**Major accident prevention illustrated by hydrocarbon leak case studies: a comparison between Brazilian and Norwegian offshore functional petroleum safety regulatory approaches**

**Abstract**

The offshore oil and gas industry still shows difficulties to develop a further improvement in hydrocarbon leak (HCL) prevention. As an initiating event of major accident[1] scenario, an HCL shows potential failures that under slightly circumstances could lead to severe consequences. Once an HCL occurs, there are learning opportunities that can lead to overall safety improvement, but recurrence or similarities between different events challenge the confidence about the completeness of improvement mechanisms and their ability to develop learning. Created after major accidents and broadly used in main offshore provinces, the functional regulatory regime (FRR) assign to companies the risk ownership, a clear mandate to develop all necessary actions on risk control. The main challenges for FRRs make the goals clear among risk owners, to lead conditions to a proper selection of risk constraints, and to support risk control by sustaining a high-risk awareness among all stakeholders. However, an accident shows failures in risk control, despite laws, regulations or other tools designed to avoid it. This article compares the Brazilian and Norwegian oil and gas offshore functional safety regulatory approaches considering the circumstances from selected HCL case studies. Accidental causation models are also considered in the discussion to support the assessment of the case studies' background, the socio-technical interactions, and the regulatory strategies, identifying improvement opportunities for HCL prevention and recurrence avoidance.

Keywords: major hazard, major accident, offshore safety regulation, loss of containment, hydrocarbon leak, hydrocarbon release, accident recurrence

## 1. Introduction

### *1.1. Challenges to major accident prevention*

There are always concerns about how safety initiatives or 'early signs' from precursor incidents were not sufficient to prevent major accidents in the oil and gas industry. Moreover, similarities between accidents also highlight challenges to accident prevention and support this kind of concerns. For instance, there are common circumstances between the Texas City refinery accident (2005), and the Macondo blowout (2010) occurred in the United States of America (USA). Also, that are also remarkable similarities between the Macondo accident and the Montara blowout, this last one occurred in Australia in 2009 (AIChE-CCPS, 2013; DHSG, 2011; Hopkins, 2012). Although major accidents are unlikely, similarities among different events reveal failures in risk control from different players, such as companies and regulators, and show how it can be challenging to incorporate previous experiences into accident prevention properly.

Despite HCLs being the main contributors to major risks in offshore production platforms, there are contextual difficulties in guaranteeing a further improvement in such major hazard events in important offshore provinces. For instance, almost thirty years after the Piper Alpha accident, the United Kingdom (UK) safety regulator highlighted concerns about lack of improvement among oil companies regarding HCL avoidance, which leads British offshore platforms perilously close to a disaster (HSE, 2018a). In the Norwegian case, although the last major accident with fatalities occurred in 1985, it does not prevent similar concerns about the efficiency of the implemented measures for major hazard control (Vinnem et al., 2010). For instance, the Norwegian offshore safety regulator pointed common shortcomings and correlations between different incidents among investigations such as the Heimdal (2010) and the Gullfaks B (2012) HCLs but has not

[1] In this paper, major accidents are events with severe consequences i.e. multiple fatalities or severe environmental damage. Hydrocarbon releases, as major accidents precursor incidents, present considerable potential, but less or no consequences to health or the environment, and are also mentioned in this paper as 'major hazard events'.

identified causes or influential factors related to such recurrence (PSA, 2011a)(PSA, 2013). In addition, a recent review criticized the Norwegian distribution of responsibilities between companies and the regulator and the regulator's methods of supervision, which has shown difficulties in specific situations related to its enforcement capability, the detection of serious safety concerns and the follow-up strategy related to projects' safety supervision and nonconformances correction (Auditor General, 2019). In the Brazilian case, it is remarkable that all twenty fatalities caused by the two last major accidents are related to crew members performing emergency response activities that resulted in HCLs ignition while trying to recover the situation control, nearby or inside the gas cloud (ANP; DPC, 2001a; ANP, 2015a; Morais et al., 2016; Motta, 2002; Vinnem, 2018a). The fourteen-year period between the Cidade de São Mateus (2015) and the P-36 (2001) major accidents was enough to the implementation of an FRR and the creation of a framework for regulator's enforcement activities in Brazil. However, such similarity shows flaws in fundamental aspects of major hazard control which might have left behind after the implementation of accident investigation recommendations and important - but insufficient - additional risk control measures. This context underscores concerns about safety improvement effectiveness considering previous accidents, highlighting how challenging is accident prevention, despite positive numbers in specific aspects (ANP, 2016a; HSE, 2018b; PSA, 2018a).

Despite laws, regulations or risk management tools designed to avoid accidents, a major hazard event shows conspicuous failures in risk control. As an accident does not finish in potential failures of companies' activities, it is crucial to assess overall accident conditions to understand multilevel interactions and support proper risk control. The similarities among different accidents suggest that the currently applied methods to learn from previous experience may not have identified, assessed or addressed proper improvement measures. Thus, this article selects similar major hazard events that occurred in offshore production platforms in the Brazilian Continental Shelf (BCS) and in the Norwegian Continental Shelf (NCS) to discuss the local context, the regulatory approach and the failures in the applied risk control. The objective is to identify leading causes and improvement opportunities for major hazard events recurrence prevention in FRRs. First, we present the concepts of accident causation to disclose fundamental aspects that link regulation and accident causation. Second, we present the historical and contextual aspects of each regulatory regime under study, as well as the main previous studies related to the current analysis. Third, two selected HCLs from each jurisdiction are described, followed by the identification of most common causal factors among case studies, used as input of the requirements and regulatory approaches' comparison. Finally, the related conditions and approaches in each FRR that may prevent or sustain similarities between incidents are assessed and discussed, considering accident causation and the differences among regulatory approaches, searching for improvement opportunities and the possible causes related to the major hazard events' recurrence.

### *1.2. Fundamental major hazard regulation concepts*

How and why accidents happen are the most fundamental questions in safety science. Trying to answer these questions, Rasmussen (1997) and Leveson (2004) provided highly respected theories on accident causation. These theories support that accidents happen by systematic influences from different socio-technical levels, including the government, the regulator, the company and the work environment. The dynamic nature of socio-technical systems allows actors in different positions to build necessary conditions for accidents, as it cannot be created by a single variation in somebody's behavior. Thus, multiple roles in multiple levels, including the regulator, dynamically influence risk constraints that control accident causation (Waterson et al., 2017).

However, one of the most complex questions regarding risk regulation is how to specify roles in safety, and how risk ownership should be distributed between state and industry (Lindøe, Preben H; Engen, 2013; Thaule-pedersen et al., 2011). The slow pace of regulatory changes facing a dynamic-regulated industry imposes challenges in performing proper risk controls relying only on regulatory prescriptions. Prescriptive regulations (PR) assign to the regulator the ability to set risk constraints preventing undesirable results. This model relies on hard laws, legally binding rules, often written in detail and created by the regulator, requiring strict ways to sustain risk control, despite not clarifying safety goals (Antonsen et al., 2017).

Conversely, functional regulation, also called non-prescriptive, risk-based or performance-based (Aven and Ylönen, 2016; Golay, 2000; Ryggvik and Engen, 2015; Saji, 2003; Skotnes and Engen, 2015), consists of recognizing that it is impossible to identify and enforce all risk constraints only from the regulator's side. The non-prescriptive model clearly expresses what to achieve rather than specifying solutions needed to sustain risk control. It is a co-regulation model that provides a balance between the typical control/command from a prescriptive approach and the control absence on self-regulatory regimes. It is based mainly on encouraging a precautionary routine, risk-based thinking, focusing on the development of creative solutions using risk assessment as the primary tool (Aven and Ylönen, 2016).

Nowadays, Brazil and Norway are leading countries regarding oil and gas production through offshore platforms. Although both countries have similar functional offshore safety regulations, both safety regulatory regimes have been developed in entirely different conditions and are supported by peculiar frameworks (Almeida, 2013; Engen and Lindøe, 2014; Ryggvik and Engen, 2015).

### *1.3. Brazilian and Norwegian offshore safety regulatory background*

In the Norwegian case, prescriptive safety requirements were established after major accidents in the North Sea region, such as the Sea Gem accident in 1965 (Paterson, 2011). The Norwegian Petroleum Directorate (NPD) has been created in 1973 and has faced severe accidents in the following years, including major fires and three serious helicopter accidents summing up 34 fatalities (Vinnem, 2013). Moreover, the Ekofisk Bravo blowout in 1977 and the Alexander L. Kielland capsize in 1980, which caused 123 deaths, highlighted the relevance of sustaining high safety standards through clear regulatory boundaries. This context led the functional regulation to supersede prescriptive requirements in the NCS (Engen and Lindøe, 2014).

On the other hand, Petrobras, the Brazilian state-owned company, faced two major blowouts in the Enchova field: the first in 1984 caused 42 fatalities and the second in 1988, resulted in platform loss. However, these accidents have not caused changes in the Brazilian regulatory regime for offshore major risk control, which remain based only on Petrobras self-regulation.

Conversely, in early-nineties, the Piper Alpha accident fundamentally changed main safety regimes in the North Sea, following Norway's first steps towards functional regulations (Barua et al., 2016; Engen et al., 2017; Engen and Lindøe, 2014). At that time, while Petrobras was overcoming important deepwater exploration milestones, still in self-regulation(ANP, 2015b), Norway established a set of fourteen 'thematic' regulations, completing the transition from a prescriptive to a functional regime (NPD, 1990).

