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A bowtie model for fuel gas leakage incidents in an FPSO engine room

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ABSTRACT

Safety and operational costs are of paramount importance in offshore facilities. Efforts to find new ways to reduce operational costs and minimize risks have led to the development of techniques in the field of safety. Routine checks and equipment maintenance are conducted based on either calendar periods or equipment uptime, using conditional monitoring, to prevent malfunctions through preventive maintenance (PM). PM is a key strategy for ensuring the integrity and process safety of safety barriers in offshore facilities. However, due to challenges in modeling dependencies, determining maintenance intervals, and updating belief in operational data, ineffective safety barriers can occur and lead to incidents. Excessive maintenance can also increase the risk of operational mistakes among workers.

This study examines safety and operational issues associated with fuel gas leak events caused by various risk factors in Floating Production Storage and Offloading (FPSO) engine rooms using the bowtie model. Within this context, safety barriers are defined, encompassing both preventive controls and mitigating measures that can be employed to minimize potential risk factors. Furthermore, the study underscores the importance of maintenance intervals for a specific set of safety barriers, necessitating periodic testing using Condition-Based Maintenance (CBM) tools for FPSO units.

1 Introduction

Condition-based maintenance (CBM) is generally referred to using various terms, such as Predictive Maintenance (PDM), Prognostic and Health Management (PHM), maintenance-based conditions, results from online monitoring, or risk-based maintenance. Initially, when it was introduced, the concept was referred to as predictive maintenance (Prajapati et al., 2012). By the late 1970s, many offshore and marine operators had applied different proactive maintenance techniques to prevent and detect failures before they occurred or to mitigate critical failures (Prajapati et al., 2012). Since then, many techniques have been developed based on trends, condition monitoring technology, software, and diagnostics solutions for machines due to increased computing power and networking. Currently, complex manufacturing systems such as onshore and offshore units require extremely complicated and costly maintenance regulations (Heng et al., 2009). Oil industry companies and majors are increasingly concerned about the costs in the O&M phase. The rising cost of O&M has become an important topic of discussion among those involved in asset integrity management (Hwang, 2015). CBM, currently used in the oil, gas, and chemical industries, has become a reliable method for the oil and gas sector, with condition monitoring of gas and oil wells both on land and in open sea (Cibulka & Ark, 2012).

In many studies, the maintenance and repair of oil and gas units have been the subject of research. Dunn & Arthur (2001) presented a study using a dedicated CBM method for large reciprocating compressors on an offshore unit. In another study, Caselitz & Gebhardt (2002) presented the results of CBM and fault estimation on offshore wind energy converters. Between 2013 and

2016, Korea supported an investigative project applying a CBM system to offloading vessels and LNG storage units. An LNG FPSO is an offshore plant that supplies liquefied gas to customers from a liquefied gas field. It is estimated that the demand for FLNG projects is increasing and will continue to increase as the demand for natural gas rises (Zhu & Arc., 2013). A recent and comprehensive article introduced a CBM system for an LNG FPSO and identified the system architecture and key components (Hwang & Arc, 2018).

FPSOs are offshore facilities used for producing, processing, and storing gas. They are often located in challenging environments, and incidents involving fuel gas leakage in FPSOs can have serious consequences, including fires, explosions, and environmental damage. Therefore, a risk analysis is essential for these systems to ensure the safety of personnel, protect the environment, maintain asset integrity, ensure operational continuity, comply with regulations, manage costs, and secure financial and insurance arrangements.

In the offshore sector, a wide range of risk analysis methodologies has been designed and implemented to analyze the complex and potentially hazardous environments at sea. These methodologies aim to eliminate or at least reduce the effects of potential risks that may occur in these challenging settings. Among these techniques, the bow tie analysis method stands out due to its various advantages and importance. The bowtie method provides a comprehensive visual representation of potential hazards, their causes, and associated consequences, making it a powerful tool for risk assessment and management. Its benefits include the ability to facilitate effective communication across multidisciplinary teams by providing a clear and intuitive visualization of complex risk scenarios. Additionally, the bowtie method allows for the identification of critical control measures and obstacles, helping operators prioritize risk mitigation strategies. Its proactive approach aids in preventing incidents and accidents, thus minimizing harm to personnel, damage to the environment, and financial losses. In the context of the offshore industry, where safety and environmental protection are of paramount importance, the bow tie method plays a crucial role in increasing risk awareness, developing safer operational practices, and supporting the sustainability of offshore efforts.

Examining the bowtie model for fuel gas leak events in an FPSO engine room holds significant scientific importance due to its capacity to systematically identify and analyze the potential risks and hazards associated with such critical events.

This study is notable for its proactive perspective, utilizing the bow-tie model to evaluate fuel gas leakage events within FPSO engine rooms. Through this methodology, it not only provides a holistic and practical framework for comprehending and managing the risks (using safety barriers) associated with these production systems but also reveals critical insights into the dynamics of fuel gas leak incidents. Moreover, the study's significance extends to its potential to uncover best practices and offer recommendations aimed at mitigating the risks linked to fuel gas leaks in FPSO engine rooms. Ultimately, the outcomes of this research endeavor are poised to enhance the overall safety, reliability, and operational efficiency of FPSO facilities, thus contributing to the advancement of offshore oil and gas industry practices and safeguarding both personnel and the marine environment.

2 Condition Based Maintenance (CBM)

All technical and managerial actions performed during this useful period are referred to as maintenance. These actions are required to restore the functionality of an asset or product. Condition-Based Maintenance (CBM) is a preventive and predictive method for maintenance actions based on periodic assessments of equipment health using data from special sensors and other external measurements from tests. CBM is often the most cost-effective approach and has a strong impact on reliability, availability improvement, and cost savings for equipment performance trends (Shin & Jun, 2015). It is also intended to check for equipment failure modes (Guillén & Arc, 2016). Therefore, CBM should be considered for all potential failure modes that could lead to economic losses (Guillén et al., 2016).

