



Learning from failures: Accidents of marine structures on Norwegian continental shelf over 40 years time period

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ABSTRACT

This paper investigates accidents, major accidents and disasters which occurred on the Norwegian Continental Shelf (NCS) over a period of more than 40 years time (1972-2013). An accident investigation based on the system life-cycle was applied on the data provided by the World Offshore Accident Database (WOAD) where the operation (in-service) stage of the life-cycle was found to be the stage with 96% and the installation stage with 4% of accident occurrences. The marine operations linked to both installation and the operation (in-service) stages are identified to be where 13% of accidents had occurred. In terms of structural types, jackets and semi-submersibles are identified with the highest number of accidents, while the highest rate of accidents per marine structure type is linked to the concrete structures where in average 5.5 accidents per each concrete structures were recorded. 1980 was the year with the highest number of fatalities on NCS within 40 years time span with the occurrence of Alexander L. Kielland disaster. There has been a reduction of number of fatalities over the years, but injuries had always been present. It was found that possible correlations can be established among occurrence of accidents and environmental loads for some months. The results and discussions contributes to learning from the 40 years accidents on the NCS with the aim of risk reduction in operation of marine structures. The predictive and preventive maintenance strategy and condition monitoring during operation (in-service) stage for each individual marine structure is promoted. However, the uncertainty is still present and risk can never be reduced to zero.

1. Introduction

Petroleum activity is the largest industry in Norway, measured in value creation and revenues to the Norwegian state. The petroleum industry has been a key to the development of the Norwegian welfare state and has laid the basis for the position of Norway among the wealthiest nations in the world [1].

After 50 years from the oil discovery, the Norwegian petroleum industry remains more important than ever and will continue to be vital for the Norwegian economy in the coming years. About 47% of the estimated total recoverable resources on the Norwegian Continental Shelf (NCS) have been produced and sold. Nevertheless, there are large remaining and unexplored oil and gas resources, and the production is expected to be high for the next 50 years as well [2]. Fig. 1 presents the historical and expected production in the Norwegian petroleum sector, from 1970 until 2023 [3].

The Norwegian gas makes an important contribution to the European energy security. Europe is the largest market for the

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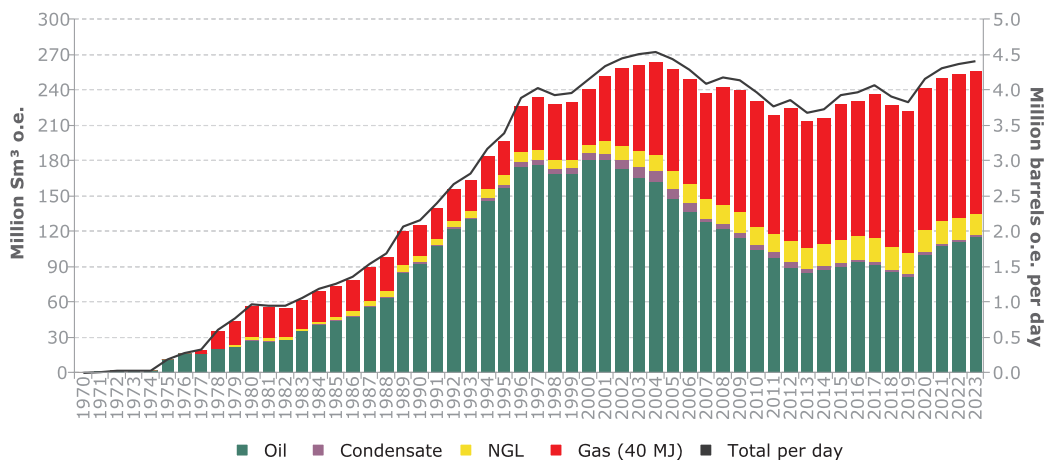


Fig. 1. Historical and expected production in Norway between 1970-2023 [3].

Norwegian oil and gas, and as per anecdotal estimations, almost every third French meal and every fifth British cup of tea are cooked by using the Norwegian gas [4,5].

The Norwegian oil and gas industry has encountered continuous innovations over the years and is at the forefront for development of the structural integrity assessment. However, the Norwegian oil and gas industry deals with demanding environments, and this industry still presents an inherent potential risk for accidents.

