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Risk identification and Bowtie analysis for risk management of subsea pipelines

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In this paper, a risk identification based on the Bowtie analysis is formulated, exploring a subsea pipeline system. Transporting dangerous materials by subsea pipelines during field operation is defined as a hazardous situation. The major pipeline causes during the field operation are also considered: external and internal corrosion; material, weld, and equipment failures; incorrect operation; and external interference. Based on this information, it is established that the main failure modes of subsea pipelines during the transport of dangerous materials by subsea pipelines are mechanical, structural, and external interference failures. Furthermore, environmental and financial aspects are considered in analysing the main consequences in the Bowtie diagram. Finally, barriers are implemented to prevent an undesirable incident or limit the consequences. The Bowtie helps structure the problem and consequently monitor the effectiveness of preventive and mitigating barriers, allowing risks to be better understood and managed over time, recording causes, consequences, and preventive and reactive controls for better monitoring.

Keywords: Subsea pipelines; risk identification; pipeline failure; bowtie analysis.

1. Introduction

The new reservoir discoveries in deep and ultra-deep waters are changing the oilfield development concepts, making the adoption of subsea production systems a more economically attractive solution. The main function of the subsea production system is to collect, control and transport the hydrocarbons from the wellhead to the production facility, which can be located offshore or onshore. Subsea pipelines are critical transport modes for oil and gas produced subsea due to their high efficiency, continuity and transport reliability and thus, they are the backbone of subsea systems (Silva et al., 2019). As hydrocarbon exploration needs to move to deeper waters, new pipe concepts such as Pipe in Pipe (PIP) and Sandwich Pipe (SP) or advanced material such as high-strength pipes have been gaining popularity as potential solutions (Bhardwaj et al., 2021, 2020a, 2020b). Subsea pipelines face new challenges in sustaining increased loadings and potential geological hazards, such as seismic activities and scouring. However, subsea pipelines operating in such extreme conditions require caution since any failure in structural integrity leads to potentially catastrophic accidents that can impact the environment, people, and organizations.

As the pipeline gathering and exporting systems play an important role in the subsea production systems, the integrity of pipeline systems is affected when the pipelines lose the ability to operate safely and withstand the loads imposed during the entire pipe lifecycle (DNV-RP-F1 16, 2009).

Unlike onshore facilities and offshore topside facilities, the subsea components and equipment have no direct access, which increases the complexity of the system. Different factors, in association with site-specific conditions, may affect the subsea production system causing accidental events with extreme consequences. This has forced the petroleum industry to integrate the early assessment of the risk level of the system during the conceptual phase of the oilfield development. It allows the identification of all integrity-related threats, even at the secondary level.

The oil industry has been learning from the accidents occurring through the years improving the industry engineering practices and supporting state designs and procedures. For example, the North Sea Piper Alpha disaster in 1988, which is considered, in terms of impact, as one of the top-five engineering disasters on the global scale (Singh et al. 2010), and the BP Macondo incident, which is well-known as Deep Horizon incident, occurred in 2010, which caused massive environmental consequences due to 87 days of leaking oil with spills of 4 million barrels (Ramasamy and Yusof, 2015). Both disasters instigate step changes in the safety criticality of the oil exploration and production systems.

The work of Aven (2022) discusses the different meanings of safety, ensuring a solid safety theory foundation. He identifies and compares the three main concepts of safety presented in the literature, classifying them as Safety I, II and III. Accordingly, the concept of Safety I means "the absence of accidents and incidents" focusing on failures and losses to ensure that “as few things as possible go wrong”. The cause-effect relationships identify the hazards and attempt to reduce the respective consequences. In contrast with the meaning of the Safety I concept; the concept of Safety II, as proposed by Hollnagel (2014), aims at ensuring "as many things as possible go right" providing a proactive approach to respond to varying conditions. The main idea is to anticipate the possible events focusing on maintaining or improving the daily performance of the system. The Safety III concept is based on a similar definition as Safety I, being described as "freedom from unacceptable losses". Both approaches focus on eliminating, mitigating, or controlling the hazards. But the main difference is that Safety III takes advantage of the learning process from the events, accidents, incidents and all possible outcomes of the system performance. Through the “Safety I” meaning, the risk concept is based on the identification of events, consequences and associated probabilities aiming at controlling the variability of the system by adopting possible barriers. Risk assessment is a systematic and scientific way to understand and predict the risk associated with failure, whereas risk management involves developing effective risk mitigation measures (Apostolakis, 2004). The risk management process is a crucial issue, aiding the decision-making process in industrial systems and transport modes with the application of tools and methodologies to support relevant activities.