CBM is performed to estimate the analysis and evaluation of key parameters of the deterioration of a substance through monitoring (Shin & Jun, 2015). Usually, noninvasive techniques are used, and the results of the trend reflect the degradation of an item. Therefore, proper alarm levels are set, and maintenance intervention schedules are triggered. When an alarm limit is reached, the monitoring interval must be reduced by one-third to one-quarter of the previous range. Conditional monitoring activities must occur frequently to forecast potential failures. The data analysis is performed as follows:

- Analysis of trends
- Identifying patterns
- Comparing data
- Testing ranges with limits
- Correlation of different technological methods
- Statistical process analysis

To link the inspection technique, equipment types, and measurement (or sampling) intervals, Table 1 should be used as a guideline.

The time-based preventive maintenance method differs from the conventional CBM approach (Ahmed & Kamaruddin, 2012). It estimates the product degradation process based on the assumption of many more abnormalities. These abnormalities do not immediately

Table 1 Equipment type and measurement (or sampling) interval

Technique	Equipment Type	Typical Measurement or Sampling Interval
Vibration analysis	Pumps, compressors, motors, diesel engines, generators, turbines, and cranes	1-3 month
Lubricant oil analysis	Pumps, compressors, motors, diesel engines, generators, and cranes, turbines	3 months
Mechanical thermography	Rotating equipment (to be done during vibration data acquisition)	Follows vibration analysis interval
Electrical thermography	Electrical panels and switchgears	6 months
Motor current signature analysis	Electrical high-voltage motors	6 months
Insulation oil analysis	Electrical high-voltage power transformers and electrostatic treater transformers	1 year
Ultrasonic noise detection	Pumps, motors, diesel engines, diesel and turbine generators, compressors, turbines, condensers, heat exchangers, electrical panels and transformers.	2-3 year
Equipment performance monitoring	Pumps, compressors, motors, diesel and turbine generators, turbines, condensers and heat exchangers	When requested by operations

Source: Authors

occur but are usually due to some sort of degradation process due to anomalies (Fu & Arc, 2004). Therefore, unlike the preventive maintenance approach, CBM focuses on fault monitoring, finding faults, and component diagnosis. CBM can be considered a technique used to reduce the predictability of maintenance tasks. It is then completed in accordance with the needs depending on the equipment condition, to recognize and address issues before any product damage occurs (Peng et al., 2010). The following categories classify the condition monitoring maintenance techniques (Telford & Arc, 2011):

- Making temperature measurements
- Dynamic monitoring
- Fuel analysis
- Corrosion monitoring
- Non-destructive inspection
- Performing electrical tests
- Observation and surveillance.

3 Major Accident Events on FPSO Units

Major Accident Events (MAEs), resulting in fatalities or large-scale oil spills, must be identified within the Hazard Identification (HAZID) process for each maritime unit. These events can be described as occurrences associated with or in proximity to facilities, such as hydrocarbon emissions or other incidents. Unfortunately, despite several significant MAEs in the past, they continue to occur during oil and gas production in the industry. Post-disasters, like the Piper Alpha incident in the UK North Sea, have prompted crucial evaluations of the regulatory system, leading to the establishment of a safety case-based objective-setting system (Craddock, 2004).

The majority of the primary causes of MAEs are attributed to human error in the marine industry. An analysis of 600 high-impact incidents revealed that 80% of them were linked to human mistakes, encompassing negligence, execution, decision-making, design, construction, and operational errors. While most of these errors occur during operations, they should not be disregarded during the design and construction phases when investigating the root causes of MAEs (Craddock, 2004).

A major accident event is defined as a situation with the potential to yield undesirable consequences. Such accidents or incidents may involve a sequence of events, potentially resulting in explosions, fires, or oil spills (Bhardwaj & Teixeira, 2011). Combustion or explosion incidents arising from inadvertent hydrocarbon releases pose a significant threat to the operational safety of offshore platforms. While considerable attention has been directed towards assessing the risk of accidents occurring over extended periods, the real-time escalation of risk from a primary accident to a severe one has often been overlooked (Jiang & Chen, 2021).

In brief, MAEs can be defined based on the project risk matrix, signifying their severity, owing to one of the following consequences:

1. People (Catastrophic – Multiple fatalities),
2. Environment,

a. Serious-Large spill (<10,000 bbls) (Serious medium-term impact on the environment)

b. Catastrophic-Massive spill (>10,000 bbls) (significant long-term impact on the environment).

MAEs are also caused by a variety of circumstances, mainly as a result of the breakdown or failure of several controls/safety barriers that have been put in place to prevent MAEs. A general list of MAEs is given below for FPSO units.

- Hydrocarbon/chemical release in production modules
- Offloading operation incident
- Loss of containment in flow lines/risers/wells
- Toxic gas release
- Fire/explosion in production modules
- Fire/explosion in accommodations
- Fire/explosion in cargo tanks
- Explosion/fire in enclosed spaces
- Severe weather emergency
- Mooring system failure
- Stability failure
- Loss of containment of fuel gas in machinery space
- Collision
- Man overboard
- Helicopter crash
- Confined space incident
- Electrical shock incident
- Work at heights incident
- Diving incident
- Injuries/fatalities or illness

4 Bow Tie Method

Bow ties are used across various industries to effectively manage safeguards during operations. The benefits of bow ties include clear communication, operator ownership, understanding the relationship between safeguards for various threats and consequences, and the visibility of safeguard health during operations. In the oil and gas industry, bow ties are primarily used to manage high-consequence risks related to process safety, particularly the loss of primary containment of hazardous substances.

Bow ties serve as a valuable tool for representing the relationship between major process safety hazards, threats, and safeguards, while considering operational risks (CCPS, 2018). This method combines traditional event trees, fault trees, and safeguard models into a single diagram (Khan et al., 2015; Ruijter 2018; Guldenmund, 2016). A bow tie also represents a single ‘Top Event’ triggered by potential threats and leading to consequences in a qualitative manner, which supports their use in communication. The diagrams differentiate between preventive (preceding) safeguards and mitigative (afterward) safeguards. Additionally, bow tie diagrams help clarify the specific threats and consequences against which the ‘safeguards’ are effective, with varying degrees of complexity (Acfield & Weaver, 2012; Smith, 2010; Azeez & Cranefield, 2015).

