas development
	Militant and kidnapper	Socioeconomic challenges fostering recruitment opportunities for militants and kidnappers.
		Perceived injustices, including environmental degradation and lack of employment opportunities, driving individuals towards militant activities.
	Piracy	Economic incentives derived from piracy, including theft of oil and other valuable resources
		Weak maritime security
	Pipeline vandalism	Economic incentives from illegal oil bunkering, encouraging individuals to vandalize pipelines.

		Perceived injustices, including environmental degradation and lack of employment opportunities, driving individuals towards militant activities.
	Lack of security personnel	Insufficient funding and resources allocated to security agencies responsible for safeguarding the region.
		Limited training and capacity-building programs for security personnel.

3.4 Fire and explosion fault tree

The fault tree analysis outcomes for Fire and Explosion hazards are visually represented in Figure 5, offering a comprehensive overview of the factors contributing to fire and explosion risks in oil facilities. Table 4 provides a breakdown of the root causes associated with each hazard, shedding light on critical issues leading to fire and explosion hazards.

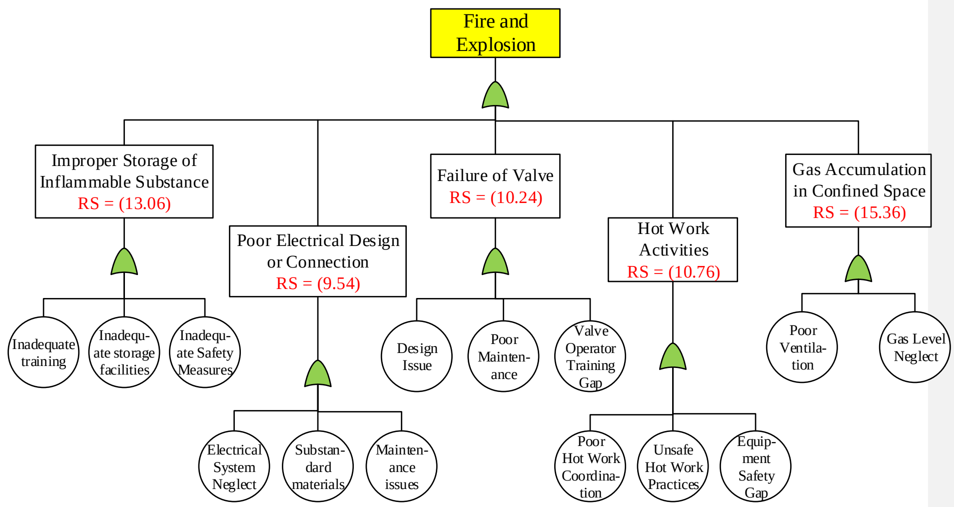

Figure 5 - Fault tree for fire and explosion.

Table 4 - Root causes for fire and explosion hazards.

Hazardous events	**Hazards**	**Root causes**
Fire and explosion	Improper storage of inflammable substance	Inadequate training and awareness among personnel regarding proper storage practices.
		Inadequate storage facilities
		Insufficient safety protocols during storage and handling of inflammable substances.
	Poor electrical design or connection	Inadequate electrical systems maintenance leading to equipment failures.
		Substandard electrical connections and components in the oil processing infrastructure.
		Lack of routine electrical inspections and upgrades in oil facilities.

	Failure of valves	Inadequate valve design
		Poor valve maintenance and inspection
		Insufficient training of personnel responsible for valve operation and maintenance
	Gas accumulation in confined space	Poor ventilation
		Inadequate gas monitoring systems in confined spaces.
	Hot work activities	Absence of effective communication and coordination among workers involved in hot work activities
		Inadequate safety measures during hot work activities
		Lack of safety guards in hot work equipment

3.5 Oil spill fault tree

The fault tree analysis outcomes for oil spill hazards are visually represented in Figure 6, providing a detailed overview of the factors contributing to oil spill risks in oil facilities. Table 5 presents the root causes associated with each hazard, shedding light on critical issues leading to oil spill hazards.