Risk identification is a crucial aspect of ensuring that safety requirements are achieved, attending to the need for assets, systems, and subsystems to function adequately (De Almeida et al., 2015). Some standard qualitative and quantitative practices popular among different industries are Failure mode and Effect Analysis (FMEA), hazard and operability study (HAZOP), Fault Tree (FT) and Event Tree (ET) (Li et al., 2016). Bowtie (BT) is a well-established technique for demonstrating the relationship among primary hazardous events, safety barriers and consequences (Sklet, 2006; Hollnagel, 2008; Duijm, 2009; Khakzad et al., 2012). The Bowtie technique can describe the cause-effect relationships and presents all the barriers and controls deployed, resulting in a qualitative and/or quantitative analysis to be implemented.

Sobral and Guedes Soares (2019) discussed the adequacy of safety barriers to hazards explaining what is the purpose of safety barriers, why and how they should be established.

In this sense, this paper addresses a discussion about risk identification and Bowtie analysis for risk management of subsea pipelines. Section 2 presents a brief theoretical background for bowtie analysis for risk management. Section 3 presents a subsea pipeline risk identification based on the

Bowtie analysis. Section 4 presents some final remarks of this paper.

2. A brief theoretical background for bowtie analysis for risk management

According to Ruijter & Guldenmund (2016), Bowtie is one of the most used methods in industries such as oil and gas and aviation. It is also observed that its use has been expanded to other economic sectors in recent years, as demonstrated in the following works.

Trbojevic and Guedes Soares (2000) used bow - tie as a tool in a ship safety management program, demonstrating how these bow-ties should be constructed and used in safety management.

Trindade et al. (2020) presented a study proposing an assessment of the main obstacles to guaranteeing sustainable aspects in civil construction based on the bowtie tool.

Muniz et al. (2018) used the bowtie methodology to provide an analysis of the effectiveness of existing controls in pipelines and provide a better understanding, especially for operators and the community, regarding the risks of pipelines and their controls, through a graphical interface contributing to a better perception and understanding of pipeline risks and can encourage companies to use the elements that make up the bowtie as guidelines in the pipeline safety management process.

Chen & Wang (2019) applied the bowtie to analyze the causes, consequences, and control methods in the petrochemical industry, considering the scenario of a pipe connection failure in tank trucks.

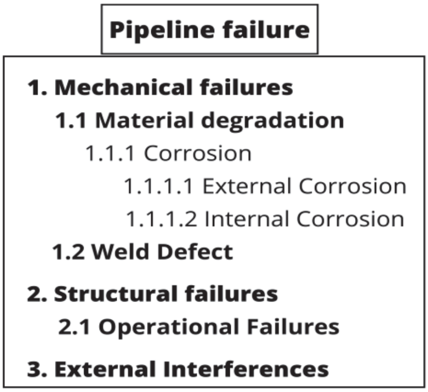
Bucelli et al. (2018) have developed event tree for the probabilistic analysis of escalation scenarios associated with offshore facilities and assessed the performance of safety barriers.

In the present context some noteworthy studies are available. Shahriar et al. (2012) have used fuzzy based bow-tie analysis risk assessment of natural gas pipeline based on social, environmental and economic consequences. Li et al. (2016) have conducted a Bow-tie analysis and developed a Bayesian Network model for leakage from pipeline. This analysis focuses on the common cause failures and conditional dependency in the leakage process.

For subsea pipeline, a recent study has conducted corrosion risk assessment through Bow-Tie approach (Yang et al. 2017).