The development of bow ties for managing process safety risks in offshore facilities, using both qualitative and quantitative methods, proves advantageous not only for enhancing the visualization of safeguards during facility design but also for their exceptional utility during operations. They focus on proactive scenario and safeguard management (Azeez & Cranefield, 2015) and have been applied in various contexts, such as managing riser loss-of-containment (Olamigoke et al., 2018), offshore drilling blowouts (Majeed, 2014), and offshore evacuations (Deacon et al., 2013). While all safeguards need management, special emphasis is placed on critical safeguards due to their pivotal role. Consequently, the bow ties are intentionally kept simple, focusing on critical safeguards to enable a clear and concise visualization of their impact on scenarios. Safeguards that are not designated as critical are generally not shown but are sometimes used to illustrate specific points.

The bowtie method is a risk analysis technique used to identify and evaluate potential hazards, top events, threats, and consequences to prevent and manage high-risk scenarios. A bowtie diagram depicts the potential sources of risk, barriers, and controls in place to prevent them. It also considers the scenarios or events that could cause the top event to occur and the ensuing consequences. This method involves classifying the basic risk factors and the criticality of barriers in preventing accidents and is often employed in the oil and gas industry.

The bowtie method involves creating a diagram with two branches, referred to as the ‘bow’ and the ‘tie.’ The ‘bow’ represents the risk or hazard, while the ‘tie’ represents the controls or safeguards in place to prevent or mitigate the risk. The bowtie diagram is divided into four main components: Threat, Consequence, Barrier, and Recovery. This method is a valuable tool for identifying and managing risks across various industries, including oil and gas, transportation, and healthcare. It aids in recognizing potential risks at different stages of a process or system and devising strategies to mitigate and reduce these risks.

This study proposes a bowtie risk analysis for Fuel Gas Leakage Incidents in the FPSO Engine Room using the following steps:

1. Identify hazards: The initial phase in risk management involves pinpointing potential sources of a flammable gas explosion. Fuel gas within the engine room constitutes a perilous risk source within the bowtie framework. This study concentrates on fuel gas explosions concerning gas release and ignition sources (along with air/oxygen). Identifying potential risk sources is paramount.

2. Identify the most important events: Once potential dangers are identified, the focus shifts to understanding how control over these dangers might be compromised.

The following barriers and/or controls are put in place to prevent gas release or ignition sources:

- Hardware and equipment design for facilities and processes.
- Alarms and other process monitoring (e.g., pressure fluctuations).
- Operational procedures (including the work permit system).
- Employee training and competence (management and process operators).

3. Identify threats: Next, consideration turns to scenarios or events that could directly trigger the most significant event. It involves examining how control over these hazards may be lost. This can occur due to corrosion/fatigue of piping and equipment within the ER, resulting in fuel gas leakage, flange connection issues in the fuel gas supply line, objects falling onto the boiler, fuel gas piping within the ER, and boiler mechanical failures.

4. Define consequences: Once the most critical event occurs, subsequent scenarios or events become possible, potentially leading to losses and damages. Determining the consequences of losing control is vital. For instance, fuel spraying while the engine is running can cause a fire, formation of a flammable atmosphere within the emergency room (ER), or internal fire or explosion with the potential to affect the accommodation.

5. Identify preventive barriers: The next step is to identify barriers that can prevent threats from reaching or causing the peak incident. These are preventive barriers designed to take actions aimed at averting the most significant event.

6. Identify recovery barriers: On the right side of the bowtie, recovery barriers come into play after the most significant event occurs. These barriers must aim to prevent or mitigate consequences, losses, and damages. They need to demonstrate actions to mitigate consequences, regain control, and manage the aftermath.

7. Identify escalation factors: The subsequent phase entails identifying specific situations or conditions where barriers might be less effective or ineffective.

8. Identify escalation factor barriers: The final step involves scrutinizing barriers designed to prevent or manage these escalation factors.

5 The Bowtie Model for Fuel Gas Leakage Incidents in the FPSO Engine Room

In this study, we have developed a bowtie model tailored specifically for analyzing fuel gas leakage events within the confines of an FPSO engine room. This effort began with a meticulous identification of potential causative factors behind such events, including factors like equipment failures, human errors, and maintenance-related issues.

Subsequently, we conducted an extensive assessment of the potential repercussions stemming from these incidents, encompassing scenarios ranging from personnel injuries to environmental harm and financial losses. To enhance our understanding of the system's resilience, we diligently pinpointed the various barriers and controls meticulously in place to prevent such events. These encompassed a spectrum of safety measures, including routine maintenance and inspections, adherence to safety protocols, and the deployment of emergency shutdown systems.

Finally, we meticulously outlined a comprehensive set of mitigation measures, strategically designed to minimize the adverse consequences of these events, including emergency response protocols and contingency plans. The resulting bowtie diagram, which elucidates MAEs related to fuel gas explosions, with a specific focus on gas release and ignition sources (coupled with air/oxygen), is thoughtfully depicted in Figure 1. This diagram encapsulates the top event, the underlying causes of failure, and the resultant outcomes.

The top event within the scope of this study represents the critical scenario of fuel gas containment loss within the machinery space and engine room of the FPSO. Our analysis further entails the definition and categorization of safety barriers and escalation factors, systematically integrated into the bowtie chart. These elements have been meticulously classified into four distinct categories, as outlined in Tables 2 and 3. The categorization criteria encompass considerations such as accountability, effectiveness, basic risk factor codes, and criticality, which are elaborated upon in the subsequent sections.