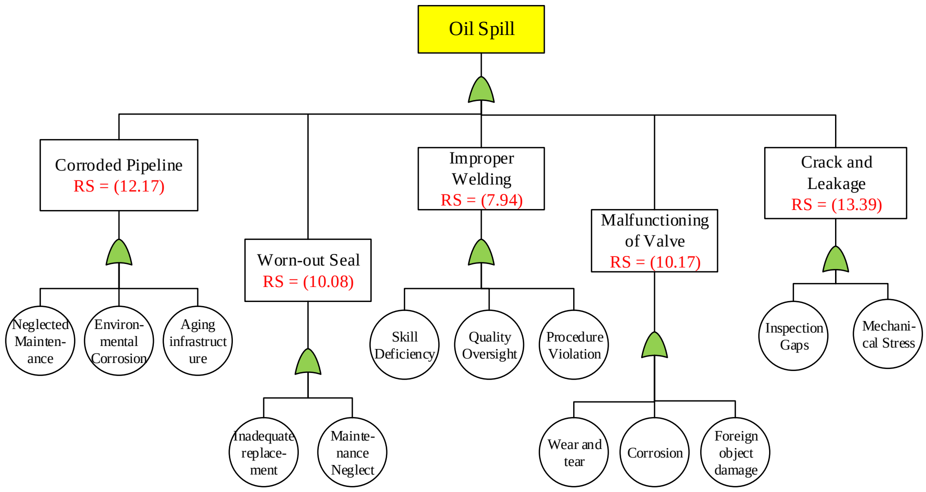

Figure 6 - Fault tree for oil spill.

Table 5 - Root causes for oil spill hazards

Hazardous events	**Hazards**	**Root causes**
Oil spill	Corroded pipeline	Inadequate inspection and maintenance
		Exposure to corrosive environments
		Aging infrastructure
	Worn-out seal	Poor maintenance practices
		Inadequate replacement schedules for worn-out seals in equipment.
	Improper welding	Lack of qualified and certified welders performing welding tasks

		Inadequate inspection and quality control during the welding process.
		Insufficient adherence to welding standards and procedures
	Crack and leakage	Lack of regular inspections and integrity assessments to detect potential leak points.
		Mechanical stress
	Malfunctioning of valve	Wear and tear
		Corrosion
		Foreign object damage

3.6 Blowout fault tree

The fault tree analysis outcomes for blowout hazards are visually represented in Figure 7, offering a comprehensive overview of the factors contributing to blowout risks in drilling operations. Table 6 provides a detailed breakdown of the root causes associated with each hazard, shedding light on critical issues leading to blowout hazards.

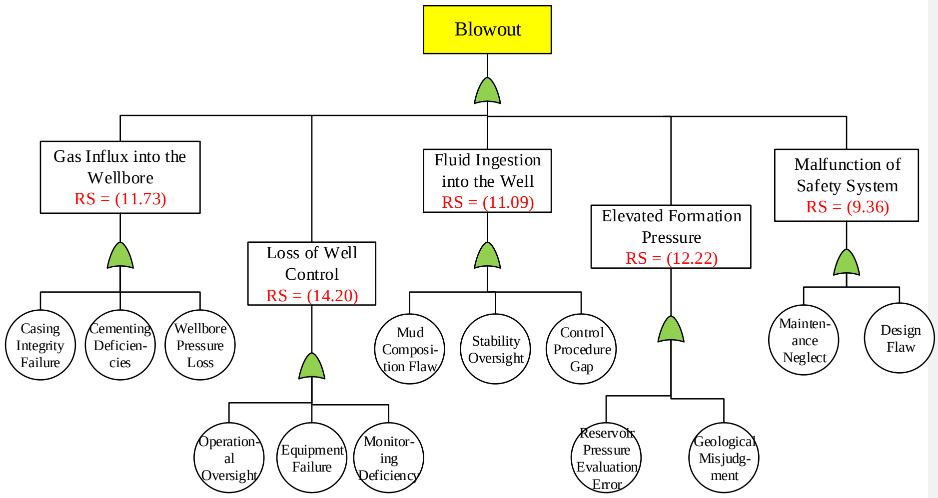

Figure 7 - Fault tree for blowout.

