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ON DISASTER RISK REDUCTION IN NORWEGIAN OIL & GAS INDUSTRY THROUGH LIFE-CYCLE PERSPECTIVE

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ABSTRACT

This paper presents the risk reduction in Norwegian oil & gas industry over the time (1975-2016) through a life cycle perspective analysis with the aim to identify the critical stage(s) both in terms of accident occurrence and cause of the accident. Fifteen accidents, major accidents and disasters for example Ecofisk 2/4 Alpha 1975, Alexander L. Kielland 1980, Songa Endurance 2016 were studied. Cases from outside of the Norwegian offshore field - the Piper Alpha 1988, the Bourbon Dolphin 2007, and the Deep Water Horizon 2010 - were also considered as comparison. For each accident and through the life cycle analysis, the occurrence stage of the accident and its main technical causes were identified and compared. It was found that a high risk is concentrated in the Operation (In-Service) stage and associated Marine Operations. Furthermore, it was observed that a high number of accidents in oil and gas industry are associated with mobile structures. All the investigated accidents have acted as powerful reminders to the oil and gas industry that a continuous improvement of risk management and reduction of uncertainty are of paramount importance in order to ensure safe operations and risk reduction for accidents, major accidents and disasters. However, a reactive learning from major accidents and disasters needs to be supported by a proactive learning and development of a dynamic risk culture in the oil and gas industry.

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INTRODUCTION

Risk in the oil and gas industry can never be reduced to zero, but it is very important to manage it to be as low as reasonably practicable - or what is known as ALARP. It is also vital to keep learning from both national and international events and particularly, to apply the acquired knowledge to the industry. This will enhance awareness of accidents and major accidents, preparedness and level of safety in the oil and gas industry. Magne Ognedal, the head the Norwegian Petroleum Directorate (NPD)'s Safety division, at the time when the Alexander L. Kielland disaster struck in 1980, and from 2004, the director general of the Norwegian Petroleum Safety Authority (PSA) for almost a decade, emphasized that "It is important to know the past in order to help improve petroleum industry safety." His name is synonymous with the development of Norway's safety regime for petroleum industry since 1980. Magne Ognedal explained that the driving force all along his career was that Norway shall never experience again anything like the Alexander L Kielland disaster [1]. Knowledge of past accidents and disasters functions as an important input to risk assessment and contributes to enhance disaster awareness and an effective mitigation and preparedness. In addition to a continuous implementation of lessons from past disasters, a dynamic learning from disasters and a proactive approach are required. Furthermore, learning from disasters is impacted by a multitude of factors and the rhythm of learning varies from one country to another [2, 3]. Major accidents and disasters have important human aspects related to fatalities, injuries, trauma and substantial socio-economical and environmental impacts. In this regard, reducing the risk from major accidents and disasters must be a key priority for the Norwegian safety regulations and oil and gas industry [4].The trends in the risk level in the petroleum industry concern all stakeholders and parties involved in the industry, as well as general public. [5].

A major accident is defined by the PSA Norway [4] as "an acute incident, such as a major discharge/emission or a fire/explosion, which immediately or subsequently causes several serious injuries and/or loss of human life, serious harm to the environment and/or loss of substantial material assets". A couple of major accidents and serious incidents in the petroleum sector in Norway and around the world were presented by the PSA Norway in the Safety - Status and Signals, edition 2012-2013. These dramatic events have been seen as key reference points for the Norwegian safety efforts and have particularly impacted the PSA's work on major accidents [4]. Major accidents and disasters in the oil and gas industry of Norway were the focus of various articles of Smith-Solbakken [6], Smith-Solbakken and Vinnem [7] and Smith-Solbakken and Dahle [8]. The focus of their work was on a detailed presentation of accidents/disasters and their consequences for oil and gas industry in Norway.

Christou and Konstantinidou [9] brought to attention that in order to increase safety in the offshore oil and gas operations, the lessons from past accidents, particularly, from major accidents, need to be identified, classified and shared. Moreover, they proposed a way how the lessons from major accidents can fit in the risk management chain such as prevention, early warning, mitigation, preparedness, emergency response, aftermath and recovery stages. Vinnem [10] emphasized that is important to document the experience from past major accidents, in a concise, but comprehensive manner, in order to model the risk to offshore installations. Therefore, Vinnem [10] clearly presented the main sequence of events for the past major accidents in oil and gas industry in the last decades. Moreover, the lessons learned from past major accidents, particularly for the design and operations stages were presented by Vinnem [10]. Furthermore, Vinnem [10] analyzed the barriers performance and barriers failure with regards to loss of containment and loss of structural capability for the past major accidents. The need for the systematic learning from accidents, major accidents and disasters in oil and gas industry is still a challenge which requires further work. The research objective of the present study targets to investigate accidents, major accidents and disasters in the oil and gas industry through a life-cycle perspective with the aim to identify the critical stage(s).