Accountability: Within this category, the responsibility for establishing and maintaining safety barriers is clearly delineated. The engineering department takes charge of the design and innovation aspects, ensuring the robustness of the barriers. Meanwhile, the maintenance and operation departments bear the responsibility for sustaining the barriers in optimal condition. Simultaneously, the HSE (Health, Safety, and Environment) department plays a pivotal role in overseeing the detection of all barriers and their conditions, while providing crucial support to other departments in adhering to organizational safety policies, thereby ensuring safe and efficient operations.

Effectiveness: This parameter gauges the efficiency of barriers and management actions in averting the most critical events or outcomes. It serves as a yardstick for evaluating the degree to which dedicated safety barriers can individually prevent the occurrence of threats and their ensuing consequences. Subsequently, these sub-items are graded, ranging from poor to excellent, to provide a comprehensive assessment. As illustrated in Table 4, some barriers may be categorized as 'poor,' not implying that they lack individual

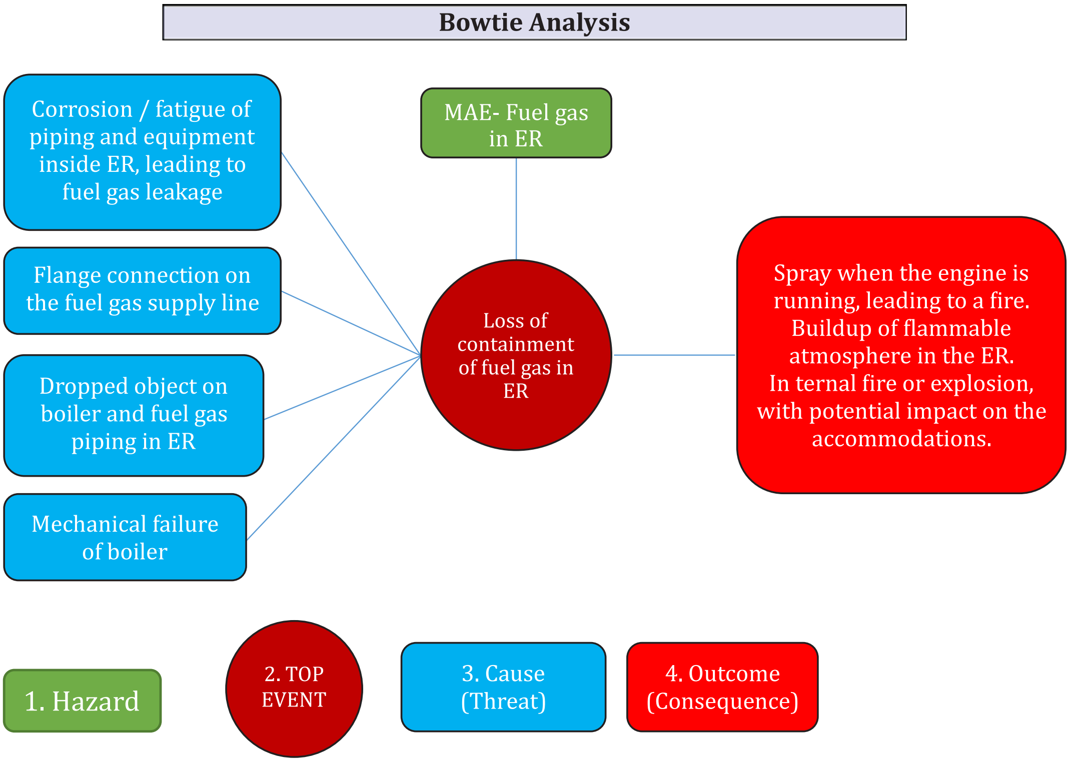

Figure 1 Bow-tie analysis for the loss of containment of fuel gas in ER

Source: Authors

Table 2 Sub-items of safety barriers classifications

Accountable	Effectiveness	Basic risk factors (BRFs)	Criticality
Engineering	Poor (-)	MM Maintenance management	Low
HSE	Good (+)	PR Operating procedures	Medium
Maintenance	Very good (++)	DE Design	High
Operations	Excellent (+++)	TR Training and OR Organization	Very High

Source: Authors

significance but rather indicating that their effectiveness primarily hinges on their synergistic interaction with other barriers. This assessment serves as a valuable indicator of the overall effectiveness of both barriers and management actions.

Basic Risk Factors (BRFs): The Basic Risk Factors (BRFs) encompassed within this framework represent the discreet contributors that, in tandem with barriers, are instrumental in mitigating the risks associated with technical and human errors leading to accidents. The inherent confidential nature of these BRFs.

Criticality: This aspect is a pivotal measure indicating the degree of importance attributed to barriers in preventing the occurrence of threats or the subsequent consequences. The sub-items encompass a range from low to high criticality, providing a nuanced perspective on the significance of each barrier within the overall safety framework.

Table 3 The Definitions of the Basic Risk Factors

Basic Risk Factors (BRFs)	Abbr.	Definition
Design	DE	Low ergonomic tools or equipment (not user-friendly)
Maintenance management	MM	Insufficient maintenance and repair work
Procedures	PR	Poor quality or availability of procedures, instructions, manuals, and manuals (specifications, application use)
Training	TR	Employees lack the necessary skills or experience and are not properly equipped or trained.
Organization	OR	Defects in the organization's structure, philosophy, operational procedures, or management techniques that lead to insufficient or poor business management.