Table 6 - Root causes for blowout hazards.

Hazardous events	**Hazards**	**Root causes**
Blowout	Gas influx into the wellbore	Inadequate wellbore integrity due to substandard casing materials.
		Insufficient cementing leading to gas migration through annular spaces.
		Failure to maintain adequate hydrostatic pressure in the wellbore
	Loss of well control	Inadequate training and preparedness of drilling crew in managing unexpected situations.
		Mechanical failure of well equipment.

		Lack of real-time monitoring systems to detect signs of well instability.
	Fluid ingestion into the well	Improper drilling mud composition and properties leading to fluid influx.
		Insufficient wellbore stability analysis during drilling operations.
		Lack of effective well control procedures in response to fluid kicks.
	Elevated formation pressure	Inaccurate reservoir pressure evaluation during well planning.
		Poor understanding of subsurface geology and pressure gradients.
	Malfunction of safety system	Inadequate maintenance and testing of safety systems and blowout preventers.
		Improper design or installation of safety equipment.

3.7 Storms and rough sea fault tree

The fault tree analysis outcomes for storms and rough sea hazards are visually represented in Figure 8, providing a comprehensive overview of the factors contributing to storm and rough sea risks in maritime operations. Table 7 presents a detailed breakdown of the root causes associated with each hazard, shedding light on critical issues leading to storms and rough sea hazards.

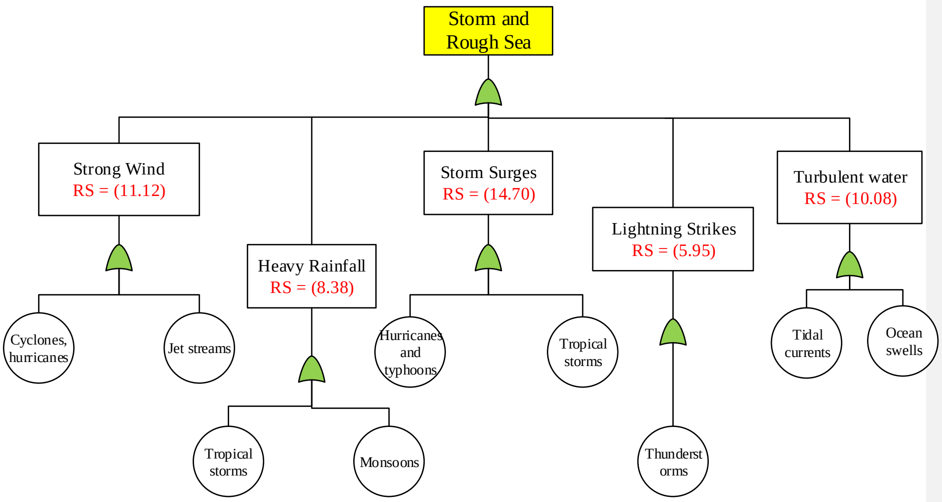

Figure 8 - Fault tree for storms and rough sea.

Table 7 - Root causes for storms and rough sea hazards.

Hazardous events	**Hazards**	**Root causes**
Storms and rough sea	Strong wind	Cyclone and hurricanes
		Jet streams
	Heavy rainfall	Tropical storms
		Monsoons
	Storm surges	Hurricanes and typhoons
		Tropical storms

	Lightning strikes	Thunderstorm
	Turbulent water	Tidal currents
		Ocean swells

4. Discussion

The Fault Tree Analysis (FTA) conducted for this study illuminates the multifaceted nature of hazards within Nigeria's oil and gas sector, revealing a complex interplay of factors leading to structural failures, gas leaks, security threats, fires, explosions, oil spills, blowouts, and challenges posed by storms and rough seas. The outcomes, as depicted across Figures 2 through 8 and detailed in Tables 1 through 7, underscore the criticality of addressing both the root causes and the systemic vulnerabilities inherent in the sector's operations.