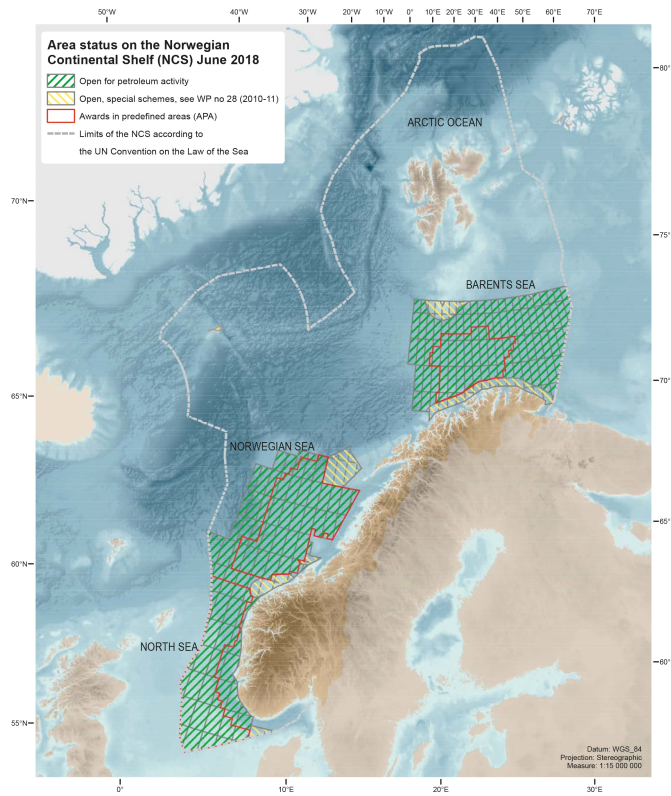

FIGURE 1: Map of the Norwegian Continental Shelf by Norwegian Petroleum Directorate (NPD) [11].

RESEARCH METHODOLOGY

A total of 15 case studies of oil and gas accidents, major accidents and disasters, over a time span of more than 40 years was considered. Among the case studies, 12 accidents/major accidents/disasters occurred on the Norwegian Continental Shelf (NCS), particularly in the North Sea and in the Norwegian Sea, see Figure 1. Other two major accidents took place on the UK Continental Shelf and one occurred in the Gulf of Mexico, USA.

As a research method for this study, the life-cycle approach was applied. The life-cycle approach has been employed in earlier studies, for instance by Faber [12], Moan [13, 14] and Torsvik et al. [15]. Faber [12] considered the life-cycle approach as a holistic approach to the risk assessment in civil engineering. The life-cycle approach takes in account all primary and secondary stakeholders and considers all phases for engineering systems like for instance the offshore structures. The life cycle approach has at its centre the safety of personnel and environment and economical feasibility, and starts its phases from idea and concept, planning and feasibility study, investigations and tests, and continues with

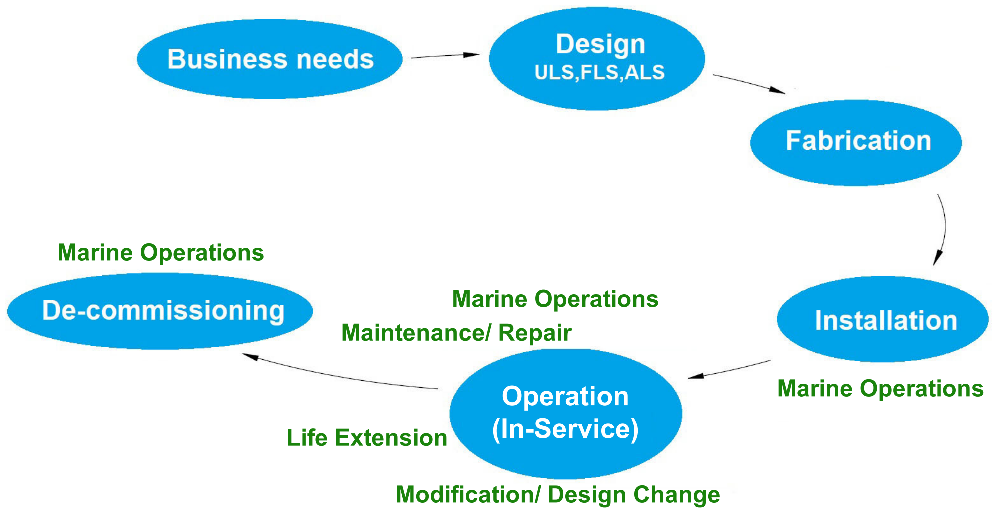

FIGURE 2: Life-cycle stages for offshore structures. (ULS:Ultimate Limit State, FLS:Fatigue Limit State, ALS:Accidental Limit State)

design, manufacturing, execution, operation and maintenance and decommissioning. Moan [13] applied the life cycle approach in the oil and gas industry. As per Moan [13] the life-cycle comprises the main phases of design, fabrication and operation. Taking in account the environmental matters, the phases of removal and reuse were also added. Moreover, Moan [14] added the installation phase to the life cycle approach and focused on the structural integrity management over the life-cycle of offshore structures. Torsvik et al. [15] utilized the life-cycle approach in a study about large offshore wind turbines.