Source: Authors

Table 4 Safety barriers & BRF Codes

Safety Barrier	Criticality	Effectiveness	Accountable	BRF Code
Material selection, pipe sizing, diesel/fuel containment integrity	Medium	Good	Engineering	DE
Flange management	Medium	Good	Engineering	DE
Minimum flange connection and double-walled piping for fuel gas line	Medium	Good	Engineering	DE
Pressure relief	Medium	Good	Engineering	DE
Exhaust steam	Medium	Good	Engineering	DE
Control of ignition sources (Gas hood room is classed as a Zone 2 area with detectors)	Very High	Very Good	Engineering	DE
Passive fire protection (fire water system and portable extinguishers)	Medium	Good	HSE Depart.	DE
Gas detection systems in the engine room	Very High	Good	Engineering	DE
Active fire protection (fixed CO_2)	Very High	Very Good	Engineering	DE
Manual fire dampers at air intakes to the engine room (to be closed in case of CO_2 release inside E/R)	Medium	Good	Engineering	DE
Forced mechanical ventilation in the engine room with 2 fans	Medium	Good	Engineering	DE
Emergency shutdown system (trips boiler, cut fuel gas, and initiates N_2 to purge lines)	Very High	Very Good	Engineering	DE
Emergency power	Very High	Good	Engineering	DE
Inspection program	Medium	Good	Operations	MM
Inspection program of lifting device	Medium	Poor	Maintenance	MM
2-year routine overhauling	Medium	Good	Maintenance	MM
Maintenance and inspection	Medium	Very Good	Maintenance	MM
Weekly tests and maintenance of fans as per PMS	Medium	Poor	Maintenance	MM
Company internal audits	Medium	Good	Operations	PR
Material and equipment lifting handling procedures	Medium	Poor	HSE Depart.	PR
Pre-job safety meetings	Medium	Good	HSE Depart.	PR
Material handling study	Medium	Poor	HSE Depart.	PR
Control of work	Medium	Good	Operations	PR
Routine tests	Medium	Good	Operations	PR
Weekly manual tests as open &closed	Medium	Good	Operations	PR
Emergency response and communication procedures	Medium	Poor	HSE Depart.	PR
Prepare work permit	Medium	Good	HSE Depart.	OR
Regular crew training	Medium	Poor	HSE Depart.	TR
Routine inspections by the safety department	Medium	Poor	HSE Depart.	TR
Escape and evacuation facilities (escape routes, emergency lighting, lifeboats, and other lifesaving equipment)	Medium	Good	HSE Depart.	TR

Source: Authors

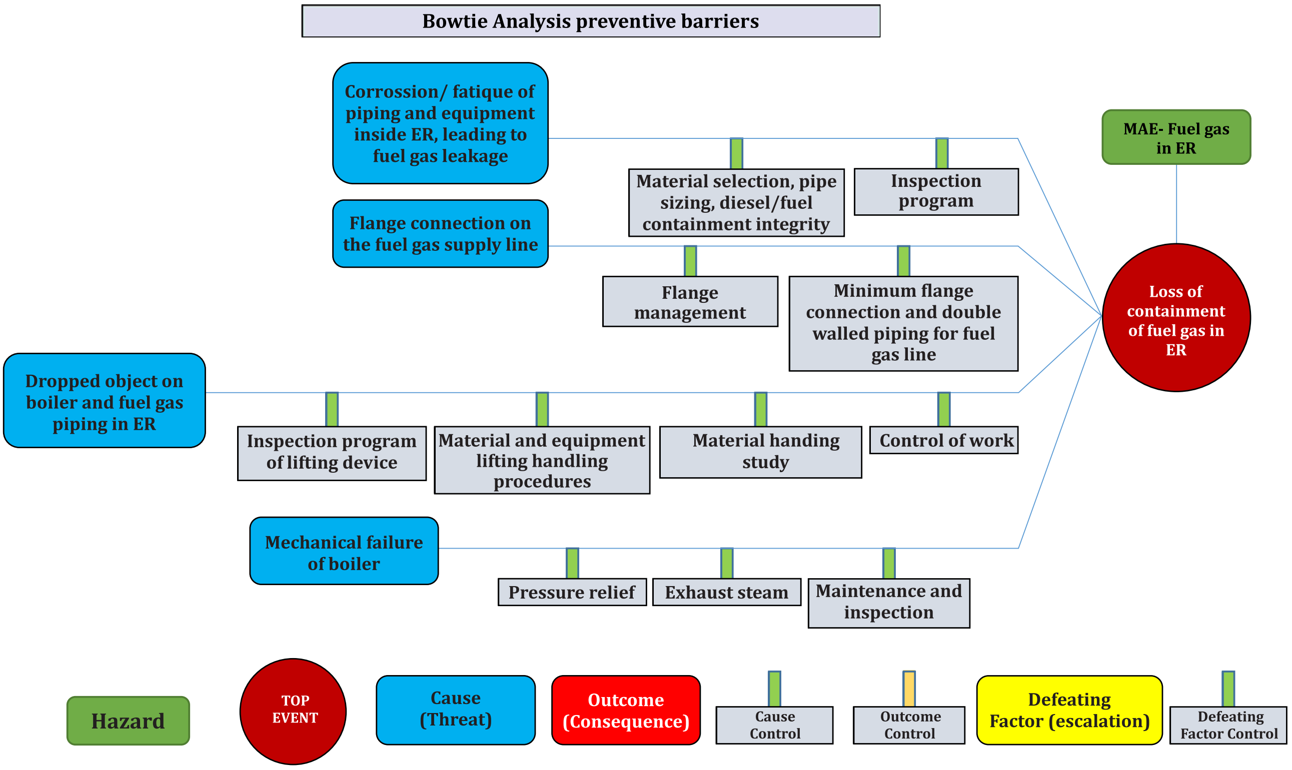

Figure 2 Bowtie Analysis preventive barriers

Source: Authors

The causes of fuel gas containment loss in the ER and the preventive barriers used to eliminate these malfunctions are examined in detail below (Figure 2):

1 – Corrosion and fatigue are common causes of damage to piping and equipment in engine rooms, leading to fuel gas leakage. Corrosion is the process by which a material is damaged and degraded because of chemical reactions in its environment. This can be caused by a variety of factors, including the presence of moisture or acidic gases, corrosive substances, and mechanical stress on the material. Fatigue is the process by which a material is weakened or damaged owing to repeated loading and unloading, such as that caused by the operation of machinery. Corrosion and fatigue can lead to cracking, pitting, and other types of damage in piping and equipment, which can create openings through which fuel gas can leak.