3. Subsea pipeline risk identification based on the Bowtie analysis

The effort of the petroleum industry must always be made to minimize risk. When the effort is made at an early stage of the oilfield development can maximize the chance of implementing a good solution. In accordance with the PHMSA database (PHMSA 2023) the major pipeline causes during the field operation are external and internal corrosion; material, weld, and equipment failures; incorrect operation; and external interference. Based on this information, it was established that the main failure modes of subsea pipelines during field operation are mechanical, structural, and external interference failures. Therefore, a pipeline failure occurs when an event affects the efficiency and safety of the fluid’s transportation. Detailed information on the failure modes is presented in Fig.1.



Pipeline failure

- **1. Mechanical failures**
  - **1.1 Material degradation**
    - 1.1.1 Corrosion
      - 1.1.1.1 External Corrosion
      - 1.1.1.2 Internal Corrosion
  - **1.2 Weld Defect**
- **2. Structural failures**
  - **2.1 Operational Failures**
- **3. External Interferences**

Fig. 1 Pipeline failure modes during the oilfield production phase.

After the identification of which harm, hazard and accidents can occur with each failure and the consequences (Fig. 2) they could result in, one of the risks reducing measures is the identification of the barriers that are required to reduce the possibility of a specific accident to occur. The risk faced at any given time can be handled to an acceptable level by the implementation of barriers preventing an undesirable incident from occurring or by limiting the consequences.

Consequences

- **1. Environmental**
  - **1.1. Sea water pollution**
  - **1.2. Loss of sea life**
  - **1.3. Topside spill**
    - 1.3.1. Fire
    - 1.3.2. Explosion
  - **1.4. Air pollution**
- **2. Financial**
  - **2.1. Production loss**
  - **2.2. Repair action cost**
  - **2.3. Cleansing costs**

Fig. 2 Consequences details from pipeline failures

External corrosion is a temperature dependent mechanism and is dictated by the environment, which in the case of subsea pipelines, can be categorized as buried, sea-floor, free exposure to seawater, near surface underwater, splash zone and atmospheric. The are some similarities with the corrosion inside tanks (Guedes Soares et al. 2008) and on the shell of tankers (Guedes Soares et al. 2011).

Eckert (2017) indicates that some barriers and their functions are relevant to prevent external corrosion. Detailed information about barriers is presented in Fig.3.

Inspection and maintenance consider crucial actions to maintain the availability of components following the operating standards required to achieve the performance required by the system. In this sense, the barrier “inspection and maintenance” is considered in this study as a relevant way to prevent or mitigate the risks. The barrier “inspection and maintenance” functions such as “measuring the pipe wall thickness”. The barrier “protective coating” has the function of “improving corrosion resistance”, and the barrier “cathodic protection” presents the function of “consuming the electrons released by the anodic reaction” protective coating and cathodic protection.

According to Eckert (2017), the common threats of internal corrosion are presented in general categories of composition-related, flow-related, surface deposit-related, and environmental cracking-related.

The composition-related is caused by the combination of water, metal, and the presence of dissolved gaseous species, as well as carbon dioxide and produced water (CO2 + PW), (Hydrogen Sulphide and produced water) (H2S + PW), and Oxygen and produced water (O2 + PW).

The presence of solids plus high fluid velocities can accelerate internal corrosion by removing the protective films, being associated with flow-related threats.

The flow-assisted corrosion can be caused by high-flow velocities and turbulence increasing the shear stresses and mass transfer of reactants to the carbon steel surface. Thus, the solid deposit leads to localized pitting, characterizing the surface deposit-related threats. The microbiologically influenced threat is caused by metabolic processes of certain types of bacteria and the acid/chemically induced threat is caused by concentrated hydrofluoric acid. The Galvanic threat is generally a result of the metal being in direct contact with a more noble metal or another conductor in the presence of an electrolyte.

According to specialists, some barriers and their functions are relevant to prevent internal corrosion.

The barrier “internal pipe coating” functions as “preventing the corrosive elements from damaging the pipe surface”. The coated layers act as barriers against hydraulic friction losses, pig wear, and the build-up of pyrophoric dust in pipes. The barrier “hot-dip Galvanization” functions as “a protective coat to fill up the hollow surfaces of the pipe”. The “chemical injection” barrier exists to “form a protective film on the metallic surface and slow the corrosive reactions” In addition, several reasons may result in weld defects, which generally is detected at a late stage. So, to prevent weld defects, consider the barrier “the inspection and maintenance” to “identify and prevent any pipeline defect”.