Risk of fire, explosions, failure of structure, capsizing or sinking, hull or mooring system failures are examples of various failure modes which may lead to loss of lives, injuries, loss of assets and impact on environment. The complexity of offshore or marine structures, their location far from shore, the environmental and accidental loads impact the evacuation of personnel and rescue [6]. In the recent years, there have been fatal accidents on the mobile drilling unit CosInnovator in 2015 and on the jack-up Maersk Interceptor in 2017. Moreover, a very serious situation occurred in October 2016, with loss of well control on the drilling rig Songa Endurance; the blowout preventer was activated and well was managed to be closed [1].

A major accident in oil and gas industry entails loss of multiple lives, injuries, serious damage to the environment, loss of substantial material assets, and significant financial assets. It can take place both on offshore and onshore facilities, and it can be in connection with transport to and from facility [1,7].

An accident is a type of failure, and the causes of failures may come from many sources. Moreover, failures can take many forms and can have different degrees and extent [8]. Failures impact a system from performing its required functions and can produce its permanent interruption [9]. Basically, a part of a system or an entire system fails when no longer comply with its design intent [10]. As an awareness note, all the designs may fail under certain conditions and at some point in time. Fundamentally, if what was designed performs how was intended over its life-cycle, then, the designed-life is successfully fulfilled. In case that the design does not perform as intended, and in addition, it causes substantial harms to humans, properties and to environment, then, a failure occurs. Furthermore, occurrence of a failure may lead to another failures and can reach to a disaster or to a catastrophic magnitude event [8].

Prevention of failures, accidents and major accidents has been, and remains, among the important tasks of stakeholders in the petroleum activities [1,11,12]. Increasing the awareness about accidents and major accidents and enhancing preparedness and level of safety in the oil and gas industry are essential objectives. Furthermore, it is important to learn from both national and international accidents and especially, to apply the acquired knowledge to the petroleum industry. "It's important to know the past in order to help improve petroleum industry safety" was among the messages from Magne Ognedal, the head of the Safety division of the Norwegian Petroleum Directorate (NPD) at the time when the Alexander L. Kielland disaster occurred in 1980, and from 2004 for almost a decade, the director general of the Norwegian Petroleum Safety Authority (PSA) [13].

Ibrion and Ibrion et al. [14,15] highlighted that knowledge of past accidents and disasters functions as an important input to risk assessment and contributes to enhance disaster awareness, mitigation and preparedness. Moreover, learning from disasters is impacted by a multitude of factors, and the rhythm of learning varies from one country to another, and from one culture to another. Furthermore, in addition to a continuous implementation of lessons from past disasters, a dynamic learning and particularly, a proactive approach is required [14,15].

Accidents and major accidents which occurred in the petroleum sector in Norway and around the world were seen by the PSA Norway [7] as key reference points for the Norwegian safety efforts which impacted the PSA's work on accidents and major accidents in the petroleum industry. Furthermore, PSA Norway [16] brought to attention that there is a limited systematic learning from accidents among operators companies and rig owners and building a culture of safety is required.

Christou and Konstantinidou [17] emphasized that the lessons from past accidents, particularly, from major accidents, need to be identified, classified and shared. In addition, 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 [18] dedicated a great part of work to investigate the application of the Quantified Risk Assessment (QRA) in the offshore oil and gas industry. Furthermore, Vinnem [18] presented lessons from major accidents from the oil and gas industry, both from the

North Sea and international industry. The main sequence of events for accidents together with the barriers performance, and the lessons learned for design and operations were analyzed. In addition, Vinnem [18] offered details about usage of risk indicators for major hazards and application of risk analysis during operations, and analysis of main offshore hazards.

Haugen et al. [19] emphasized that monitoring the risk of major accidents is a key element for the risk management in petroleum industry. Consequently, necessity to develop major accident risk indicators emerged. The basis for development of risk indicators is a risk model which includes technical, operational, human and organizational factors.

Major accidents and disasters in the oil and gas industry of Norway were the focus in various articles by Smith-Solbakken [20], Smith-Solbakken and Vinnem [21], and Smith-Solbakken and Dahle [22]. Their studies have offered a detailed presentation of the accidents/disasters and their consequences for the oil and gas industry in Norway.