To prevent fuel gas leakage due to corrosion and fatigue, it is crucial to regularly inspect and maintain piping and equipment in the engine room. This includes cleaning, removing accumulated dirt or debris, replacing damaged components, and applying protective coatings or corrosion inhibitors. Measures to reduce the risk of fatigue should also be implemented, such as designing equipment to withstand operational stresses, using fatigue-resistant materials, and conducting regular inspections to identify potential fatigue issues.

2 – A flange connection is a mechanical joint commonly used in fuel gas supply lines. It consists of two mating flanges bolted together with a gasket to create a secure, leak-free seal. Proper installation is crucial, with flanges aligned and tightened to the correct torque. A gasket provides the seal, and even tightening ensures a secure connection. Regular inspections and maintenance should be performed to ensure the flange connection remains in good condition and can effectively seal the fuel gas supply line.

3 – Dropping an object onto a boiler or fuel gas piping in an engine room can pose a serious safety hazard. Even a small object can potentially ignite the fuel gas, leading to fires or explosions, or cause damage to the boiler or piping, resulting in leaks or malfunctions. Therefore, implementing proper safety measures to prevent objects from falling into the engine room is crucial. This includes establishing clear handling and transport procedures, using protective barriers or guards, and training personnel in safe handling practices. Regular inspections of the boiler and fuel gas piping to detect any damage are also essential. If an object does fall onto the boiler or piping, assess the damage immediately and proceed with necessary repairs. In case of significant damage, consider shutting down the boiler or fuel-gas system, evacuating the area, and completing the repairs safely. Adhering to proper procedures and taking neces-

sary precautions ensures personnel safety and prevents equipment damage.

4 – Mechanical boiler failures can significantly disrupt operations and pose safety risks. Potential causes include component wear and tear, corrosion, and inadequate maintenance.

Common signs of mechanical failure in a boiler include unusual temperature or pressure increases, increased noise or vibration, and visible leaks or damage. If mechanical failure is suspected, immediately shut down the boiler and initiate repair or replacement of damaged components. To prevent such failures, regularly inspect and maintain the equipment, use high-quality parts, follow the manufacturer's maintenance recommendations, adhere to proper operating procedures, and monitor the boiler's performance for early issue detection.

Here is a detailed explanation of the recovery barriers used to mitigate top event impacts (Figure 3):

1. Control of ignition sources is crucial in industries handling flammable or explosive materials. Ignition sources like sparks, open flames, and hot surfaces can lead to fires or explosions when they contact flammable substances.

2. Passive fire protection (PFP) is a fire safety system designed to contain and control fires, rather than extinguishing them actively. PFP systems employ various methods and materials to create barriers or enclosures that can delay the spread of a fire, providing time for firefighting or safe evacuation.

3. Gas detection systems are used in engine rooms and other areas where flammable or toxic gases may be present to detect their presence and alert personnel to potential hazards. These systems can help prevent accidents and injuries by providing an early warning of the presence of dangerous gases, allowing personnel to take appropriate action to evacuate the area or shut down equipment.

4. Active fire protection (AFP) is a fire safety system designed to actively extinguish a fire or prevent it from spreading. AFP systems use various methods and materials to suppress or extinguish fires, such as water, foam, or dry chemicals.

5. Manual fire dampers are devices installed in engine rooms or other areas to block air intake vents during a fire. They are manually activated in response to fire alarms or other indications. The goal is to suppress or extinguish the fire by cutting off oxygen flow.

6. Forced mechanical ventilation uses fans or other mechanical means to supply fresh air to engine rooms or enclosed spaces and remove contaminants generated by equipment operation.

7. Emergency shutdown systems (ESD) automatically or manually stop equipment or processes in emergencies, preventing accidents and injuries by quickly responding to potential hazards.

8. Emergency response and communication procedures guide responses to emergencies and facilitate effective communication between departments or teams.

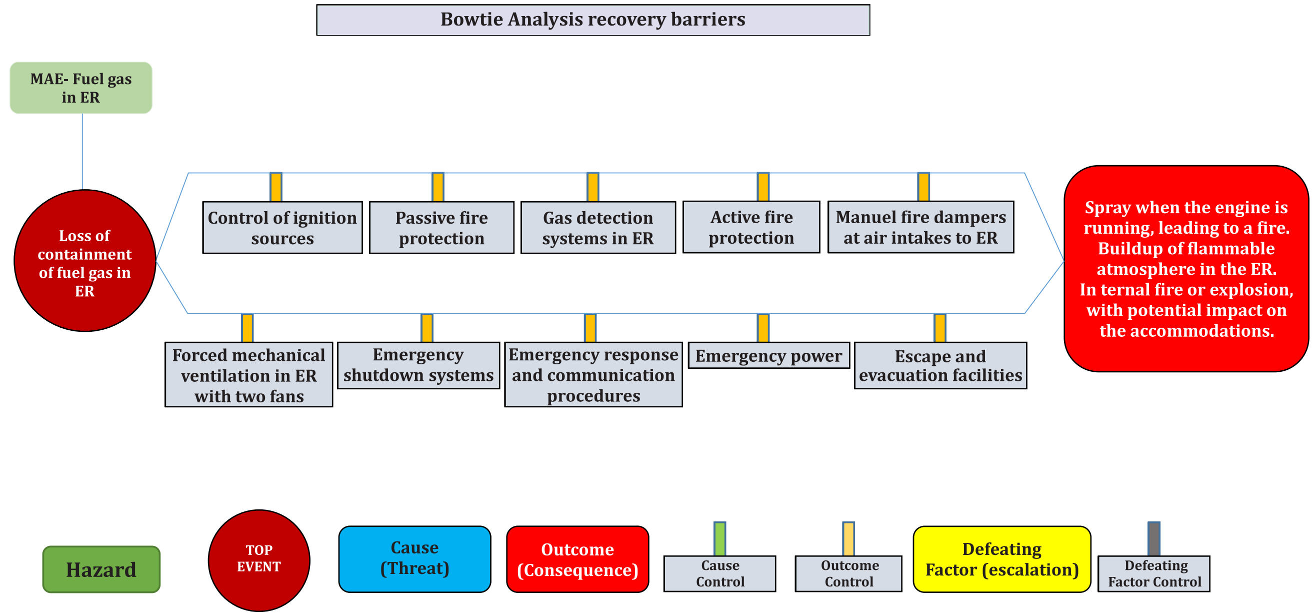

Figure 3 Bowtie Analysis with the recovery barriers

Source: Authors

9. Emergency power is a backup power source used during power outages to ensure essential equipment and systems continue to operate.