Structural failures are primarily attributed to design and construction deficiencies, reflecting a significant gap in expertise, resource allocation, and oversight. The sector's reliance on substandard materials and overloading practices further exacerbates the risk of such failures, pointing to a dire need for stringent regulatory enforcement and enhanced quality control measures.

Gas leaks, as revealed by the analysis, stem from a variety of mechanical and design flaws, including valve and seal failures, which are often overlooked due to insufficient maintenance and inspection regimes. This indicates a pressing need for rigorous operational standards and regular safety audits to prevent such occurrences.

Security threats highlight the socio-economic and environmental grievances of the host communities, with militancy, piracy, and vandalism emerging as symptomatic of deeper underlying issues. Addressing these threats requires a holistic approach that encompasses socio-economic development, enhanced community engagement, and strengthened security measures.

Fire and explosion hazards are largely due to improper handling and storage of inflammable substances, poor electrical design, and inadequate safety protocols. This underscores the importance of comprehensive safety training, adherence to best practices in storage and handling, and regular maintenance of electrical and mechanical systems to mitigate these risks.

Oil spills are often the result of infrastructure degradation, poor maintenance, and non-compliance with standard operational procedures. The sector must prioritize infrastructure integrity, enforce strict maintenance schedules, and ensure adherence to environmental and safety standards to minimize the occurrence of oil spills.

Blowouts point to critical lapses in well control, inadequacies in drilling equipment, and flaws in safety system design or maintenance. Enhancing crew training, improving equipment quality, and implementing advanced monitoring technologies are essential steps toward preventing such catastrophic events.

Storms and rough sea conditions pose significant risks to maritime operations, necessitating improved weather forecasting, enhanced structural resilience, and the implementation of adaptive operational strategies to safeguard against these natural phenomena.

The FTA conducted in this study has illuminated a range of safety and operational risks within Nigeria's oil and gas sector, pinpointing critical vulnerabilities such as structural failures, gas leaks, and security threats. While these findings are specific to the Nigerian context, a comparative analysis with studies from other regions reveals both unique challenges and common patterns that transcend geographical boundaries.

Similar to the vulnerabilities identified in this research, studies conducted in other oil-producing countries have reported issues related to infrastructure integrity, environmental hazards, and the socio-economic impacts of oil and gas operations. For instance, Badida *et al*. (2019) found that natural hazards significantly affect oil and natural gas pipelines in North America, suggesting that challenges related to structural integrity and environmental risk are not unique to Nigeria but are a global concern within the industry. Furthermore, Lavasani *et al*. (2015) highlighted the importance of quantifying risks associated with abandoned oil and natural gas wells, indicating a widespread issue of aging infrastructure and the need for robust decommissioning practices.

The aspect of security threats, including militancy and piracy, while particularly pronounced in Nigeria due to the socio-economic and political landscape, finds echoes in other regions such as the Niger Delta and parts of the Gulf of Guinea where similar socio-economic grievances have led to security challenges for oil and gas operations (Nwalozie, 2020). This suggests that the underlying causes of security threats are rooted in broader socio-economic disparities rather than being unique to any single geographical location.

Comparing the operational risks identified in this study with global incidents, it becomes evident that while the specific manifestations and intensities of these risks may vary, the oil and gas industry worldwide faces a common set of challenges. For example, the Deepwater Horizon oil spill in the Gulf of Mexico and the Piper Alpha disaster in the North Sea underscore the universal need for stringent safety protocols, rigorous risk assessments, and continuous improvement in safety practices to mitigate the risks of major accidents and environmental damage (Mendes *et al*., 2014).

This global perspective emphasizes the importance of international collaboration, knowledge sharing, and the adoption of best practices to enhance safety and sustainability within the oil and gas sector. It also highlights the potential for findings from localized studies, such as this one focused on Nigeria, to contribute valuable insights to the global discourse on oil and gas safety and risk management.