In 1997, the Brazilian National Agency of petroleum, natural gas, and biofuels (ANP) has been created as the oil and gas regulator for BCS. At first, it was mainly focused on attracting more investments through periodic bidding rounds (ANP, 2015b). However, in 2000, two major environmental accidents related to pipeline failures increased concerns about the reliability of Petrobras safety self-regulation. These concerns were highlighted by the P-36 platform accident in 2001, which caused 11 fatalities and the platform sinking (Figueiredo et al., 2018). After an extensive study about different regulatory models, the Brazilian Offshore Safety Regime (BSR) was established by ANP in 2007. The BSR created a functional approach inspired by the Norwegian Safety Regime (NSR) aiming to fill the regulatory gap on major risk control (ANP, 2007; Ryggvik and Engen, 2015).

### *1.4. Regulatory safety regimes*

#### *1.4.1. The Brazilian offshore safety regime (BSR)*

The offshore regulation structure in Brazil is complex and presents overlapping requirements from different authorities. For each main issue, there is one authority with a specific way to elaborate, approve and enforce regulations (Ornelas, 2014). The Economy Ministry sustains the occupational health and safety (OHS) requirements through prescriptive regulations (NRs). The Brazilian Environmental Agency (IBAMA) regulate environmental requirements through licensing processes and prescriptive regulations. The Brazilian Navy enforces the International Maritime Organization (IMO) and local maritime requirements through prescriptive rules. Finally, the major hazard prevention is regulated by ANP through functional regulations which compose the BSR.

The BSR is based on assigning the responsibility for oil companies to implement, sustain and improve risk management, aiming to prevent accidents, protecting human life and the environment. The BSR is composed of regulations based on management systems as follows: i) the operational safety management system for offshore drilling rigs and production platforms (SGSO) (ANP, 2007), ii) the operational safety management system for subsea systems (SGSS), such as flowlines, risers and pipelines (ANP, 2015c), and iii) the operational safety management system for well integrity (SGIP) (ANP, 2016b).

Before starting operations, an offshore platform must have the operational safety documentation (DSO) approved by the ANP. The DSO does not include information about risk identification or management, as it only describes the technical project and presents an overview of the company's procedures correlated to ANP requirements. In the BSR, the ANP's role is to enforce SMS implementation and continuous improvement through documentation analysis, performance review, incident investigation, and regular audits. It also includes informal actions to promote risk awareness among different stakeholders such as data disclosure, thematic meetings, workshops, standards and guidelines development, and safety alerts.

### *1.4.2. The Norwegian offshore safety regime (NSR)*

The regulatory framework in Norway is given by the Petroleum Law (NPD, 2015) and the Working Environment law (Lovdata, 2005). The Petroleum Safety Authority for offshore safety (PSA) was created in 2004, addressing some concerns regarding conflicting roles in safety and market regulation while it was performed by the NPD (Nilsen and Størkersen, 2018). Four main regulations compose the NSR: i) framework regulations for health, environment, and safety (HES) (PSA, 2018b), ii) management regulations (PSA, 2018c), iii) facilities regulations (PSA, 2018d) and iv) activities regulations (PSA, 2018e), all enforced by the Petroleum Safety Authority (PSA).

The Norwegian safety regulations for offshore petroleum sector are described as functional and based on the internal control principle, assigning to the oil companies the risk ownership. There is no submission of risk evaluations for authorities approval or acceptance, but the work performed by the industry may be subjected to audit by the authorities. The supervisory activities from the regulator are considered on a case-by-case basis, and a consent system makes the practical implementation of the regulations in the operational phase. The risk owner applies for the consent granted by the PSA upon evaluation of application and support documentation. Other supervisory activities consist of technical audits, incident investigations, performance review, and topic studies.

The NSR also relies on strong support from tripartite structures, including participation from employers and employees in main regulatory safety activities (Skotnes and Engen, 2015) (Engen et al., 2017). The safety forum, the regulatory forum and the "working together for safety" initiative promote important communication which supports a common view regarding several practical aspects of the safety regime.

## *1.5. Previous studies*

Regarding accidents recurrence, Vinnem (2010) highlighted that is difficult to assess lessons learned from major accidents. If such learning takes place, there are correlations between HCLs frequency and safety climate assessments. It could explain the recurrence of HCL events based on a lack of maturity in the safety culture as also restated by Olsen et al. (2015), who considered the safety climate as an organizational barrier.

Specifically about HCLs under NSR, Vinnem (2012) analyzed 175 hydrocarbon releases that occurred between 2001 and 2010. The study revealed that leaks are more frequent during night shifts or preparation activities for maintenance tasks. It has indicated that planning, preparation, and reinstatement are more relevant for HCL occurrence than the maintenance itself.

Mendes et al. (2014) discussed the framework of safety offshore regulatory regimes of Norway, the UK, and the USA. The study proposed reforming the Brazilian oil and gas safety regulatory framework by adopting three improvement actions: the UK's Safety Case regime, the Norwegian 'barrier management' and increase investment in safety research and development. More specifically, Ryggvik and Engen (2015) assessed challenges when regulatory regimes are transferred between countries, using as a case study the elements used in BSR that have been originated in the NSR. The study concluded that important formal, informal and context-related elements from NCS were not implemented into the BSR. Furthermore, the regulatory regimes must not count only on written regulations, as it will undoubtedly be shaped by social, cultural and political relations.

Considering FRRs, Skotnes and Engen (2015) stated that a functional regulatory regime creates a large degree of autonomy regarding how companies establish safety systems and how difficult is to identify improvements using additional rules from authorities. Moreover, Årstad and Engen (2018) argued that major accidents may be viewed as failures of risk ownership and that improving this aspect may help resolve particular systemic issues highlighted in investigation reports.

Regarding the NSR performance, Engen et al. (2017a) described the results of a joint assessment of health, environment, and safety (HES) conditions and trends in the Norwegian petroleum industry, concluding that high standards are in place. Among the specific recommendations, the results point to learning lessons from previous experiences and improving bi/tripartite collaboration.

## 2. Case studies and related main causal factors

Relevant accidents have occurred along the years in both BCS and NCS. Two similar accidents from each jurisdiction have been selected to be analyzed regarding causal factors and circumstances. This selection considered that each event should be an HCL, present considerable potential or consequences, and have public investigation reports from the regulator's investigations. The main aspects related to selected case studies are presented as follows, as well as the most frequent causal factors.

### *2.1. Case study 1: The P-36 explosion and sinking (Brazil - 2001)*

The P-36 was the biggest semi-submersible production platform in the world, converted[2] from a drilling rig made in 1994 and operating for Petrobras in Roncador field, Campos Basin, Southeast of Brazil (Forbes, 2013). On 15th March 2001, two explosions caused eleven fatalities and further scenario worsening led the platform to sink on 20th March 2001. The ANP and the Brazilian Navy set up a joint investigation and the accident report states causes and non-conformances, summarized as follows (ANP; DPC, 2001a).

On 15th March 2001, a few minutes after midnight, the emergency aft-starboard slop tank ruptured by internal overpressure. The pressure increase has been caused by a blind flange installed in the

[2] A conversion is an usual term in offshore when an built project has a major change in his concept to perform another activity. It is the case when a drilling rig is modified to became a production platform, such has occurred to P-36.

tank's vent line and flow generated by a connection with the production header during a transfer operation. Despite the requirements to operate emergency slop tanks only in emergencies, it was common to use these tanks to collect residual liquids from other systems, which demanded frequent transfers from these tanks. Moreover, transfer operations between the emergency slop tank and the production header were not in the operations manual. As the pump used to drain the tank had been out of service, a blind flange has been installed in the vent line to prevent liquid ingress into this tank. However, the tank's discharge isolation was made just by closing a valve, and therefore, the tank has been pressurized once this valve was not designed to retain high pressurized fluids.

The tank rupture caused damage to water lines, which started to flood the aft starboard column, and an oil and water mixture has been released, together with gas from the production header. The gas has been detected in the top tank and main deck area, and an emergency shutdown was activated. The emergency response was set up and the incident command assigned an emergency response team (ERT) to assess the situation. The ERT went to the aft starboard column, accessed the third and fourth levels and reported a mist and poor visibility on the accident site. Seventeen minutes after the tank rupture and while ERT members were performing activities around the damaged systems, an explosion occurred, killing eleven members of the ERT and causing severe damage nearby (O Globo, 2001).

On the day before the accident, some accesses between aft column compartments were left open due to preparations to maintenance work to be performed on the next day. After the explosion, these compartments were flooded with water from damaged systems, which were connected to the sea. The crew tried to keep the platform leveled during the emergency response actions, including abandonment, and seawater has been admitted by gravity into the other columns. However, no measures were taken trying to avoid flooding in the aft starboard column, and both ballast pumps on the starboard side were out of service. In addition to system conditions, the emergency response actions led the platform to a critical draft, and after several attempts to recover the P-36 stability, the platform sank on 20th March 2001.

Regarding the P-36 accident, it can be concluded that the main causal factors were related to: i) the change in emergency slop tank usage; ii) not follow the procedure, transfering liquid from emergency slop tanks directly to the production header; iii) the loss of containment; iv) the flammable cloud ignition; v) the change in the platform's compartment; and vi) improper actions to platform inclination control.