10. Escape and evacuation facilities provide means of escape during emergencies, enhancing personnel safety by enabling exits to safe locations.

6 Discussion

The systematic framework for risk management is exemplified through the utilization of the bow-tie model in the context of fuel-gas leak events within an FPSO engine room. Employing bowties for Major Accident Events (MAEs) serves as a robust methodology for scrutinizing BRFs and assessing safety barrier efficacy.

In Figure 4, we present a comprehensive depiction of the imperative need for safety barriers across all BRFs, categorized as "Design (DE)," "Procedure (PR)," and "Maintenance Management (MM)" risk factors. They are ranked from most critical to least critical, offering a clear hierarchy of priorities. Figure 5 delves further into the criticality levels associated with the utilization of BRF Codes, portraying them as percentages for enhanced clarity. Notably, "Education (TR)" and "Organization (OR)" exhibit lower criticality levels, accounting for 10% and 3%, respectively.

In our evaluation of safety barriers, it becomes evident that those with elevated criticality levels have achieved commendable effectiveness levels, predominantly categorized as "Very Good" or "Good." For example, the safety barrier titled "Control of ignition sources (Gas hood room is classified as a Zone 2 area with detectors)" demonstrates "Very Good" effectiveness. These findings can be extrapolated to other safety barriers with a similar criticality level, necessitating a minimum standard of "Very Good" or "Good" effectiveness for optimal risk mitigation.

Contrarily, safety barriers of a criticality level marked as "Medium" mandate a more stringent criterion for effectiveness. Notable examples requiring immediate attention and improvement encompass "Inspection program of lifting device," "Weekly tests and maintenance of fans as per PMS," "Material and equipment lifting handling procedures," and "Material handling study." Furthermore, the effectiveness of "Emergency response and communication procedures," "Regular crew training," and "Routine inspections by the safety department" safety barriers is alarmingly assessed as "Poor." This underscores the imperative need for comprehensive enhancements and restructuring to bolster the overall safety landscape.

This thorough assessment underscores the gravity of the situation and reinforces the urgency to fortify safety barriers across the spectrum, affirming a steadfast commitment to the protection of personnel and assets within the complex operational framework. The significance of this comprehensive risk assessment process lies in its ability to guide decision-makers in meticulously evaluating all identified risk factors and subsequently implementing tailored measures to miti-

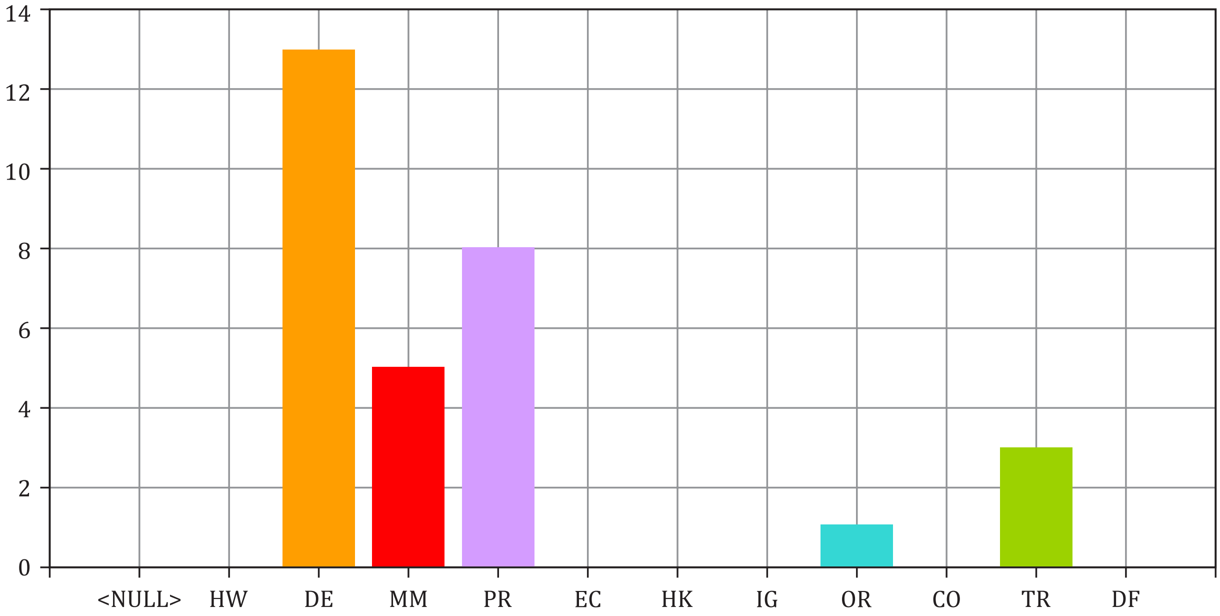

Figure 4 Barrier groups as per BRF Code

Source: Authors

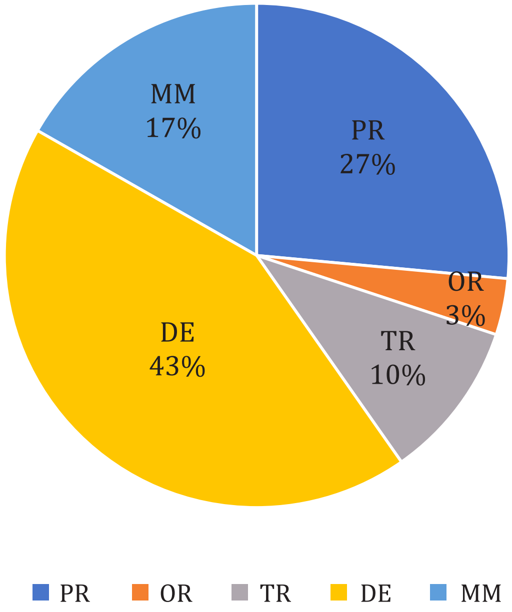

Figure 5 Percentages of BRF Codes

Source: Authors

gate the associated risks. These measures may encompass the implementation of control or rescue barriers, enhancements in training protocols and procedural guidelines, or even modifications to the design of equipment and processes.