The life-cycle approach applied in this paper is illustrated in Figure 2. The design in this life-cycle approach is based on the limit state design method considering ultimate, fatigue and accidental limit states (ULS, FLS and ALS) as emphasized by Moan [13,14]. Moreover, the marine operations are incorporated into the stages of installation, operation and de-commissioning as shown in the Figure 2. For the installation phase, there are various marine operations such as light and heavy lift operations and towing operations. For the operation phase, the anchor handling operations are examples of marine operations. Anchor handling operations refer to all kinds of operations including an anchor, for instance, anchoring floating platforms, and normally, comprise deploying anchors and recovering anchors. Other type of marine operations refers to the offshore offloading operations from a Floating Production Storage and Offloading (FPSO) to a shuttle tanker [13]. Furthermore, the maintenance/repair, the modification/design change and the life extension are part of the operation phase. Moreover, the operation stage is named as operation (in-service) stage due to various functionalities of the marine structures. Some structures are used in oil and gas productions – like fixed platforms or floating production storage units – and others are used as accommodation units or drilling platforms. With reference to the maintenance and repair, on general basis, annual and intermediate inspections take place for offshore structures and extensive and major inspections are carried out every 4 or 5 years. Repairs might involve structural modifications which require to be carefully considered [14]. The modification/design change can occur over the operation (in-service) stage, but it is important to keep a record of it and and to carefully assess its impact on the “as-designed” and the “as-built” structures [14]. The life extension confronts various challenges on the NCS and many of facilities reached to their original planned end of life, but the business needs require their life extension. Therefore, inspections for life extension and a continuous status monitoring are required as risk reduction measures. The Norwegian authorities make decisions about de-commissioning, based on application of both national and international regulations [16].

As a remark, the life-cycle in this paper refers to the “marine structures life-cycle”, not to the oil and gas “field life-cycle”.

CASE STUDIES

Ecofisk 2/4 Alpha in 1975

Ekofisk 2/4 Alpha was initially a combined production, drilling and quarters installed in 1972 and came on stream in April 1974. On the 1st November 1975, a breach occurred in the riser and led to ignition of gas on the Ekofisk 2/4 Alpha. The flow of gas from the riser was immediately shut down and the fire was managed to be completely extinguished after two hours. However, three people lost life and three others got injured because of a failure to lower in safe manner a life saving capsule. This accident is considered as the first major accident in the Norwegian offshore operations. The loss of integrity of the riser was due to severe corrosion, in the splash zone of waves, beneath platform. During installation work, the riser had been damaged by a vessel and dented. afterwards, the damaged section of the riser was removed and replaced with new pipe. Nevertheless, corrosion protection provided for this part of riser was quite superficial and was further affected when the production started [10, 17].

Deep Sea Driller in 1976

The Deep Sea Driller accident occurred in the very early stages of the petroleum operations in Norway, and has been called as "the forgotten accident". The Deep Sea Driller rig with a crew of 50 men was in transit from an offshore location to a yard on the Norwegian West coast, Fedje, not far from Bergen. The rig was escorted by two vessels, a supply vessel and a converted fishing vessel which did not have sufficient towing power. In the middle of the night, when approaching the coast, the weather conditions dramatically changed and a strong storm towards hurricane level took place. The rig owner had declined the request for an experienced pilot to manoeuvre the rig into fjords. Moreover, one of engines of rig was unavailable and the towing lines could not be transferred to the supply vessel. Consequently, the Deep Sea Driller rig drifted against the rocks and grounded around 02:00, on 1st March 1976. The crew waited couples of hours for helicopters and finally, evacuated the rig by using a lifeboat. Due to weather conditions, darkness and dangerous rocks, 7 people had to sit on top in order to guide the handling of boat. However, the boat grounded and all 7 people, except one, lost their lives. The rest of the crew was either saved by helicopter or managed to save themselves out of sea. Later on, the rig was repaired and renamed Byford Dolphin. Nevertheless, the tragedy was linked again with this new name. In 1983, a severe diving bell accident occurred, and 5 people died and one suffered severe injuries [10].