### *2.2. Case study 2: The FPSO Cidade de São Mateus explosion (Brazil – 2015)*

The platform Cidade de São Mateus was originally a cargo vessel made in 1989 and further converted in 2008 to a Floating, Production, Storage and Offloading platform (FPSO). It was designed to produce natural gas and oil to Petrobras in Espírito Santo Basin, at Camarupim and Caparupim Norte fields, Southeast of Brazil. On 11th February 2015, after a water-condensate mixture leak inside the pump room, an explosion caused nine fatalities. The ANP performed an independent investigation, and the accident report describes several details and twenty-nine causes (ANP, 2015d), summarized as follows.

On the day of the accident, the crew was transferring residual liquid between two cargo tanks when a leak occurred inside the pump room through a failure of an onboard-made spade[3]. The overpressure occurred while an operator closed all valves in the discharge system of a positive displacement pump, while there was still steam supply to power it. Before the accident it had been usual to marine operators, based on experience, to consider the pump stopped even with some steam supply indication. Although the conversion project scope planned to upgrade the marine system control with a remote direct indication about pump operation, it has not been implemented. The same has occurred to valves in the marine system, as several them did not have remote position indication and could not be remotely operated. Thus, to manage the cargo system

[3] A blind spade is a tool used to isolate sections of pipes, mainly for maintanance purposes.

operations in the CDSM, the marine operator have had strict communication with a field operator who has handled valves and pumps, following marine operator instructions.

Although the cargo tanks were designed to store oil or an oil-condensate mixture, the platform stored just condensate since it started to produce, as only gas wells were connected to the platform. This change was made just before the commissioning phase, without following the management of change requirements and has changed all risk identification regarding the project. The condensate reacted with the cargo tank valves sealing, which led valves not to retain liquid while closed, and the crew was not able to sustain different tank levels. As several valves were inside the cargo tanks, it demanded line isolations and tank entrance to carrying out the repairs. As repairs were going on, it was decided to maintain platform production even with many changes that included important restrictions regarding marine system operation. In addition, the cargo pipes were the same design to the cargo vessel construction and did not follow the same standards of the process plant. Moreover, there were no spare parts available for marine systems and in many situations, there was not enough space between joints to install proper spades. Thus, the crew used to manufacture low profile parts to fit it in the system and perform planned maintenance activities.

Furthermore, these several misbehaviors by the marine team may be supported by the fact that some positions were not filled. There was no supervision since the platform started its production, even with job activities designed for this position. The marine superintendent on duty had been on board for only ten days before the accident, without no specific guidance, because all prior marine superintendents had left the platform staff some months before the accident. There was a period when only operators oversaw all marine system-related activities, even though they were not prepared to perform or accumulate other job-related activities.

The pump had been stopped just before the gas alarms went off, revealing gas through three detectors located at the bottom of the pump room. It activated the closure of the automatic dampers and turned off the ventilation system but did not stop platform production. The ERT was set, and three different groups were sent into the pump room with breathing apparatus despite alarms on their portable gas detectors. The first team members visually confirmed the leak point in a flange where the onboard-made spade had failed. The third team was ordered to clean the spillage and try to fix the leaking flange, which at that time no longer had an apparent leak. As they were starting to clean up the leakage using pressurized water in fire hoses, an explosion occurred and caused nine deaths.

There was a mixture of lack of situation awareness and operational discipline by the crew during the emergency response, including the incident command staff and the ERT members. People left meeting points, used elevators, went to their cabins and have been exposed to a flammable atmosphere without any sign of hesitation. When the explosion occurred, the overpressure killed eight people inside the pump room or close to its entrance door. However, one person died at his meeting point inside the engine control room. The overpressure caused general damage to the accommodations through an elevator shaft, and another twenty-four people were wounded, some of them inside the accommodation block.

The ANP performed a comprehensive investigation, and regarding this accident, it can be concluded that the main causal factors were related to (ANP, 2015c; Vinnem, 2018a): i) the change in cargo tank usage to store condensate; ii) the cargo tank system degradation; iii) the marine team mismanagement; iv) operating a positive displacement pump with its discharge closed; v) the loss of containment; vi) the expose personnel to risk; and vii) the ignition of a flammable atmosphere caused by emergency response actions.

### *2.3. Case study 3: The Gullfaks B gas leak (Norway – 2010)*

The Gulfaks B is a fixed platform operated by Equinor since 1988 in Gulfaks field, Norway. On 4$^{th}$ December 2010, a gas leak occurred in connection with leaking test after maintenance work on the choke valve for a production well. The gas released lasted about one hour and summed up

800 kg of gas, with an estimated initial rate of about 1.3 kg/s. The PSA has performed an investigation (PSA, 2011b), and the leading causes and circumstances are described as follows.

On the day of the incident, the platform was in normal operation, and maintenance work on a choke valve represented a planned activity, involving disassembling, inspecting and resetting the valve. As the diesel pump usually used to perform the leak test was not available, and there was no formal procedure to the test, the crew defined an alternative method. It consisted of using a well to pressurize and inject water, but despite engage several crew members, the discussion did not identify the injection point. While performing the test, a gas leak occurred, and two well emergency shutdown valves (ESDV) had been unintentionally pressurized to open position. Further actions prevent these valves from being remoted operated by the control room, which led the leak to last for about one hour.

According to gas detection records, the gas cloud covered almost all the North Mezzanine Deck Manifold area, but it has not ignited. Two process technicians were exposed to methane gas, without significant injuries and the platform crew mustered. The leak could have been even worse if it has occurred under only slightly different circumstances, which would increase the probability of a gas cloud ignition, and the risk of an explosion with major potential.

According to the PSA investigation report (PSA, 2011b), the causal factors that contributed to the incident were: i) do not identify test requirements for barriers in the isolation plan; ii) do not plan in detail all steps of the maintenance activity; iii) the failure in risk identification related to pressure increase; iv) maintenance deficiencies related to the manual master valve; v) the unintentional deactivation of the emergency shutdown system; vi) roles not clarified to perform the maintenance activity; vii) do not develop a strategy for barriers, including lack of performance requirements; and viii) the failure in updated risk analyses studies.

### *2.4. Case study 4: Heimdal gas leak from a ruptured spool piece (Norway – 2012)*

The Heimdal is a fixed platform operated by Equinor in Heimdal field, Norway. On 26th May 2012, one of the most severe incidents on NCS during the last years occurred at the platform, when a major gas leak released about 3.5 tons of gas. The PSA investigated the incident (PSA, 2012a), and the main causes and circumstances are described as follows.

On the day of the incident, the platform was on the last day of a planned shut down for maintenance purposes, just a couple of hours before resume production. In connection to the test of two ESDVs, some valves were operated in the wrong sequence, which increased the pressure of a spool piece in the gas pipes, resulting in an initial gas release rate of 16.9 kg/s. The release was shut off after 252 seconds, but the emergency lasted for 3.5 hours. No ignition occurred, but simulations performed by the operator demonstrated that the gas cloud has spread over the entire top deck of the installation. No personnel was affected, but until the installation was considered safe, all people on board waited inside the lifeboats ready to be launched.

Preparations for testing ESDVs included the blowdown of a bleed-off pipe section of the flare system. This pipe section included the main control valve (HCV), operated from the central control room, and three manual isolation valves. The HCV had a pressure rating of 180 bar, while the final manual isolation valve before the flare had a design pressure of 16 bar. The change in pipe design pressure was just downstream the HCV, something not consistent with current industry practice but usual at the time the platform was designed, more than 30 years ago.

As the production personnel rushed to finish the job during the lunch break and the operator involved in task planning was unavailable, the task was assigned to an inexperienced process operator. This process operator in charge of the operation has not been involved in the task planning, performed by an experienced operator, and was not aware of the change in pressure rating. The blowdown has been initiated by opening the HCV without ensuring that all three downstream valves were open. The last isolation valve, which functioned as the last barrier to the flare, remained closed and was exposed to a pressure of 129 bar, almost ten times the system design pressure.

As a result, the gasket broke and the sealing around the flange led the gas to leak out into the local process module. As soon as the control room was notified by the operator about the leak in the process area, the control room operator shut the HCV. The valve finally closed after about four minutes, stopping the leak.

The main causal factors pointed by PSA through the investigation report were (PSA, 2012b): i) the deficient design solution; ii) the failure to identify the inadequate design solution; iii) the insufficient descriptions about how to perform the task; iv) a poor documentation management; v) a poor risk assessment during task planning phase; vi) a lack of expertise and risk awareness; and vii) a poor knowledge management and lack of learning from previous incidents.

### *2.5. Identification of comparison issues based on case studies*

Each regulator sustains its practices regarding accident investigations, causal factors and causes descriptions. Thus, the case studies' causes and circumstances have been analyzed in thematic analysis, correlating causal factors to one of the seventeen management practices (MP) established by the SGSO (ANP, 2007). The thematic analysis has been chosen to develop a common base of discussion, considering the authors' experience and events' similarities, which are not clearly included in each investigation report. It consists of developing categories based on similar wording and then grouping these categories into clearly related and higher-level themes (Fyffe et al., 2016). First, the analysis consisted of grouping circumstances surrounding causal factors into themes using percentages for each case study considered. Second, the average of the percentages was calculated among all case studies, and a rank of themes was obtained. Table 1 shows the main analysis results, including the considered data for each topic and case study, as well as the average considered to select themes.