By conducting a thorough analysis and addressing the identified risks judiciously, it becomes feasible to substantially diminish the likelihood of accidents or incidents and, in turn, ensure the utmost safety of both personnel and equipment, ultimately underscoring the paramount importance of a proactive approach to risk management.

7 Conclusions

Maintenance systems encompass a multitude of influential factors and performance indicators related to uncertainties, failure probabilities, site constraints of environmental factors, maintenance duration, frequency, scheduling, and operational conditions. Within the realm of Operational requirements, the impact of time required to execute activities and site constraints assumes paramount significance in the existing literature. Consider, for instance, the influence of the time needed to complete activities for FPSO operations, a crucial factor that not only maximizes the utilization of maintenance personnel resources but also enhances FPSO condition, while taking into account design features, operational conditions, deteriorations, and the repercussions of neglecting maintenance. This comprehensive examination underscores the scope for further research that should seamlessly integrate the impact of activity duration and site constraints into the maintenance plan. Such integration has the potential to significantly enhance asset condition due to maintenance execution, ultimately contributing to the formulation of an optimal maintenance system.

Bow-tie models, commonly applied to process safety hazards, offer a versatile tool for effectively managing high-consequence structural and marine risks, particularly those intricately tied to operational actions. The Bowtie Model serves as an indispensable framework for comprehending the intricate interplay between hazards, threats, consequences, and controls within the context of an FPSO engine room fuel gas leakage scenario. By grasping these intricate relationships, organizations can proactively implement tailored controls that serve to prevent, mitigate, and recover from such incidents. This ultimately amplifies the safety and integrity of FPSO facilities while simultaneously identifying various threats capable of causing fuel gas leakages. Furthermore, it delineates the barriers, comprising both preventive controls and mitigation measures, necessary to minimize risks. Preventive controls encompass activities such as regular inspections and maintenance of fuel gas systems, protective coatings, and overpressure protection, all of which work synergistically to reduce the probability of fuel gas leakage incidents. On the other hand, mitigation measures, including gas detection, ventilation, ignition source control, and emergency shutdown systems, are instrumental in curtailing the impact in case of a leakage. However, the bowtie model also brings into focus the escalation factors that can exacerbate the severity of an incident subsequent to a fuel gas leakage. Prominent among these escalation factors are the failure of safety-critical systems, congested layouts with limited access, uncontrolled ignition sources, and weak blast resistance.

The effective implementation of preventive controls and mitigation measures, coupled with the management of escalation factors, becomes pivotal in reducing the risks emanating from fuel gas hazards within FPSO engine rooms to As Low As Reasonably Practicable (ALARP) levels. The bowtie model furnishes a structured approach for the comprehensive risk assessment of complex hazardous scenarios offshore. It further empowers organizations to formulate intricate barrier management strategies, thereby fortifying overall risk control and bolstering safety performance.

Employing CBM techniques and potential failure maps is a promising approach for optimizing maintenance activity planning for offshore assets. This approach not only reduces the risk of equipment failure but also enhances reliability and safety, ultimately minimizing the likelihood of accidents and injuries.

This study also delves into MAEs relevant to FPSO units. The investigation of a propellant explosion in a nacelle using a bowtie diagram offers both theoretical and visual definitions of safety barriers. A bowtie diagram, complete with relevant links, provides engineers with quick insights into the various operations associated with FPSO units.

Vigilant upkeep and periodic condition surveys of safety barriers are crucial practices to ensure their optimal functionality and effectiveness in fulfilling their safety functions. The timing of these activities depends on factors such as equipment type, complexity, operating environment, and maintenance history. Organizations must meticulously review and adhere to guidelines and regulations when determining appropriate intervals for maintenance, inspection, and condition surveys of safety barriers. By following these protocols and regularly conducting these activities, organizations can ensure proper equipment maintenance, thereby enhancing their ability to fulfill safety functions and reducing the risk of accidents and injuries.

Gas leakage in the engine room typically originates from gas-burning boilers within FPSO units. Consequently, these boilers require multiple maintenance intervals and inspections for various equipment and purposes. They are also equipped with diverse safety and emergency shutdown systems designed to prevent unwanted incidents and accidents. An in-depth analysis of safety barriers using four distinct criteria to preempt threats and mitigate MAEs consequences reveals that “Design (DE)” and “Procedure (PR)” risk factors are particularly critical, with higher percentages compared to other risk factors. While the “Organization (OR)” and “Training (TR)” risk factors are also present, they register lower percentages. This clearly highlights the criticality of maintenance intervals for safety barriers, as perceived by FPSO operation engineers.

The potential for introducing a CBM within the maritime industry is still in its nascent stages, offering an exciting avenue for future research from various perspectives. Explorations may include predictive maintenance modeling, the applicability of big data in the maritime sector, and the utilization of cloud and server capacities transitioning from offshore installations to on-shore facilities. Moreover, delving into the organizational impact of adopting new technologies, examining the integration of personnel with new automation levels, and exploring the influence of artificial intelligence on existing roles and tasks within organizations holds immense relevance.

Simultaneously, the bowtie method continues to be a valuable tool, readily adaptable to various MAEs and specific safety equipment maintenance intervals, such as fire detection systems and pressure safety valves. It offers invaluable insights into risk assessment and aids in decision-making processes, all while aligning with regulatory policies.

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