Ecofisk Bravo in 1977

Ecofisk Bravo is a combined production, drilling and quarters platform which was installed in 1972 and came on stream in 1974. In the spring of 1977, the oil production from the Ecofisk Bravo was around 150 000 barrels oil per day which represented almost half of the whole production of the Ekofisk field. On 22 April 1977, during the maintenance work on the production well, a blowout occurred during the assembly of BOP (Blow Out Preventer). This was the first serious uncontrolled oil blowout which took place on the NCS. No injuries and fatalities occurred and all 112 members of the crew were evacuated within 15 minutes. After eight days of oil and gas spill, from 22 April until 30 April 1977, the situation with the well was finally settled. However, the worst oil spill in the Norwegian history occurred and based on initial estimations, the oil spill was calculated to reach to about 20,000 barrels (bbls)/day. As per recent calculations, the amount of oil was reduced to just 9 000 bbls/day. This accident highlighted serious deficiencies in the Norway's preparedness for oil pollution and environmental impact. Moreover, it fueled many debates and criticism about the environmental impact from oil and gas resources. This accident laid the foundation for strict environmental requirements on the NCS and put the oil pollution on the political agenda, and speeded up the creation of an oil spill clean-up organization [4, 6, 17].

Alexander L. Kielland in 1980

The Alexander L. Kielland was a platform in the shape of pentagon which was built at the French shipyard CFEM (Compagnie Francaise d'Entreprises Metalliques) in Dunkirk. The platform was built as a drilling platform, but later on, it was changed and transformed into a residential platform or so-called flotel (floating hotel) for several installations on the Ekofisk field. The owner of Alexander L. Kielland was Stavanger Drilling II and the operator was Phillips Petroleum. The last location of Alexander L. Kielland was bridge connected to the fixed drilling platform Edda 2/7 C, in the Ekofisk area, North Sea. The Alexander L. Kielland platform was designed to have 10 anchors, but due to location of the Edda 2/7 C neighboring platform and pipelines at the bottom, only 8 anchors were used. However, this reduction in the number of anchors was not pre-approved by the Norwegian Maritime Directorate. On 27 March 1980, around 18.30, the semi-submersible flotel Alexander L Kielland capsized and 123 people from a total of 212 people on board lost their lives. This was the worst accident which occurred on the NCS and the worst industrial accident in the Norway's history. The flotel lost one of his five legs in severe gale-force wind and because of the fracturing of a weld in the support structure. This was followed by a severe listing to the rig and within 20 minutes from the initial failure, the rig capsized completely and floated upside down with only the bottom of the columns visible on the sea surface. The Alexander L. Kielland disaster was immediately followed by the appointment of an official commission of enquiry. This represented the first occurrence of this kind of investigation in the Norwegian offshore operations. Prof. Torgeir Moan, at the NTH university (nowadays NTNU), was responsible for the technical examinations and technical parts of this investigation. The investigation commission presented a very extensive report in November 1981. The accident investigation report revealed that one of the bracing failure which was due to fatigue caused a succession of failures for all bracing attached to leg. Moreover, the weld of the bracing which initiated the failure contained cracks since the rig was built and the cracks developed over time and the remaining steel was less than 50%. As a conclusion, in case of Alexander Kielland, the initial fatigue failure of a brace was due to lack of fatigue design checks, fabrication defects and an inadequate inspection of structure [14]. This disaster had a big impact on Norway and on the Norwegian oil and gas industry ever since. The Alexander L. Kielland disaster had great significance in terms of safety developments on the NCS, including regulations, regulatory regime and division of regulatory responsibilities. The new Petroleum Activities Act came into force in 1985, and the the plethora of agencies previously involved in regulating the oil and gas industry in Norway were replaced by the Norwegian Petroleum Directorate (NPD). The NPD was put solely in charge of developing regulations and to have an overall responsibility for supervising safety and working environment in oil and gas industry. Nowadays, this responsibility has been taken over by the PSA. According to Magne Ognedal, what happened with the Alexander L. Kielland was unthinkable and the probability that it would happen was low, but the consequences were huge. Therefore, "In order to be able to manage risk, a detailed understanding of both elements is required." [1]. After the Alexander L. Kielland disaster, the internal control (management) systems and risk-based regulations were developed and these were seen as fundamentals from both the industry side and the regulators. A memorial monument entitled "Broken link" was unveiled on 27 March 1986, by the Crown Prince Harald of Norway, at Smiodden, in Kvernevik, Stavanger, in the memory of all people which died in the Alexander L Kielland disaster. Annual commemorations have been performed since that time [4, 8, 9, 17].

West Vanguard in 1985

West Vanguard was a rig which was built by Trosvik Mechanical Workshop, in Brevik, in 1982. On 6 October 1985, while an exploration well was drilled on the Haltenbanken, in the Norwegian Sea, a shallow gas blowout occurred on the West Vanguard. The ignition of gas occurred after 20 minutes, and a strong explosion took place and killed one person. This accident was the first fatal accident of this type on the NCS. Many critics were addressed to the Norwegian Petroleum Directorate which did not revise the regulations and safety requirements after a similar event which occurred in the fall of 1984, but without ignition of gas. After this accident, the oil and gas industry implemented a number of measures in order to reduce the risk of shallow gas blowouts on the NCS. One of the most important lessons from this accident was the need to drill a pilot borehole for maintaining a better control when encountering shallow gas pockets [4, 7].