Table 1. Case studies, root causes, and correlation with SGSO practices

| Management Practice | P-36 | CDSM | Gullfaks B | Heimdal | Total | Average |
|---|---|---|---|---|---|---|
| MP17: Safety practices and procedures for risk control of special activities | 1 (10.0%) | 0 | 4 (50.0%) | 2 (25.0%) | 7 | 21.3% |
| MP16: Management of change | 3 (30.0%) | 5 (17.2%) | 0 | 0 | 8 | 11.8% |
| MP3: Personnel qualification, training and performance | 0 | 2 (6.9%) | 1 (12.5%) | 2 (25.0%) | 5 | 11.1% |
| MP10: Project, construction and installation | 1 (10.0%) | 5 (17.2%) | 0 | 1 (12.5%) | 7 | 9.9% |
| MP1: Safety culture, commitment and management responsibility | 1 (10.0%) | 4 (13.8%) | 1 (12.5%) | 0 | 6 | 9.1% |
| MP15: Operational procedures | 1(10.0%) | 3 (10.3%) | 1 (12.5%) | 0 | 5 | 8.2% |
| MP12: Risk identification and analysis | 0 | 2 (6.9%) | 1 (12.5%) | 1 (12.5%) | 4 | 8.0% |

| | | | | | | |
|---|---|---|---|---|---|---|
| MP 14: Major emergency planning and management | 2 (20.0%) | 3 (10.3%) | 0 | 0 | 5 | 7.6% |
| Others | 1 (10.0%) | 5 (17.4%) | 0 | 2 (25.0%) | 8 | 13.0% |

The result shows that about 90% of root causes circumstances were correlated to eight themes. The NCS presents a high number of causal factors related to safety practices and procedures for risk control of special activities and personnel qualification, training, and performance. On the other hand, the BCS the result points out that management of change and project, construction and installation are the most frequent causes among Brazilian case studies. Conversely, the management of change is not presented among Norwegian case studies as well as just one cause from the Brazilian case studies was correlated to the causal factor related to safety practices and procedures for risk control of special activities.

Thus, the BSR and NSR established requirements for the selected themes presented in Table 1 will be described as well as the background related to each theme and its connections to major hazard events prevention. The authors used all selected themes trying to develop a coherent debate to connect ideas related to risk management, which demanded that the sequence presented in Table 1 has not been followed. In addition, as all case studies are related to the operation of production platforms, the comparison and analysis will cover only these related activities, although all considerations regarding safety may have broad meaning and application.

## 3. Regulatory requirements' comparison

### *3.1. Project, construction, and installation*

Norwegian authorities have for an extended period focused substantially on HES requirements for new projects. This focus started in 1979 when the NPD wrote a letter to Statoil and Mobile Exploration stating that if the layout of the planned Statfjord B platform were an exact copy of the Statfjord A, the project would not be approved (Vinnem, 2013). After its first major accidents, Norway developed a quite extensive set of regulations, covering new projects, construction, and operational requirements, as well as management of HES issues. The effect of this emphasis in the project has been that some strong demands to the layout of installations have been developed over time, and some of them are unique in a worldwide perspective.

The NSR is strongly supported by international and national standards (NORSOKs)[4], developed by the industry and clearly required by the regulator. This context has led the NCS to have some well-known prescriptive requirements, relating to minimum standards for projects and emergency response, such as fire protection and evacuation routes, which in principle always will be applicable, regardless of the results of a risk assessment (PSA, 2018d; Vinnem, 2014a).

The BSR relies on non-prescriptive requirements for platform projects, such as performing risk assessments and identifying and applying standards and good project practices (ANP, 2007). These standards and requirements are within companies' control and are checked by the regulator when the platform has already been built, relying on the term 'best practices' and a case-by-case supervisory approach (Fernando et al., 2014; Morais et al., 2014).

PSA has a significant role in the development of new projects and, as few platforms have been converted, the most common approach in NCS is to build new installations according to local specific requirements. It is not the case in BCS where there is no focus on prescriptive project

[4] The acronym NORSOK means 'the Norwegian shelf's competitive position' and was introduced in 1994 to cut costs and improve competitiveness on the Norwegian continental shelf (Standards Norway ).

safety requirements, there is no direct demand for specific standards and the use of converted platforms is more common.

### 3.2. *Risk assessment*

The risk assessment is the process where decision-making is performed using risk acceptance (or tolerance) criteria, supported by resources such as risk analysis tools, methods, knowledge, experts and proper communication (Almeida, 2018; Aven, 2017). The risk assessment is a cardinal requirement with direct effect on risk constraints[5] definition in various levels and activities (Aven and Ylönen, 2016). In the high-level, the organization's risk assessment aims to control project risks, such as major hazard scenarios of a platform. In low-level, it is related to daily activities, such as work permits or management of minor changes.

In the high-level, the quantified risk assessment (QRA) is the most used method to support risk management for an offshore project. The QRA join together information from dispersed knowledge using models that correlate systems' failure probability to the likelihood of initiating events, human errors, and failures of the components (Vinnem, 2013). The risk picture produced by the risk analysis try to solve an organization's challenge, translating in reports 'a collection of truths' based on expert opinions and conclusions (Aven, 2016). On the other hand, qualitative risk assessments are more usual in low-level decisions, and it usually includes only knowledge of the personnel directly involved in the task.

The BSR does not specify or directly require the definition of a risk acceptance criteria or risk assessment technique, which is under companies internal control (ANP, 2007). The risk assessment is needed for a project, management of change and work permits for proper decision-making and risk control, using qualitative or quantitative methods without distinction regarding different levels of an organization. Trying to assure appropriate outcomes, the ANP defines among the risk assessment requirements that companies must choose suitable methods, and provide adequate resources such as knowledge, multidisciplinary personnel and reliable sources of information. There are also requirements that correlate risk constraints identification in risk assessment as input to safety critical elements and emergency scenarios definition, which must be managed by companies through the project operation phase, assuring risk constraints' availability and reliability.

In the NCS, the risk management framework is based on requiring risk owners: i) to formulate a set of acceptance criteria for major accident risk and environmental risk, including specific values for all personnel on installation and for specific groups, loss of main safety functions for offshore petroleum activities, acute pollution and damage to third party (PSA, 2018f); ii) to carry out risk analyses to provide a balanced and comprehensive risk picture, providing support for decisions regarding major accident and environmental risk, including sensitivities and uncertainties (PSA, 2018f); iii) to consider that risk analyses must be carried out as the basis for making decisions (PSA, 2018f); iv) to implement the risk reduction process using 'as low as reasonably practicable' (ALARP) criteria (PSA, 2018b); and v) to work for continuous improvement in all operations (PSA, 2018b). These requirements are supported by international and national standards, and the internal control principle is implemented without limitations in the Norwegian regulations. It implies that companies as risk owners have the responsibility to formulate the risk acceptance criteria and make the comparison to risk analysis results, as well as the subsequent decision-making about the risk control measures (Engen and Lindøe, 2014). Besides, the PSA has also changed the concept of risk placing more emphasis on the uncertainty dimension, claiming that it would lead more clarity to the decisions about risk-reducing measures (Vinnem, 2014a).

### 3.3. *Management of change*

The management of change (MOC) is a systematic process to assess risks before modifications through screening permanent or temporary changes, identifying, planning, approving and making available risk control measures (Kelly, 2013). The MOC consists of the fact that changes in

[5] In this text, risk constraints are also mentionded as barriers, risk control measures, safety critical elements, safety function or safeguards.

systems, procedures and personnel will occur during an installation lifetime, either to take advantage of an opportunity or to fix a problem (Desmond, 2013). This systematic process includes: i) change identification and classification; ii) change planning and risk assessment; iv) change communication, and v) change implementation and follow-up. Although the regular use of MOC by organizations to address potential uncontrolled risks caused by changes, there is a lack of studies or research regarding MOCs and their effects on risk management (Gerbec, 2016).

The NSR does not have a specific MOC requirement, but risk management demands make MOC a natural system to be implemented, as frequently observed in NCS operations. On the other hand, the BSR has a specific MOC requirement to changes in systems, procedures, and people, demanding that permanent or temporary changes must be identified and managed regarding risk control before being implemented. Furthermore, this MOC requirement is one of the most common types of non-conformance pointed out by ANP during field audits (ANP, 2016a).

### *3.4. Personnel qualification, training, competence and performance*

As part of risk control, organizations require proper and skilled staff, with the knowledge, ability, and experience to undertake critical tasks (HSE, 2011a). Competence is a combination of knowledge, skills, and experience and requires a willingness and reliability that work activities will be performed following required standards, rules and procedures (HSE, 2011b). On the other hand, training is one of the tools used to achieve a systematic acquisition of knowledge and skills with the goal of developing necessary competencies for effective performance in work environments (Nazli et al., 2014). Thus, personnel competence is not only a set of minimal training requirements but also includes all initiatives to support, develop, and retain a proper level of knowledge among an organization staff.

The International Maritime Organization (IMO) has competence requirements regarding all personnel involved in offshore operations, such as safety induction for visitors or specific training depending on the activity performed by crew members. The basic training covering firefighting, sea survival and first aid required by IMO is a common practice in oil and gas provinces (IMO, 2014). Despite the importance of IMO required training to prepare offshore personnel to general emergencies, there is still a remarkable not include among offshore training how to act in cases of non-ignited HCLs.