Ibrion [23] after analysis of 12 major accidents on the NCS, two on the UK Continental Shelf and one in the Gulf of Mexico, USA, identified that a high risk is concentrated in the operation (in-service) stage for the life-cycle of marine structures. Moreover, the marine operations linked to operation (in-service) stage was found also to be one of stages with high risk of accidents.

However, the need for a systematic learning from accidents, major accidents and disasters in the oil and gas industry over long period of time is still a challenge which requires further work. The research aim of the present study targets to investigate accidents, major accidents and disasters in the oil and gas industry through a tempo-spatial perspective, and by making use of a life-cycle approach, in order to further learn from accidents in terms of risk reduction and mitigation within each life-cycle stage. Furthermore, the study targets to identify which stages of life-cycle are critical and where the accidents occurred most. Within the following section, the research methodology is presented and is followed by the section of case studies over time and space; the time interval is over 40 years (1972-2013), and the space refers to the Norwegian Continental Shelf. The section of analysis and discussions is further presented.

2. Research methodology

An accident investigation approach based on the system life-cycle has been employed in this article. The life-cycle approach has been used in earlier studies, by Faber [24], Moan [6,25], Torsvik et al. [26] and Ibrion et al. [23].

Faber [24] has considered a holistic approach for risk assessment in civil engineering considering all phases of engineering systems, like for instance, the offshore structures. The approach has at its centre 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 design, manufacturing, execution, operation and maintenance and decommissioning.

Moan [25] applied a life-cycle perspective to structural integrity management within the oil and gas industry. According to Moan [25] the life-cycle comprises the main phases of design, fabrication and operation and takes in account the environmental matters; the phases of removal and reuse were also added. Furthermore, Moan [6] added the installation phase to the life cycle and focused on the structural integrity management over the life-cycle of offshore structures.

Torsvik et al. [26] has a life-cycle view on business needs, design manufacturing, operations, life extension and decommissioning, in a study about large offshore wind turbines.

Ibrion et al. [23] applied a life-cycle approach in the study of 15 oil and gas accidents, major accidents and disasters within a period of more than 40 years; the accidents took place on the Norwegian Continental Shelf, the UK Continental Shelf and the USA Gulf of Mexico.

The approach used in this study is inspired by the accident investigation from Ibrion et al. [23] and based on the life-cycle illustrated in the Fig. 2. The work adopts a systems life-cycle safety analysis and hazard control actions of past accidents. The dynamics of an accident are categorized and studied from the perspective of the system life-cycle stages. In this way, past accidents may be contextualized and decomposed into their main features, as compared to a glass prism that separates a beam of white light

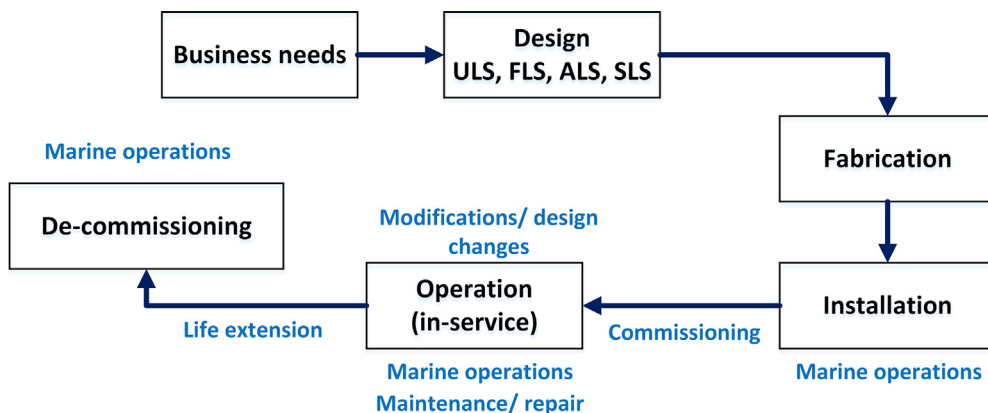


Fig. 2. Life-cycle stages for offshore structures. (ULS: Ultimate Limit State, FLS: Fatigue Limit State, ALS: Accidental Limit State, SLS: Serviceability Limit State).

into its constituent spectrum of colors [27]. The accident investigation approach includes the following steps:

- Definition of context at the time of the accident: Time (e.g. year and month); Environmental conditions (e.g. waves and wind); Typology of structure involved.
- Comparison of fatalities, injuries and degree of damage severity per accident.
- Classification of main event types.
- Categorization in life-cycle stages.
- Accident analysis from life-cycle stage perspective.