Piper Alpha in 1988

On the evening of 6 July 1988, on the Piper Alpha a substantial gas leak occurred from a condensate pump which had been shut down for maintenance. It was shortly followed by ignition and a strong explosion. Piper Alpha was a big production installation with a steel jacket, and was on stream since 1976. Initially, it had been built to produce crude oil, but it was gradually converted to gas. Since the Piper Alpha was originally designed for crude oil, its firewalls were dimensioned to protect against the heat of an oil blaze, rather than the pressure from a gas explosion. The gas explosion which occurred in 1988 blew out a number of panels in a firewall, and one of the fragments sliced through a condensate pipeline and that initiated another fire. Piper Alpha was originally built in accordance with recognized principles by putting the most safety-critical functions of platform as far as possible from areas such as the control room and quarters. Nevertheless, these principles were broken when the platform was modified in order to receive and process gas from other installations. For instance, the location of the gas compression area close to the control room was significant for the progress of the accident. Moreover, the firewater pumps were supposed to start automatically when flames were detected, but they had been put in manual mode because diving was conducted from time to time near the installations and it was assessed that may pose a risk to divers. Furthermore, the emergency shutdown system on Piper Alpha was activated immediately after explosion, but the fire was further maintained and strengthened because the Tartan and Claymore fields continued to send gas to the Piper Alpha. Two hours after the first explosion, Piper Alpha broke up and the topside, including the quarters, disappeared beneath the waves. From 226 people on platform, 167 lost their lives (1 person died later in hospital) and 2 were also killed on a standby ship taking part in the rescue operation. Magne Ognedal declared about the Piper Alpha disaster that "It was a terrible reminder of what can go wrong if we fail to manage risk properly in this business". A public inquiry into the Piper Alpha disaster, chaired by the Scottish high court judge Lord Cullen, began its work in November 1988 and requested input also from the NPD and Magne Ognedal. Their inquiry showed a great interest in the way the risk was handled in Norway after the Alexander L. Kielland. The Piper Alpha disaster led to many changes into the UK's offshore safety regime, including the transfer of responsibility for safety from the Department of Energy to the Health and Safety Executive [4].

Treasure Saga 2/4-14 in 1989

On 20 January 1989, the Treasure Saga was drilling in the 2/4-14, north-east of Ekofisk and encountered a higher than expected pressure. Treasure Saga tried to seal the well, but the cement plug disintegrated. A strong gas flow developed on the drill floor, and the BOP on the seabed was activated. The trial to restore control over the well was unsuccessful and the Treasure Saga has to move off of site. For almost a year, 20 000 barrels of oil/ per day flowed out into the bedrock, beneath the seabed, from what was known as the "phantom well". Treasure Saga managed to drill a relief well and the well was managed to be killed on the 13 December 1989. The Operator Saga Petroleum struggled for 14 months to deal with a sub-surface blowout in the well 2/4-14 and just in March 1990, a properly plugged well was abandoned. Unfortunately, one person was killed on Treasure Saga in connection with the handling of drill pipes on the drill floor [4, 10].

Ocean Vanguard in 2004
On 14 December 2004, the semi-submersible mobile drilling unit Ocean Vanguard, formerly known under the name of West Vanguard, encountered the failure of two anchor lines. Two anchor winches failed to hold the anchor lines which ran out in an uncontrolled manner, and consequently, the rig drifted 160 m off location. Moreover, the movements of the platform caused the failure of drilling riser and the rupture of the tension system. Furthermore, the BOP at the sea floor got a six degree permanent inclination, the anchor winch system was damaged and the well was lost. The consequences could have been more severe, as it was a high risk from an occurrence of a blowout and a severe structural damage to take place. Fortunately, the staff did not encountered any injuries or fatalities [10].

Snorre A in 2004
Snorre A is a North Sea tension-leg platform (TLP), an integrated drilling, production and accommodation platform, with 42 wells below the installation and two subsea templates with production and injection wells. On 28 November 2004, Snorre A confronted an uncontrolled gas blowout. The gas was detected under the drill floor, on one of the cellar decks and in two modules on the seventh and eighth stories, but the blowout did not ignited. The personnel of 216 people was evacuated in different stages and in the end, only 35 people were present on the platform in order to regain control of the situation, to handle the emergency and to kill the well. The situation was very dramatic and tense, as reached to the point that Snorre A, could not be assisted either by sea or by air. Finally, the crew of 35 people managed to halt the blowout by pumping large amount of oil-based mud into the well. This accident was categorized by the PSA Norway as one of the most serious in the Norwegian oil history and only the chance prevented it to turn into a major accident and disaster on the NCS [4, 10].