Regarding the NSR, there are general competence requirements, assigning to risk owners the responsibility to provide training to the necessary extent and have, at all times, personnel with the required competence to carry out activities in a prudent manner (PSA, 2018g). Besides, many detailed requirements on occupational qualifications and training are also covered under the working environment regulations, such as work with hazardous chemicals, asbestos, biological agents and maintenance of work equipment (Ministry of Labour and Social Affairs, 2018). Moreover, the use of NORSOK standards and Norwegian Oil and Gas Guidelines also supports these competence, qualifications and training requirements (Norwegian Oil and Gas, 2016).

The BSR demands from risk owners the identification of levels of competence for each function in an organization, including abilities and specific knowledge to perform function related activities. Moreover, training requirements are classified in three categories: awareness training, general training, and specialized training. Furthermore, NRs also have specific training demands both to personal and major hazard safety, such as electric equipment, boilers, pressure vessel and pipeline operations (MTE, 2017, 2016). However, there is no Brazilian national standard[7] to support competence for offshore activities.

[7] In this paper, a national standard is considered as a specific pattern developed with broad participation of different risk owners, recognized as a good practice in a country jurisdiction. Thus, it not includes a standard pattern developed inside a specific risk owner or translations from international standards.

### *3.5. Safety practices and control procedures for special activities*

There are quotidian situations in platform operations that demand system interventions, such as planned maintenance, inspections, and change implementation. Part of the risks related to expected activities is controlled by operational procedures, which defines the way to perform a specific activity. However, in case of activities not covered by procedures, the permit-to-work (PTW) is one of the most versatile tools to guarantee risk control, despite the lack of research regarding PTW related activities.

The PTW is usually a formal written system and regularly cover activities before, during and after a specific task, such as risk identification and assessment, different levels of approval, communication among affected personnel, task safety review and system status awareness. It also has to cover or be correlated to procedures such as area task preparation, isolation plans, system identification, safety reviews and personal protection (Iliffe et al., 1999). As a result, instructions to perform a task, considering risk controls, are defined by the personnel directly related to the activity. Frequently, the services such as system isolations or simultaneous operations, which cannot be properly covered/mentioned/discussed in a specific PTW may be affected by or affect a particular task covered by a PTW. Thus, activities are commonly considered and planned among all related personnel in several meetings along platform daily operations, such as PTW meeting, pre-shift dialogue, pre-job safety review or simultaneous operations procedures.

The BSR requires that companies must define activities covered by an established, documented and monitored PTW system. In addition, the BSR also requires companies the specify activities where simultaneous operations may include new threats, such as special logistics or tasks that demand critical safety elements unavailability (ANP, 2007).

The NSR requires risk control through procedures during critical activities or before performing system interventions not covered by operational procedures. In this sense, the NSR clearly describes critical activities and has comprehensive requirements for planning, clearance activities and isolation plans, all supported by international and national standards and guidelines (PSA, 2018g).

### *3.6. Operational procedures*

Operational procedures are formal instructions that show standardized ways to perform a task, controlling risk associated with the human intervention in systems and equipment. Good operational procedures describe the related processes, the hazards involved, the tools needed, the demanded safeguards and the main controls for process risk (AIChE-CCPS, 2007). Making the boundary of safe operations visible through operational procedures is desirable in theory but is challenging in practice as important gaps may happen mainly imposed by the procedure robustness, the activity's perceived flexibility, and the safety culture (Hale and Borys, 2013). Thus, sustaining operational procedures that prescribes safety rules in a dynamic environment demands the support from a robust risk management as it must deliver suitable procedures and consider the peculiarity of activities that must be performed, several characteristics from equipment and systems that must be handled, and the human beings that have the behavior shaped by dynamic influencing factors.

The NSR requires that the responsible party shall set criteria for when procedures shall be used to prevent faults, hazards and accident situations. It must ensure that users must take part in the formulation and revision of unambiguous procedures, that also must be user-friendly and adapted to the user's competence. The Norwegian requirement establishes that procedures must be tested before use to check design and content, established and used to fulfill the intended functions (PSA, 2018e). The BSR has similar requirements regarding operational procedures establishment and formulation, but also requires specific procedures for startup and shut down installations and simultaneous operations (ANP, 2007).

### 3.7. *Major emergency planning and management*

Emergency response is designed to limit incident consequences and has the potential to control the situation or make it worse, causing less or more losses. That is one of the reasons why the likelihood of failures related to the emergency response must be included in risk assessments (Deacon et al., 2010; Skogdalen et al., 2012). When an incident occurs on an installation, the emergency response plays the role to protect lives by safely removing personnel from danger zones. However, there is an essential difference between an offshore platform and an onshore facility: once an incident happens, the operational staff acts in emergency response, as external support may be onshore, and additional resources may be only available after some time and if the situation gets worse.

In the NCS, emergency response requirements demand that companies carry out emergency preparedness analyses, define hazard and accident situations, select and design performance requirements for emergency response. There is a strong link between risk assessment and emergency preparedness, supported by guidelines, international and national standards (PSA, 2018f). Among supporting procedures, there are prescriptions regarding required minimal scenarios as well as all necessary actions to be taken as soon as possible when an emergency occurs, so that: i) the right alert is addressed, ii) hazardous situations do not develop into accidents; iii) the personnel can be rescued in accident situations; iv) the personnel on the facility can be quickly and efficiently evacuated at all times; and v) the condition can be normalized when the development of a hazardous situation or accident has been stopped (Skogdalen et al., 2012).

The BSR relies on companies' risk identification or other internal requirements as input to emergency preparedness scenarios and procedures (ANP, 2007). It does not have any support standard or prescriptions for establishing minimal scenarios for emergency response planning or includes procedures, alerts or emergency actions, including abandon and rescue.

### 3.8. *Safety culture, commitment and management responsibility*

The safety culture is a challenging, complex, multidimensional and relatively new concept, which has been turned popular among safety scientists after the Chernobyl accident in 1986 and has been defined as an organizational atmosphere where safety is known to be accepted as a priority (Van Nunen et al., 2017). The prevailing organizational safety culture is recognized as the most significant influence on safety behavior from the workforce, which has a positive or negative impact in performance (Givehchi et al., 2017). It is influenced by social and cultural factors in both geographic and organizational contexts and reflects a solid safety commitment in all organizational levels, including high management and work environment (Corrigan et al., 2018). Biased risk perception can cause misjudgments of potential-hazardous risk sources, leading to poor behavior and inappropriate action and decision toward risk (Almeida, 2018; Rundmo, 1997).

The Norwegian offshore industry, from its modest start, had many fatal accidents and a bad reputation. After some time, Norway gained experience to overcome foreign-inspired philosophies, attitudes, and cultures (Vinnem, 2011). Nowadays, the PSA safety culture requirement is based on the assumption that it is possible to regulate the intangible (Antonsen et al., 2017; PSA, 2018b) and is defined as:

> *A sound health, safety and environment culture that includes all phases and activity areas shall be encouraged through continuous work to reduce risk and improve health, safety, and environment.*

The PSA considers that this requirement is properly addressed when risk owners organize continuous, critical and thorough work to reduce risk and improve health, environment, and safety (HES) aspects. It includes: i) systematic, continuous and broad-spectrum monitoring methods to prioritize efforts based on risk reduction and management regulatory principles; ii) continuous efforts and critical assessments regarding potential goal conflicts and efficiency; iii) a clear understanding that culture is not an individual quality, but developed through the interaction between people and given framework conditions; iv) the development of a collective learning through competence enhancement, participation and systematic and critical reflection at all levels; and v) that the HES work cannot be viewed independently from other value-creating processes in the organization.

On the other hand, the BSR has a safety culture requirement that covers only tangible requirements such as resource availability, policy and organizational structure definition, and frequent leadership visits to the work environment.

## 4. Regulatory enforcement activities comparison[8]

It seems contradictory that regulators address the risk ownership only to the companies while accident causation models sustain multilevel interactions as a condition to an accident happen. However, this strategy supports risk control in a dynamic, proactive and adaptative approach as well as the challenges in daily operations of complex systems such as offshore platforms. In this context, functional regulatory regimes require dedicated and robust supervision from a regulator, using both formal and informal tools, as it must not only count on written rules to keep the regime together and in continuous improvement (Engen and Lindøe, 2014).
Therefore, to understand the impact of each regulatory approach to the risk dimensions, any comparison must consider different aspects regarding regulators' enforcement activities supporting risk control. The main aspect of enforcement practices from both Norwegian and Brazilian regulators are discussed as follows.

### *4.1. Regulatory incident investigations*

Incident investigation is a complex and fact-based process to describe the most likely sequence of facts and related causes of an undesirable safety outcome. It has been used as one of the most valuable sources for safety improvement in regulatory supervision activities, as it directly links incident causes to risk management failures. As a result, the regulator' incident investigation is an important tool in overall safety as lead regulators to understand risk control failures, to share incident facts to the offshore community as well as to plan and demand improvement actions, trying to avoid similar situations.

Investigations frequently rely on investigators experience and knowledge, information assessment, and method used. This process is frequently pressured by deadlines and analysis not entirely (or explicitly) transferred to a final report. It could lead readers to find one or more non-developed issues associated with aspects at various levels, which could contribute to the conditions of an accident sequence (Vinnem, 2018b). The wrong choice of an investigation methodology can support these discussions about regulatory investigation results, as it can limit the investigation scope and promote a search for violations instead of finding underlying causes and contributing factors (Bye et al., 2016).