It is important to note that the day-to-day operation of the pipeline system aims to maintain its integrity and prevent failure. The pipeline system maintenance provides efficient operation and verification guaranteeing the system's safety. So, how to prevent operational failures? The barrier "inspection and maintenance" aims "to ensure the pipeline is suitable for the intended purpose and continued service”.

An external interference failure can occur due to a combination of misrecognition of the external activities surrounding the pipeline system and, consequently, insufficient protection measures. A way to manage this event is the “protection measures” that “withstand the possible external loads previously identified”.

Moreover, there are two main barriers that can minimize the environmental and financial impacts: oil containment boom and skimmer, which, respectively, aim at “containing the oil to prevent further spreading” and “removing the oil floating at the water surface through physical separation process” (Etkin and Nedwed, 2021).

Ruijter & Guldenmund (2016) details the bowtie structure. The bowtie diagram presents a top event, understood as the moment when control is lost, positioned in the centre of the diagram. On the left side of the bowtie are the multiple causes (threats), and on the left are the multiple consequences. Other essential elements are the barriers, which are responsible for eliminating or preventing (when located on the left side of the diagram) and responsible for recovering or mitigating the loss of control caused by the occurrence of the top event. So, to perform the bowtie methodology, it is necessary to choose the system/subsystem, defining at least these elements described above (top event, causes, consequences, and barriers). Based on the information presented in this section, a bowtie diagram is constructed with the software BowtieXP to structure the relations among the top event, causes, consequences, proactive barriers, and reactive barriers (Fig.3).

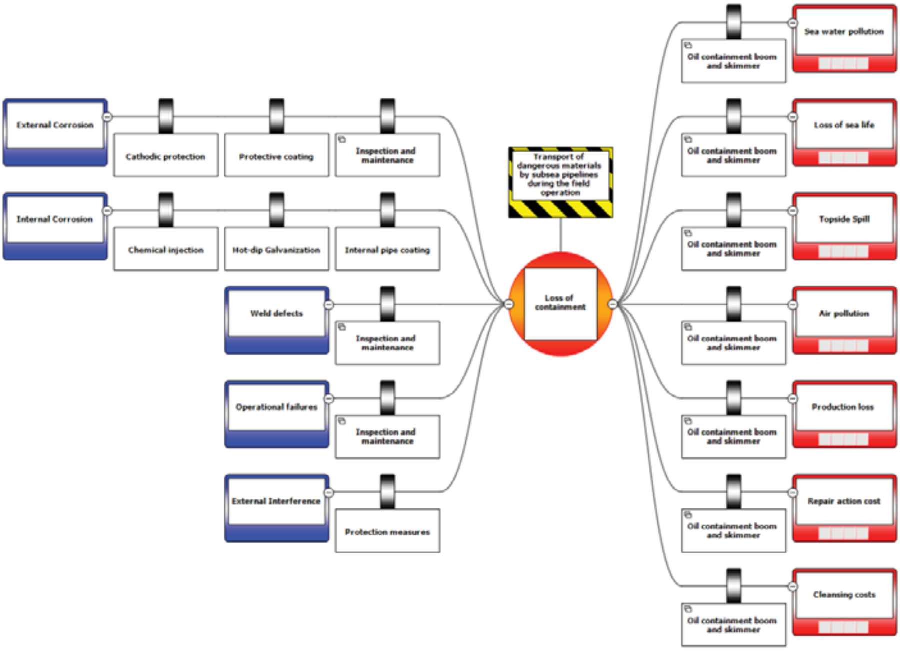


Fig. 3 Bowtie diagram.

4. Conclusions

This work presents a risk identification and Bowtie analysis for risk management of subsea pipelines. A bowtie diagram is presented to structure the decision-making process with better information visualization. Based on the diagram, the decision maker can make decisions to manage risks.

Thus, mitigation policies can be improved and promote the efficient use of resources, and safety for everyone involved in the context, avoiding losses in terms of lives, the environment, and financial aspects.

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