Bourbon Dolphin in 2007
The Bourbon Dolphin vessel was delivered to the company, Bourbon Offshore Norway, at the beginning of October 2006. It was designated as a DP2 Anchor Handling Tug Supply Vessel, built and equipped to perform anchor handling, towing and supply operations in deep water. The vessel was put into operation immediately, and until the disaster in 2007, Bourbon Dolphin completed 16 assignments. Starting from end of March 2007, the Bourbon Dolphin was on a contract for the oil company Chevron. The contract concerned the anchor-handling in connection with movement of the drilling rig Transocean Rather, on the Rosebank oilfield, in the west of Shetland. On Friday 12 April 2007, around 09:00, the Bourbon Dolphin began to run out chain for the last anchor, anchor 2. When all the chain was out, the Bourbon Dolphin drifted considerably off the mooring line and asked the rig for assistance. The Highland Valour vessel was sent to assist the Bourbon Dolphin, but did not succeed in securing the chain. During the attempts to maneuver the Bourbon Dolphin, away from anchor 3 and to further handle anchor 2, the vessel developed a serious list to port and its engines stopped. The capsizing of the Bourbon Dolphin happened suddenly and with no warning. The crew lost 7 people and also the son of the master, a boy of 14 years old; the vessel sank on 15 April. Among others, it was found out that the load conditions were over the capacity of the vessel and the Bourbon Dolphin did not have sufficient stability to handle lateral forces [18].

Big Orange XVIII/Ecofisk 2/4-W in 2009
Originally, Ekofisk 2/4 W was a bridge support, but in 1989, it was converted to a unstaffed water injection platform. On 8 June 2009, the Big Orange XVIII well stimulation vessel collided with unstaffed Ekofisk 2/4 W water injection platform. The direct cause of the accident was a failure to deactivate the autopilot of the Big Orange XVIII before the vessel entered the safety zone around the North Sea field. Luckily, Big Orange XVIII missed hitting Ekofisk 2/4-X and 2/4-C, and passed under the bridge between these two staffed installations, but collided with Ekofisk 2/4-W. Nobody was injured, but the collision caused extensive material damages to both platform and vessel. It has been regarded as a major accident because of the big financial loss and because the integrity of several facilities was put at a high risk. The operator ConocoPhillips removed the whole installation for Ekofisk 2/4 W and permanently plugged the wells [4, 17].

Deep Water Horizon 2010
On 20 April 2010, a blowout occurred, followed by ignition and a powerful explosion on the Deepwater Horizon drilling rig, in the Macondo field, in the US Gulf of Mexico. Eleven people died and 17 suffered serious injuries. The Deepwater Horizon drilling rig, after burning for almost 36 hours, sank on 22 April 2010. More than four million barrels of oil escaped, before the well was capped more than three months later, and this produced an unprecedented environmental disaster [4, 9]. The National Commission into the Macondo accident recommended that new US regulations can be modelled based on the UK and the Norwegian legislation [10].

Gullfaks C in 2010
On 19 May 2010 occurred a lost of control of the well 34/10-C-6 A on Gullfaks C platform. No injuries took place and no oil

spillage, but PSA brought to attention this accident was very serious and under slightly different circumstances, it could have emerged into a major accident taking the shape of a sub-surface blowout and/or explosion. This was particularly critical, especially the accident occurred less than one month after the Deep Water Horizon 2010. Moreover, the Gullfaks C 2010 highlighted that the lessons from the Snorre Alpha blowout in 2004 were pending to be learned [4, 10].

Floatel Superior in 2012
Floatel Superior is a semi-submersible floating unit with hotel facilities and topside storage to support offshore installations for hydrocarbon recovery. During the night of 6-7 November 2012, when the Floatel Superior was on the Halten Bank, close to Njord A, in the Norwegian Sea, an unsecured anchor caused eight holes in the hull, water intrusion in two tanks and local damage to a third tank. This caused a list of 5.8 degrees and the risk of overall list to reach close to the design limit of 17 degree. From all 374 people on board of the Floatel Superior, 336 people were evacuated by helicopter. After investigation, it was found out that an anchor bolster lost three braces on the night of accident, as a result of damage which had occurred and developed over the time. Moreover, all 8 anchors developed damages during transportation of the Floatel Superior in high waves conditions to the Norwegian Sea. Furthermore, all eight anchors have repeatedly hit fixing surfaces and structural components on the bolsters. Design choices with regard to anchors, bolsters and hull contributed also to this accident [19].

Songa Endurance in 2016
Songa Endurance is a semi-submersible drilling facility and the first of four Cat D rigs. On 15 October a well control incident occurred on the drilling rig Songa Endurance. The Songa Endurance was working in the Troll field, near the Troll B, when complications occurred during the work on removing the production string from the well. The blowout preventer was activated and the well was closed. When the accident occurred, there were 107 people on board, but no injuries were reported and there was no risk of an oil spill [20].