Various methods and models have been suggested to support focused and efficient approaches to accident investigation (Lundberg et al., 2012). The PSA has committed to using the MTO analysis (Rollenhagen, 2011) for more than a decade and ANP investigations usually indicate causal factors diagrams and fault trees. Although not all incident reports clarify the investigation methods used, it can be seen that among both regulators linear methods are preferable, as analysis and causes are limited to the safety management level inside the risk owner's domain.

On the other hand, some system-based techniques have been developed to take control of a system thinking approach and lead a broader accident analysis. This systemic thinking is reflected in a new generation of accident analysis tools and methods, such as Accimaps, the systems-theoretic accident model (STAMP) and the functional resonance analysis method (FRAM). They are used in order to highlight the different contribution by roles that are sometimes underplayed or

[8] The enforcement activities described in this paper are related to all conditions created by the regulator to support risk owners to develop high standards of risk control and awareness. As fines are applied exactly when the opposite occurs, it was not on the scope of this paper.

neglected by other accident analysis techniques, e.g., governments, regulators, organizational factors. More developed methods may also include the dynamic connection between individual cognition, decision-making, and motivations in accident scenarios (Waterson et al., 2017).

Based on case studies and investigation techniques used, the regulatory investigations may not consider all cases in different causation levels, including their flaws. It may be relevant to enforce risk ownership but may lead investigations to miss important conclusions to overall safety improvement (Vinnem, 2018b; Vuorio et al., 2017). In the end, improper investigation method selection would result in support for the recurrence of HCLs as investigations may not be able to point all causes, contributing factors, and all possible improvement actions.

### *4.2. Regulatory field audits*

A regulatory field audit is an opportunity for testing risk controls in practice by joining together the regulator, the risk owner, the platform and its daily activities. By the regulator side, is a moment to assess in practice adherence to established requirements and see how quotidian operational situations challenge written rules. By the risk owner side, is an opportunity to understand regulatory expectations better, to assess the maturity level of risk control efforts, and to demonstrate the execution of the risk ownership mandate.

In BSR, ANP audits are the primary enforcement tool, designed to cover all new platforms before start production and at least half of all in operation by year, which leads to more than sixty audits in production platforms every year (ANP, 2016a). The platform selection and the audit scope are supported by safety performance indicators based on activities performance data, but the audit frequently covers an overall safety management assessment (Almeida and Figueiredo, 2014). The PSA performs around two hundred audits and verifications on an annual basis in around two hundred facilities, which corresponds to an approximated average of one audit per facility per year[9] (PSA, 2018h). However, the PSA audits are frequently more specific about selected themes in risk management. Despite the difference in the scope size, both countries consider similar audit approaches, sustaining a high number of activities and expected platforms coverage.

The PSA supervisory role through audits of the industrial actors and projects has come under some scrutiny recently in Norway, as an independent review assessed the last 10–15 years of regulator's audits (Auditor General, 2019). As a result, the analysis has determined that in four defined cases PSA's audit practices found to be inadequate to reveal non-compliances in Norwegian offshore and onshore installations.

Although the relevance of the regulator's presence watching over safety aspects, the absence of supporting initiatives, i.e., standards or guidelines, can enhance companies' improper commitment to an FRR. For instance, instead of searching to implement best practices to comply with a specific functional requirement, under specific conditions, risk owners may wait for regulatory audit results to plan minimal compliance activities or confirm companies' practices as enough to fulfill the rules. It may be more important considering the limitations of assessing intangible aspects such as human factors and safety culture in a brief period of a regulatory audit.

### *4.3. Dialogue among stakeholders*

Communication with a correct, direct and undoubted message seems to be the most effective way to engage risk owners and other industry players to continuous safety improvement. Rather than trying to control behavior based on deviations, the focus should be on making the boundaries explicit and known, and by giving opportunities to develop coping skills (Stoop and Dekker, 2012; Waterson et al., 2017).

[9] The number of facilities cannot be expressed more exactly because onshore, offshore production facilities and mobile units are published together by PSA, including construction and fabrication sites for new facilities, and manufacturers of critical equipment.

In the NCS case, the basis of all Norwegian legislation of industry and enterprises is the so-called 'tripartite approach', often referred to as the 'Nordic model'. In this approach, three parties, i.e., employers, employee unions and authorities have a balanced relationship, which shall oversee the implementation of all requirements regarding health, the environment, and safety (Engen et al., 2017). In Norway, the tripartite approach is applied on a national level and is mirrored within the company by a bipartite approach, where management and unions cooperate on all aspects of HES, according to the Norwegian working environment law (Lovdata, 2005). There are four main tools for tripartite dialogue in the NCS: the safety forum, the regulatory forum, working together for safety and the white paper.

The safety forum is the main instrument used in tripartite dialogue (PSA, 2018i), where representatives of the industry, employee unions and authorities meet several times a year to discuss relevant issues and initiatives, under the leadership of the PSA Director. The presentations and the minutes of meetings are in the public domain, and a conference is organized annually to spread the results wider throughout the industry.

The regulatory forum is another arena in the tripartite dialogue established by the PSA to facilitate information, discussion, consultation, and feedback. It includes the development and maintenance of framework documents for petroleum activities, adaptation to EU/EEA regulations, other international frameworks and norms. It also considers the practical implementation and use of the HSE regulations and the exchange of viewpoints relating to contents and experiences in connection with the application of individual regulatory work.

Working together for safety is tripartite, but informal participation focused on finding practical solutions for the implementation of standard procedures in the offshore industry (SfS, 2018).

The white paper on HES in petroleum activities is a publication prepared by the Ministry of Labour and Social Affairs, which has the overall responsibility for HES in industry, including offshore petroleum (Ministry of Labour and Social Affairs, 2018). It is issued about every fourth year and represents the Government's ambition relating to HES in the Norwegian petroleum industry, with input from a tripartite ad-hoc working group. The first white paper was issued in 2001 and formulated that ambitious goal that the Norwegian petroleum industry shall be world-leading in HES matters.

Dialogue is also incorporated into the BSR in a less structured way, mainly based on company and regulator participation in safety meetings, industry discussions and the development of regulations. However, there is not a clear structure or permanent forums such as those present in the NSR. The most regular discussions are conducted with the Brazilian Oil and Gas Industry Institute (IBP) through workgroups, mainly to discuss specific issues with regulatory review and development without workforce participation. For instance, the IBP developed well-related guidelines as a direct result of SGIP discussions. Despite a clear intention to create other patterns from the companies' side, it was the first directive from industry in ten years of the BSR.

### *4.4. Safety performance review*

Performance review processes are designed to assess the actual status in a determined scope to support decisions regarding further efforts to address undesirable outputs, pursuing established objectives. It gives opportunities to decision-makers to check the direction of planned actions and to correct the course of initiatives. Regarding safety, it is important to develop the right framework, including tools and routines to safety performance review, both from a leading and lagging point of view (Almeida and Figueiredo, 2014).

The annual reporting of HES performance for the entire NCS, called the risk level project (RNNP), is a foundation for a common understanding and follow-up by the PSA looking for trends in Norwegian operations on the national level (Engen, 2017b). The performance data in the risk level project are based on voluntary reporting by all companies participating in offshore and onshore petroleum operations through dedicated reporting formats and shared databases, such as for environmental spills (EEH, 2018).

With industrywide participation, the RNNP annual report provides an excellent opportunity for the authorities to guide the industry regarding what is considered essential for the industry to focus on in their efforts to improve health, environment, and safety. The report is based on lagging indicators as well as leading indicators and covers occupational injuries, major accident hazards, occupational disease, minor and major environmental releases, the safety climate as well as perceived risk. The RNNP report also gives a good overview of exposure data in terms of produced volumes and man-hours by various employee groups (PSA, 2018a).

The RNNP report also covers the safety climate with a large number of questionnaire variables, which for a long period showed quite limited variations. The large variations in the last survey (PSA, 2018a) demonstrate that the indicators are capable of reflecting extensive changes in workforce perception and the safety climate based on changes resulting from the low oil price environment. The safety climate is usually considered to be the closest one can come to an assessment of safety culture, although it is not the same. It has been shown that there are challenges that appear to be unsolvable in the NCS, as the indicator scores were very stable for a long time (Antonsen et al., 2017).

In the BSR, the annual performance review is among the regulator's responsibilities (ANP, 2007). All the data considered in the performance review are based on incident reporting regulations (ANP, 2009), regulatory audit results and activity data reports established by ANP to support the BSR framework. As a result, a safety and environmental performance report (SEPR) is released annually with a safety data analysis, including a data comparison between Brazil and other countries from the International Regulators' Forum for offshore safety (IRF) (ANP, 2016a).

The performance review in BSR has been discussed in the annual safety and environmental workshop (SOMA)(ANP, 2018a). In this event, the ANP invites safety-related professionals to discuss safety performance, incident investigation results and other relevant issues that represent safety challenges. All segments are represented in these events, such as oil companies, drilling contractors, platform operators, service companies, unions, universities, consulting companies, regulators and associations. The SEPR and SOMA can lead to specific actions or demands by the regulator. However, it is still mainly based on pointing out the companies flaws and regulatory initiatives, mostly related to lagging information collected and analyzed from the regulator's side (ANP, 2018b, 2016a).

One of the strongest points of the risk level project is that it gives an overview of petroleum HES that is as neutral and objective as possible. Right from the start, it has been recognized by the parties in the tripartite cooperation as a trustworthy overview of petroleum HES conditions and aspects (Vinnem et al., 2006). Before the publication of the first report and in other matters that are not covered by the risk level project, it was evident from time to time that there may be little trust between the parties, especially between employers and employees, in the description of controversial issues. Trust and agreement on problem description are essential prerequisites to reach an agreement on potential solutions and are therefore very important for further development.