5. Conclusion

The comprehensive Fault Tree Analysis (FTA) conducted within Nigeria's oil and gas sector, as detailed in this study, underscores a constellation of systemic risks that span from operational to environmental and socio-economic domains. Through meticulous examination of structural failures, gas leaks, security threats, fires and explosions, oil spills, blowouts, and the impacts of storms and rough seas, this analysis has illuminated the multifaceted and interconnected nature of hazards that the sector contends with.

Key findings reveal that many of the hazards are rooted in deficiencies in design, construction, maintenance, and operational procedures, compounded by broader issues of regulatory oversight, community relations, and environmental management. The sector's vulnerability to security threats and natural disasters further exacerbates these challenges, underlining the need for a holistic approach to safety and risk management.

In conclusion, enhancing safety in Nigeria's oil and gas sector requires a concerted effort that addresses both the technical and operational aspects of risk, as well as the socio-economic and environmental conditions that contribute to the sector's vulnerability. This entails not only the implementation of rigorous safety standards and practices but also the engagement with host communities, the enforcement of environmental protections, and the strengthening of regulatory frameworks. The proposed mitigation measures, derived from the fault tree analyses, offer a pathway toward reducing the likelihood and impact of hazardous events, contributing to the sector's overall sustainability and resilience. Moving forward, continuous monitoring, evaluation, and adaptation of safety protocols will be essential in navigating the complex risk landscape of Nigeria's oil and gas sector.

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Not applicable

References

Comentado [A1]: All references must be written in the formats given below, which are based on **American Psychological Association – APA**.

Badida, P., Balasubramaniam, Y., & Jayapriya, J. (2019). Risk evaluation of oil and natural gas pipelines due to natural hazards using fuzzy fault tree analysis. *Journal of Natural Gas Science and Engineering*, *66*, 284-292. https://doi.org/10.1016/j.jngse.2019.04.010

Baig, A., Ruzli, R., & Buang, A. (2013). Reliability analysis using fault tree analysis: a review. *International Journal of Chemical Engineering and Applications*, 169-173. https://doi.org/10.7763/ijcea.2013.v4.287

Benson, C., Dimopoulos, C., Argyropoulos, C. D., Mikellidou, C. V., & Boustras, G. (2021). Assessing the common occupational health hazards and their health risks among oil and gas workers. *Safety Science*, *140*, 1-6. https://doi.org/10.1016/j.ssci.2021.105284

Cheliyan, A. S., & Bhattacharyya, S. K. (2018). Fuzzy fault tree analysis of oil and gas leakage in subsea production systems. *Journal of Ocean Engineering and Science*, *3*(1), 38-48. https://doi.org/10.1016/j.joes.2017.11.005

Cortes, J., Martino, D. D., Duran, D., López, J. M., Pons-Prats, J., & Sánchez, J. M. S. (2023). Development and implementation of a direct evaluation solution for fault tree analyses competing with traditional minimal cut sets methods. *IEEE Transactions on Reliability, 72*(1), 248-257. https://doi.org/10.1109/tr.2022.3175243

Dong, Y. & Yu, D. (2005). Estimation of failure probability of oil and gas transmission pipelines by fuzzy fault tree analysis. *Journal of Loss Prevention in the Process Industries, 18*(2), 83-88. https://doi.org/10.1016/j.jlp.2004.12.003

Ferdous, R., Khan, F. I., Veitch, B., & Amyotte, P. R. (2007). Methodology for computer-aided fault tree analysis. *Process Safety and Environmental Protection*, *85*(1), 70-80. https://doi.org/10.1205/psep06002

Kaushik, M., & Kumar, M. (2022). An application of fault tree analysis for computing the bounds on system failure probability through qualitative data in intuitionistic fuzzy environment. *Quality and Reliability Engineering International*, *38*(5), 2420-2444. https://doi.org/10.1002/qre.3084

Lavasani, S. M., Ramzali, N., Sabzalipour, F., & Akyüz, E. (2015). Utilisation of fuzzy fault tree analysis (ffta) for quantified risk analysis of leakage in abandoned oil and natural-gas wells. *Ocean Engineering, 108*, 729-737. https://doi.org/10.1016/j.oceaneng.2015.09.008