ANALYSIS & DISCUSSIONS

The 15 case studies of accidents, major accidents and disasters on the NCS, UK and US Continental Shelf presented in Case Studies section are summarized in Table 1. A quick look over the table reminds the message of Magne Ognedal, the former PSA director: “The level of risk in this business is high, but can be managed. That demands full attention - 24 hours a day, seven days a week throughout the year. The industry can never relax.” [4].

From the accidents’ data presented in the Case Studies section, the stage of accident occurrence in the life-cycle was identified. Moreover, it was identified in which stage the main technical causes and contributors to accidents’ occurrence are situated. Table 2 presents the accident occurrence, the main technical causes and the stage of life-cycle which they are associated with.

It can be noted from the Table 2 that the accidents occurred mainly in the Operation (In-Service) stage of the life-cycle. The Marine Operations linked to Operation (In-Service) stage are on second place with regards to the occurrence of accidents. This results are shown in quantitative way for each phase of life-cycle in Table 3. It is evident that the occurrence of accidents, from the case studies, is about 67% in Operation (In-Service) stage and 33% in Marine Operations linked to the Operation (In-Service) stage. Moreover, it can be observed that the main technical causes of the accidents can be even rooted to the design stage (14%). It should be noted that these values in Table 3 should not be treated as absolute values, but as indicators to the level of associated risk to each stage of the life-cycle.

It is also observed in Table 2 that several main technical causes to accidents’ occurrence were connected to the Operation (In-Service) stage. Moreover, on the second place are the Marine Operations linked to Operation (In-Service) stage where the accidents causes are placed. The third place is shared by Design stage and the Marine Operations linked to Installation.

The question which may raise here is why a high risk is associated with the stage of the operation and marine operations within the life-cycle of marine structures. A marine structure is made to fulfill a set of functions during its designed life while is In-Service or Operation. The design is carried out based on the existing knowledge and design codes with the aim to address or account for known uncertainties. When the structure comes to operation it is then exposed to several uncertainties which may have not been accounted for, or underestimated. Uncertainties associated with the field condition, environmental changes (higher wave and wind loads than what were considered), the equipment used in operation, maintenance work, human factors, safety culture, a complex regulatory structure, or even new type of hazards can be among new challenges. This high risk in the Operation (In-Service) stage highlights the importance of the preventive maintenance and condition monitoring in oil and gas industry and a dynamic risk assessment approach.

From Table 3 it is also interesting to observe that about 19% of the technical problems which have caused accidents of offshore structures are in design and fabrication stages. This highlights the Leveson [21] remarks that an accident is a complex process and in order to have a complete understanding of an accident, to learn from it and to prevent its future occurrence, the identification of all causal factors is required together with a comprehensive analysis of all multiple technical and social system levels. Moreover, the foundation for an accident is laid years before accident occurrence. Furthermore, a broad view of the accident mechanisms which expand the investigation

TABLE 1: Accidents, major accidents and disasters in the oil and gas industry over more than 40 years time span.

Accidents	Date	Place	Number of people on board	Fatalities
Norwegian Continental Shelf				
Ecofisk 2/4 Alpha	1 November 1975	Ekofisk, North Sea	71	3
Deep Sea Driller	1 March 1976	Fedje, near Bergen, North Sea	50	6
Ecofisk 2/4 Bravo	22 April 1977	Ekofisk, North Sea	112	0
Alexander L. Kielland	27 March 1980	Ekofisk, North Sea	212	123
West Vanguard	6 October 1985	Halten Banken, Norwegian Sea	80	1
Treasure Saga 2/4-14	20 January 1989	Albueskjell field, North Sea	75	1
Ocean Vanguard	14 December 2004	Halten Banken, Norwegian Sea	86	0
Snorre A	28 November 2004	Tampen area, North Sea	216	0
Big Orange XVIII/Ecofisk 2/4-W	8 June 2009	Ekofisk, North Sea	21/0	0
Gullfaks C	19 May 2010	North Sea	over 100	0
Floatel Superior	6/7 November 2012	Njord A, Halten Banken, Norwegian Sea	374	0
Songa Endurance	15 October 2016	Troll field, North Sea	107	0
UK and US Continental Shelf				
Bourbon Dolphin	12 April 2007	North Sea, UK	15	8
Piper Alpha	6 July 1988	North Sea, UK	226	167 (+2)
Deep Water Horizon	20 April 2010	Macondo field, Gulf of Mexico	126	11

TABLE 2: Accident occurrence and main technical contributors/causes in the stages of life-cycle .