## 5. Discussion

This section presents the interaction between risk and regulatory requirements and approaches related to the case studies' circumstances and similarities. The discussion considers assessing how the regulatory requirements and enforcement support risk control in offshore projects considering equipment, systems and human failures. It analyzes how regulatory written rules and enforcement activities together influence risk control in BSR and NSR offshore activities.

### *5.1. Offshore projects' risk and case studies*

An oil and gas platform project considers that hazardous substances and people must share the same small space in an offshore environment. As fire and explosion are platform major hazards, the project includes actions to avoid HCLs or minimize their effects, using independent systems designed to control process deviations and release amounts. Moreover, further risk reduction is obtained by ensuring that among all possible scenarios, no one can lead to a rapid escalation to the extent that personnel will not have time to abandon the platform safely. The design also is often made by planning the installation layout considering accidental workloads, protecting temporary shelters, escape routes and accommodation, isolating hazardous areas and delaying structural failures. Furthermore, a proper project must support the operation strategy based on reliable risk models that can support safeguards and redundancies identification, avoiding that initiating events, such as human errors, lead to the final effects of an accident (Stoop and Dekker, 2012).

The regulation of early phases of offshore projects is quite challenging in both regimes, but the NSR has established relevant requirements that support offshore projects' risk constraints. Norwegian authorities have repeatedly claimed that the opportunity to influence the safety of new installations is by far the best in the early project phases, as once a project is built it is too difficult to change it in an oil and gas offshore environment. On the other hand, one of the criticisms about the regulator's enforcement in Brazil is related to the fact that it does not cover the platform's early design stages and it is focused only in pre-start-up safety audits (Fernando et al., 2014; Silvestre et al., 2017). Besides, there is no direct requirement in the BSR for risk acceptance criteria definition or disclosure by risk owners, which leads to total internal risk control of projects by companies. As national standards in Brazil do not cover platform project requirements, and Petrobras has the majority of the operating facilities, the company still sustains its standards as a monopoly legacy.

There are doubts if FPSO's accommodation and pump room projects in converted installations such as in the CDSM, a common situation in Brazil, would comply with Norwegian requirements (Vinnem, 2018b). However, the NCS has particular requirements for platform projects, which could explain why newly built installations may, therefore, be more attractive. Conversely, the use of pre-existing systems in conversions and a total internal risk control scenario could also lead companies, under specific conditions, to adapt practices and systems leading to non-desirable situations, increasing the project risk (Morais et al., 2014). Indeed, both BCS case studies were related to converted units under the company's internal control based on risk assessment results and the organization's management. For instance, the risk control in place in the P-36 used to accept the direct interconnection between high-pressure production systems and low-pressure emergency tanks. Furthermore, almost fourteen years after the P-36 accident and under the BSR, the risk control in practice in the CDSM[10] accepted the related risks of an unfinished upgrade in the cargo control system.

Similarly, the risk may also be increased in operations carried out using démodé safety concepts, such as in the Heimdal case study. In these cases, the 'grandfather clause' has often been used in the marine industry, whereby new technical requirements are not applied to existing vessels. The Norwegian regulations also call for compliance with all existing technical requirements when an existing installation, which may have been built to a lower standard in the past, is going through a major modification or upgrade (PSA, 2018c). However, if it is not the case, risk management has an important role in identifying and sustaining proper operational safeguards, fulfilling the gap left by the absence of projected safety barriers or enhanced safety concepts. In general, projects that not consider inherent safety concepts impose the need for more safety rules during project operations, narrowing operational safety margins and imposing more importance to human performance in the overall risk picture.

### *5.2. Operational risk and human factors in case studies*

Platform projects are complex and built to be manned, operated and maintained to keep production with a substantial economic impact. Major accidents have severe consequences, including the economic dimension, but are quite rare and workers may not face even an HCL

[10] The regulatory safety audit prior platform's start-up was not in place by the time the CDSM started its production.

while working offshore. It may lead to a dangerous feeling of safety, even in a highly hazardous facility and the challenge is to develop high-risk awareness in an environment that demands several daily activities and where the main particular aspects are the remoteness and the need to be self-sufficient (Vinnem, 2011).

Despite several developments regarding specific technical solutions to risk reduction of platform projects, there are still substantial challenges for clearly including human reliability analysis (HRA) into the overall offshore oil and gas risk evaluation (Boring, 2015; Gould et al., 2012). As the risk control is based on the structured identification of potential accident scenarios and the use of risk acceptance criteria to identify and sustain safeguards, avoiding that local errors lead to major consequences, the human component is frequently underestimated in offshore risk management (Stoop and Dekker, 2012). The actual standard risk reduction measures in platforms'design are often based on installation layout considering accidental workloads, protecting temporary shelters, escape routes and accommodation, isolating hazardous areas and delaying structural failures. However, among BSR and NSR, there is no specific requirement to include the HRA studies into risk management of offshore installations, which impose high uncertainty regarding the human aspects in risk estimation.

Regarding emergency response procedures, human errors have been pointed out as the cause of relevant accidents such as: i) Ekofisk Alpha (Norway, 1975); ii) Deepsea Driller (Norway, 1976); iii) Ocean Ranger (Canada, 1982); iv) Glomar Java Sea (China, 1983); v) Enchova (Brazil, 1984); vi) Piper alpha (the UK, 1988); and vii) Usumacinta (Mexico, 2007). The P-36 and CDSM accidents should be added to this list, as both investigation reports showed human errors during emergency actions, as ERT members have acted inside or near a gas cloud, probably causing the explosions (ANP; DPC, 2001a; ANP, 2015a; Vinnem, 2011). Furthermore, human errors are likely to occur in emergency response operations due to: i) the limited ability to train individuals for a real emergency, as they are relatively rare; ii) a lack of understanding about the event itself as decisions are made often considering incomplete, confusing or even contradictory information; iii) the situation urgency that demands too many activities and decisions in a short period of time; and iv) the harsh, hazardous and maybe new environment caused by the accident damage, which can delay or hinder the emergency response (Woodcock and Au, 2013). Thus, the human error contribution in emergency response activities of offshore facilities has proven to be quite high and relevant not only in both Brazilian case studies but in the offshore industry as a whole.

Depending on the context, both in normal or in an emergency, offshore activities will result in support or degeneration of safety barriers that may not always be available or reliable, generally in reaction to the pressure towards cost-effectiveness (Dekker, 2017; Rasmussen, 1997; Waterson et al., 2017). For instance, considering the case studies, it may be familiar to the reader situations such as operational changes without proper risk control, poorly planned tasks, procedures not followed, lack of knowledge to perform a task, and safeguards unavailability. However, inadequate resourcing, lack of competency or underdeveloped managerial processes are conditions created by decisions made considering the organization's values in a determined context, influencing the human performance (Almeida, 2018).

Regarding this context, human performance has to be considered in offshore risk control as it is related to all case studies conditions and causes. As laws, regulations, and procedures are never followed to the letter, task instruction is an unreliable standard for judging behavior, as behavior is context-dependent (Rasmussen, 1997). This 'context-dependent performance' is the most important bond between human behavior and safety culture, as the safety management in a dynamic context must consider the mechanisms that influence behavior rather than only points human errors and violations. Several studies support the human factor relevance in offshore risk and have shown the critical role played by safety culture, especially regarding the occurrence of HCLs (Vinnem et al., 2016, 2010; Vinnem and Røed, 2015). Thus, the prevailing organizational safety culture is recognized as a major influence on workforce behavior regarding safety, which is reflected in organization performance (Givehchi et al., 2017). As a consequence, an effective organization risk management plan must consider that human behavior is dynamic and variable, and it does not finish with a good project (Bradley, 2017).

*5.3. Regulatory regimes' impact on risk control*

Accident causation models establish that risk control is based on the definition and support of risk constraints. The main difference between prescriptive and functional regulatory approaches is related to the roles regarding risk constraints definition[13]. Despite the FRR seems to bring flexibility to address risk control in a highly complex and dynamic context such as offshore platforms, it also demands high engagement from all parties enforced by regulatory supporting initiatives that may influence the risk control. The primary challenges for regulators in FRRs are making clear the goals among risk owners, leading to an appropriate selection of risk constraints, promoting a continuous improvement environment and high-risk awareness among all stakeholders, and identifying the risk constraints that are unnegotiable and must remain under regulatory control through prescriptions.

Assigning to companies the definition of risk constraints to dynamic-complex systems, regulators aim a more flexible risk control supported by risk-based thinking. In this model, some safeguards are defined through international or national standards, supporting an external control not directly controlled by the regulator. In the internal control, company standards, procedures, and safety rules support risk constraints that also relies on behavior that is taken out of the comfort zone by the challenge of never-ending goals from regulatory requirements. The regulatory enforcement activities in a supervision role join all pieces together, challenging the risk control defined by companies to be always improving and supporting the development of an environment that underscore all risk constraints. However, it is a considerable challenge to both Brazilian and Norwegian regulators sustain enforcement activities and understand their impact and limitations in risk control.