Mbanugo, C. E., Agunwamba, J. C., & Eke, M. N. (2011). Risk analysis applied in oil exploration and production. *Nigerian Journal of Technology*, *30*(2), 73-79. https://www.ajol.info/index.php/njt/article/view/123527/113059

Mendes, P. A., Hall, J., Matos, S., & Silvestre, B. (2014). Reforming Brazil's offshore oil and gas safety regulatory framework: Lessons from Norway, the United Kingdom and the United States. *Energy Policy, 74*, 443-453. https://doi.org/10.1016/j.enpol.2014.08.014

Nassaj, A., & Barabady, J. (2016, December). Fault tree analysis of oil and gas distillation tower and application of Bayesian networks. In *2016 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)* (pp. 1669-1673). IEEE. https://doi.org/10.1109/IEEM.2016.7798161

Nwalozie, C. J. (2020). Exploring contemporary sea piracy in Nigeria, the Niger Delta, and the Gulf of Guinea. *Journal of Transportation Security*, *13*(3), 159-178. https://doi.org/10.1007/s12198-020-00218-y

Purba, J. H., Lu, J., Zhang, G., & Pedrycz, W. (2014). A fuzzy reliability assessment of basic events of fault trees through qualitative data processing. *Fuzzy Sets and Systems*, *243*, 50-69. https://doi.org/10.1016/j.fss.2013.06.009

Purba, J. H., Tjahyani, D. S., Susila, I. P., Widodo, S., & Ekariansyah, A. S. (2022). Fuzzy probability and α-cut based-fault tree analysis approach to evaluate the reliability and safety of complex engineering systems. *Quality and Reliability Engineering International, 38*(5), 2356-2371. https://doi.org/10.1002/qre.3080

Ramezanifar, E., Gholamizadeh, K., Mohammadfam, I., & Aliabadi, M. M. (2023). Risk assessment of methanol storage tank fire accident using hybrid fta-spa. *Plos One, 18*(3), e0282657. https://doi.org/10.1371/journal.pone.0282657

Tian, H., Huang, Y., He, J., Liu, P., & Qu, W. (2013). Application of fault tree analysis in the reliability analysis of oil-gas long pipeline. In *International Conference on Pipelines and*

Trenchless Technology 2012: Better Pipeline Infrastructure for a Better Life (pp. 1436-1447). https://doi.org/10.1061/9780784412619.147

Vesely, W. E., Goldberg, F. F., Roberts, N. H., & Haasl, D. F. (1981). *Fault tree handbook* (pp. 216). Washington, DC: Systems and Reliability Research, Office of Nuclear Regulatory Research, US Nuclear Regulatory Commission. https://apps.dtic.mil/sti/citations/tr/ADA354973

Wang, D., Zhang, P., & Chen, L. (2013). Fuzzy fault tree analysis for fire and explosion of crude oil tanks. *Journal of Loss Prevention in the Process Industries, 26*(6), 1390-1398. https://doi.org/10.1016/j.jlp.2013.08.022

Yang, Y. (2017). Boolean algebra application in simplifying fault tree analysis. *International Journal of Safety*, *1*(01), 12-19. https://doi.org/10.24900/01011219.2017.0301

Yousfi Steiner, N., Hissel, D., Mocoteguy, P., Candusso, D., Marra, D., Pianese, C., & Sorrentino, M. (2012). Application of fault tree analysis to fuel cell diagnosis. *Fuel Cells*, *12*(2), 302-309. https://doi.org/10.1002/fuce.201100072

Yuan, C., Cui, H., Tao, B., & Wang, W. (2018). Fault tree analysis for emergency process of fire accident in oil-gas storage and transportation. *Journal of Hazardous, Toxic, and Radioactive Waste*, *22*(3), 1-9. https://doi.org/10.1061/(ASCE)HZ.2153-5515.0000402

Zhao-mei, X. U. E. (2011). Research on FTA of fire and explosion in the crude oil gathering transport combination station. *Procedia Engineering*, *11*, 575-582. https://doi.org/10.1016/j.proeng.2011.04.698