Accidents	Accident occurrence and stage of life cycle	Main technical causes and stage of life-cycle
Norwegian Continental Shelf		
Ecofisk 2/4 Alpha 1975	Operation (In-Service)	Marine Operations in Installation/ Operation (In-Service)
Deep Sea Driller 1976	Marine Operations in Operation (In-Service)	Marine Operations in Operation (In-Service)
Ecofisk Bravo 1977	Operation (In-Service)	Operation (In-Service)
Alexander L. Kjelland 1980	Operation (In-Service)	Design/Fabrication/Operation (In-Service)
West Vanguard 1985	Operation (In-Service)	Operation (In-Service)
Treasure Saga 2/4-14 1989	Operation (In-Service)	Operation (In-Service)
Ocean Vanguard 2004	Marine Operations in Operation (In-Service)	Design/Marine Operations in Operation (In-Service)
Snorre A 2004	Operation (In-Service)	Operation (In-Service)
Big Orange XVIII/Ecofisk 2/4-W 2009	Marine Operations / Operation (In-Service)	Marine Operations in Operation (In-Service)
Gullfaks C 2010	Operation (In-Service)	Operation (In-Service)
Floatel Superior 2012	Marine Operations in Operation (In-Service)	Design/Marine Operations in Installation and in Operation (In-Service)
Songa Endurance 2016	Operation (In-Service)	Operation (In-Service)
UK and US Continental Shelf		
Bourbon Dolphin 2007	Marine Operations in Operation (In-Service)	Marine Operations in Operation (In-Service)
Piper Alpha 1988	Operation (In-Service)	Operation (In-Service) - Modification/ Design Change)
Deep Water Horizon 2010	Operation (In-Service)	Operation (In-Service)

TABLE 3: Accident occurrence and main technical causes in the stages of life-cycle.

Life-cycle stage	Accident Occurrence	Main technical causes
Design	0%	14%
Fabrication	0%	5%
Operation (In-Service)	67%	47%
Marine Operations (In Operation)	33%	24%
Marine Operations (In Installation)	0%	10%

TABLE 4: Type of case study offshore structures.

Production structures	Mobile structures
Ecofisk 2/4 Alpha 1975	Deep Sea Driller 1976
Ecofisk Bravo 1977	Alexander L. Kjelland 1980
Piper Alpha 1988	West Vanguard 1985
Snorre A 2004	Treasure Saga 2/4-14 1989
	Ocean Vanguard 2004
	Big Orange XVIII/Ecofisk 2/4-W 2009
	Gullfaks C 2010
	Floatel Superior 2012
	Songa Endurance 2016
	Bourbon Dolphin 2007
	Deep Water Horizon 2010

beyond the proximate events needs to be encouraged [21]. PSA [4] advised also that a number of technical, operational and organizational factors can individually or collectively cause an accident and influence its development.

According to PSA [16], the structures in oil and gas are divided into two main categories: production structures and mobile structures. This categorization was applied to all case studies of this present study, as shown in Table 4, and it was observed that a high number of accidents involved the mobile structures in oil and gas industry. This brings to attention the uncertainties associated with environmental conditions in each field, and the necessity to carefully monitor and plan the operations and marine operations linked with each marine structure. A study of PSA [16] confirmed also that a high number of accidents between 2000-2014 are related to mobile structures (77% involved mobile structures and 23% production structures).

CONCLUSIONS

In this paper, 15 accidents and disasters over 40 years were analyzed through a life-cycle perspective, in order to identify the stage/s linked to the accidents' occurrence and their main technical causes. Based on the analysis of case studies, it was identified that a high risk is concentrated in the Operation (In-Service) stage within the life-cycle of marine structures in oil and gas industry. In addition, the Marine Operations during Operation (In-Service) stage was found to be one of the stages with the highest risk of accidents. Moreover, it was observed that a high number of accidents in oil and gas industry are linked to mobile structures. Furthermore, the main technical cause/s of the accidents were found to be not necessarily in the same phase of the life-cycle where the accident occurred. In other words, the occurrence of the accident in one stage of life-cycle can be rooted to other stages, sometimes back to design and fabrication. This highlights the importance of knowledge transfer and transfer of expertise among various offshore energy fields, for instance from the oil and gas industry to the wind energy in order to avoid potential accidents. Nevertheless, the risk is never static in the Norwegian offshore energy field, and the necessity for a dynamic learning is continuously highlighted and needs to be further incorporated in the Operation (In-Service) stage and the associated Marine Operations where high numbers of accidents are recorded. This calls for better preventive maintenance and condition monitoring during operation and better planning in marine operations. Moreover, a reactive learning from major accidents and disasters needs to be continuously supported by a proactive learning and development of a dynamic risk culture as the uncertainty in the operation can only be reduced until some extent. Nevertheless, among the main targets in the offshore oil and gas industry shall be a continuous monitoring and implementation of a dynamic risk assessment approach.

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