There are differences and similarities in both regimes regarding the requirements related to minimal risk evaluation studies to be performed in offshore platform's project. Despite the same internal control principle performed by companies, the risk ownership in Norway demands quantitative risk assessment as the base to demonstrate risk evaluation of offshore installations. Conversely, a qualitative risk analysis would be enough to comply with the BSR under specific situations. Although the quantitative risk assessment is the most used risk evaluation approach for offshore projects in the offshore industry, both offshore regulators have no direct requirement that demands structured HRA methods to identify the human contribution to initiating events of accidental scenarios. Considering that underperformance in operational risk control can be found in the conditions surrounding all the case studies, the importance of human errors in accident causation is highlighted in the present case studies. The use of HRA techniques is something that should be followed by the offshore industry, which may improve the definition and support of human-related risk constraints. It would lead safer projects that consider possible human errors, mistakes, and violations as well as the identification of the most important performance influencing factors that might have supported the human errors observed in case studies.

The lack of prescription from a regulator, such as the absence of a specific requirement for MOC procedures in NSR, can be seen as a sign of proper practices performed by risk owners[15]. However, it can be noticed from the Norwegian case studies that operational changes happened in the execution of planned activities. For instance, the unavailability of regular equipment led operators to use an alternative pressure source Gulfaks B and the planned activities were not followed by an inexperienced operator in the Heimdal accident, mainly because of the lack of knowledge about the task planning and the system characteristics. As a common condition in the offshore industry, both compared safety regimes have old project concepts and the offshore conditions may lead crews to adapt practices, supporting risk increase. In the end, both regimes accept that the risk imposed by non-inherent safe projects is controlled by operational rules

[13] As BSR and NSR are based on functional regulation principles, thus the comparison in this paper gives no basis for comparing prescriptive regulations against functional regulations. For comparisons between prescreptive and functional regimes see (Lindøe et al., 2013).

[15] The management of change is a common practice in PSAs audit outputs as a practice of the industry. For instance, see (PSA, 2018j, 2017).

followed by crew members that are exposed to several influencing factors that may not guarantee proper performance, increasing the relevance of the human actions in the overall risk.

Furthermore, it is noteworthy that all fatalities in BSR case studies are related to people performing emergency response activities, pinpointing the need to focus more on protecting the crew actively while conducting emergency response without unnecessary risk exposure. The lack of national or international standards required directly by the regulator and the use of converted units in projects under total internal risk control undermine the risk constraints imposed by the BSR when compared to the NSR. Besides, Norwegian demands for emergency preparedness are more prescriptive, including specific aspects to protect people in project design and regarding emergency procedures, something that depends on risk assessments outputs in BSR. The projects' safety regulation in place in the BSR framework still relies mainly on risk owners' control that has been proven not to be enough to prevent similarities between P-36 and CDSM accidents.

In the supervision role, both BSR and NSR regulator use field audit and incident investigation as tools that help the identification of failures in risk control and lead further improvement opportunities. In fact, regulatory investigations and audits represent opportunities to verify in practice how written requirements are included in platforms' daily operations. The use of audits by both regimes is at a similar level, but the limited time and scope of these activities may limit the possibility and the quality of findings, and therefore their ability to lead further improvement. For instance, considering the Brazilian context, the influence of a regulatory approach based only in audits just before the production phase may be quite limited to project safety assurance. In this case, the result of the regulatory regime regarding project relies mainly on the efficiency of the audit itself, instead of clarifying minimal standards to be considered by different stakeholders and processes involved in a platform project i.e. project developers, risk analysts, vendors, consultancies and certification. Besides, once a relevant incident occurs, both regimes perform investigations and make a public report available, encouraging cross-industry learning. Actually, the current analysis would be almost impossible if regulators did not release public reports including accident details. In these cases, it was observed that NSR focuses its investigations more on events related to major hazard, whereas BSR is limited to severe accidents. However, regulators' investigation effects may be limited if the selected method is not effective to assess all aspects in all causation levels. Thus, the limitations of current tools used by both BSR and NSR must be considered by the regulators and proper methods have to be available to facilitate and improve the scope and results of audits and investigations.

Moreover, the BSR and NSR also have requirements and actions designed to enforce safety behavior among stakeholders. However, the comparison has shown fundamental differences regarding the use of intangible concepts in regulations, such as safety culture and uncertainty, the dialogue forums and performance review framework. For instance, the NSR imposes a consistent impact on Norwegian industry using the "sounds like" safety culture approach, while the Brazilian requirements regarding safety culture and risk are based only on tangible aspects such as leadership visits. In addition, the uncertainty concept included in risk definition brings to the NSR the challenge for risk evaluations clearly communicate the uncertainty related to each risk estimation for better decision-making. Besides, the dialogue principles are the same in both compared regimes, but the NSR has more formal dialogue and performance review forums, all supported by the tripartite approach. Thus, the combination between intangible concepts and discussion forums promoted for dialogue among all industry's parties sustains a proper environment for proactive behavior regarding safety and supports the dynamic identification of situations that may impose risk increase for offshore activities.

## 6. Conclusion

This paper compared the Brazilian and Norwegian offshore safety regimes, based on conditions and similarities between four hydrocarbon leaks (HCLs) used as case studies. The main objective was to support the identification of improvement opportunities in major hazard events avoidance. Accident models show that risk control is based on the definition and support of risk constraints among different parts of the industry context, including the regulator, the companies and the work environment. Thus, the lack of supervision through enforcement activities from a regulator may support undesirable conditions in major accident causation, even after assigning safety responsibility to the companies.

Consequently, the functional regulatory regime (FRR) approach is not concluded with a set of non-prescriptive requirements and frequent audits as it also demands a good balance between dialogue, performance review and other enforcement activities to build and support commitment, risk awareness, and safety culture. Moreover, the FRR also demands strong supporting elements controlled outside the regulatory domain, e.g., standards and guidelines, as well as companies with high ability to promote and sustain risk control solutions as part of an undoubted risk ownership mandate. Furthermore, in FRR the regulator must also be able to identify and maintain under its scope unnegotiable major hazard constraints as prescriptive requirements.

Despite the experience in regulating safety for offshore industry is almost thirty years apart between the Brazilian and Norwegian regulators, considering the comparison results, regulatory approaches in Brazil and Norway are similar in concept and challenges. An important aspect is how regulators ensure and support engagement from all risk-related parties to develop the right risk constraints at all accident causation levels. About this aspect, the Norwegian Offshore Safety Regime (NSR) have more developed industry initiatives related to standards, guidelines and performance review, clearly supporting constraints outside the regulator. Thus, based on a comparison of regulatory approaches, further improvement can be made to the Brazilian Offshore Safety Regime (BSR) by giving more structured support to stakeholders develop dialogue, performance review, standards, and guidelines. On the other hand, the BSR has specific requirements regarding the management of change (MOC) while the NSR does not have. Despite MOC is a common practice in NSR to address several other regulatory demands, the lack of a specific requirement in NSR should be assessed regarding the possible enforcement effects that a regulatory requirement would create.

More specifically, the Brazilian case studies showed that the BSR should consider improving constraints regarding risk acceptance criteria, as well as project and emergency response requirements. These issues are under internal companies' control and show recurrent circumstances in both considered case studies, two major accident in converted platforms summing up to twenty fatalities among emergency response members. To properly support risk constraints, the BSR should consider further studies to ensure: QRA studies for platform projects, national or international standards required directly by the regulator, support to the development of national standards, the identification of conditions to use converted units, and clear boundaries regarding emergency response planning and procedures. This Brazilian context would also be supported by regulatory enforcement in early project phases, an issue that is more developed in NSR but seems to be challenging and should be a focus of further studies in both regulatory regimes.

Human underperformance was found to be remarkable and dominant among causes of all case studies. Human reliability is also considered another challenging issue to both regimes and should help to sustain related risk constraints designed to avoid or prevent accidents considering human interactions with the platform systems. For instance, it could help to evaluate when an old and less safe project concept should be not accepted or what kind of risk constraints should be included in project concepts to avoid human errors such as observed in all case studies. Furthermore, the lack of management of change and permit-to-work attractiveness to research seems not to support HCL prevention, as previous studies have pointed out that preparation activities and interventions are the most common circumstances when an HCL occurs. As these procedures are routinely performed during daily operations, it brings opportunities to understand and assess human-related aspects. Thus, including human reliability studies as part of risk assessment, as well as understand the performance shaping factors related to human underperformance in tasks, should help to prevent accidents, and could be better used by the offshore industry and safety research community.

The recurrence of hydrocarbon leaks (HCLs) may lead to doubts regarding whether all lessons from previous events were incorporated into a continuous improvement environment. It can be a symptom that not all causes are identified through incident investigations or improper lessons are assigned to prevent the recurrence of events. Moreover, the analyzed case studies show considerable effects of recurrent latent failures and the need to guarantee proper investigation methods to identify flaws at all accident causation aspects and levels.

The safety culture seems to be important in HCL prevention, as different studies pointed out strong correlations between HCL occurrence and the safety climate assessment, as an indirect measurement of the safety culture. It seems clear that a proper safety regime should demand risk awareness and commitment tools at all accident causation levels, even using intangible concepts such as safety culture and uncertainty. Thus, an effective regulatory regime must ensure that proper initiatives are in place to address, assess and continuously support the development of safety culture. As safety culture is context dependent and offshore companies operate in different countries, it would be an opportunity for future work to develop a comparison between two different operations from the same company in different safety regimes. It could lead to further discussions about how local influences, including native culture and regulatory practices, may affect the company's approach regarding safety.

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