The life-cycle starts with business needs and design stages. The design in this life-cycle approach is based on the limit state design methods considering ultimate, fatigue, accidental, serviceability damage limit states (ULS, FLS, ALS, and SLS). Further details about limit state design methods are presented by the NORSOK standards, for instance N-0001/2004, and also discussed by Moan [6,25]. As per PSA [16], foundation for a safe structure is prepared by experienced and expert engineers in design phase.

The next stage within the life-cycle is represented by fabrication. This stage of the life-cycle can encounter various challenges like for example, the necessity of an adequate monitoring of fabrication process by engineering companies, operators, rig owners and requirement for experienced engineers and fabrication experts. It is also highly important that during fabrication stage, the environmental conditions of a specific area, like for example, for the NCS, are taken in consideration, and also the Norwegian requirements, and the NORSOK standards are respected and implemented. A lack of follow up will dramatically impact the safety, increase financial risk and open the way for re-design and modifications [16].

The following stages within the life-cycle are represented by installation, operation (in-service) and de-commissioning. It is observed that the marine operations are part of all of these stages, as shown in the Fig. 2. Within marine operations, an important place is given to a proper planning taking in account the planning principles as per DNVGL-ST-N001, other relevant rules and regulations, and operational requirements. Moreover, the weather windows and environmental conditions are of high importance for marine operations. A weather window is described as the time interval when operations can be performed, and parameters such as wind speed, wave height, wave period, and currents can rapidly vary in time [28]. The tough environmental conditions on the NCS bring many challenges to marine operations.

For installation phase, there are various marine operations such as light and heavy lift operations and towing operations. For 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 or recovering them. Other type of marine operations refers to the offshore offloading operations from a Floating Production Storage and Offloading (FPSO) to a shuttle tanker. Other type of marine operations are linked with supply vessels [25]. There are also other type of marine operations, for instance, for the exploration phase of an oil field, there are marine operations such as seismic screening operations and Remotely Operated Vehicles (ROV) operations. The organization of marine operations is very complex and requires a high qualification and training for personnel (job training, site safety training, simulator training), familiarization with planned operation, site specific briefing, communication between involved parties, vessels and structures, weather forecasting, field engineering, operation management and risk management [28].

Between installation and operation stages, it can be observed in the Fig. 2, the commissioning which through testing, checking, verification and documentation assure that all systems, processes and components meet operational requirements.

The operation stage is named in this life-cycle as the operation (in-service) stage, see Fig. 2, 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. The maintenance/repair, the modification/design change and the life extension are part of the operation (in-service) phase, see Fig. 2 [23]. 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 [6].

The modification/ design change can occur over the operation (in-service) stage, and might take place due to planned changes of platform functions, updated knowledge about environmental loads, damages, and life extension. However, it is important to keep a record of it and to carefully assess its impact on the “as-designed” and the “as-built” structures [6].

The life extension confronts various challenges on the NCS and many of facilities have reached to their original planned end of life, but the business needs require their life extension [16]. A consent from the Petroleum Safety Authority and Norwegian Petroleum Directorate is required in order to use marine structures beyond the original design lifetime. The application of operator for this consent must be submitted one year before the planned lifetime expires. The operator shall ensure that the safety and technical integrity are maintained and safe-guarded on an ageing marine structure [1].

With regards to the de-commissioning stage, the Norwegian authorities make decisions about de-commissioning, based on application of both national and international regulations [16]. For example, during processing of the cessation plans for Ekofisk I and Frigg, permission was given to leave the concrete substructure and protective wall on the Ekofisk tank in place, as well as the TCP2 concrete substructure, on the Frigg field. In other cases, it was decided to remove disused facilities and transport them to land, with examples of such facilities including Odin, Nordøst Frigg, Øst Frigg, Lille Frigg and Frøy [5].

Various organizations, such as PSA, are involved in de-commissioning stage on the NCS. With concerns to the environmental matters on the NCS, the Norwegian Environment Agency has the supervisory responsibility and the Norwegian Labour Inspection Authority is the authority responsible for the onshore scrap yard [1].

It is essential to make an important remark that the life-cycle in this study refers to the “marine structures life-cycle”, and not to

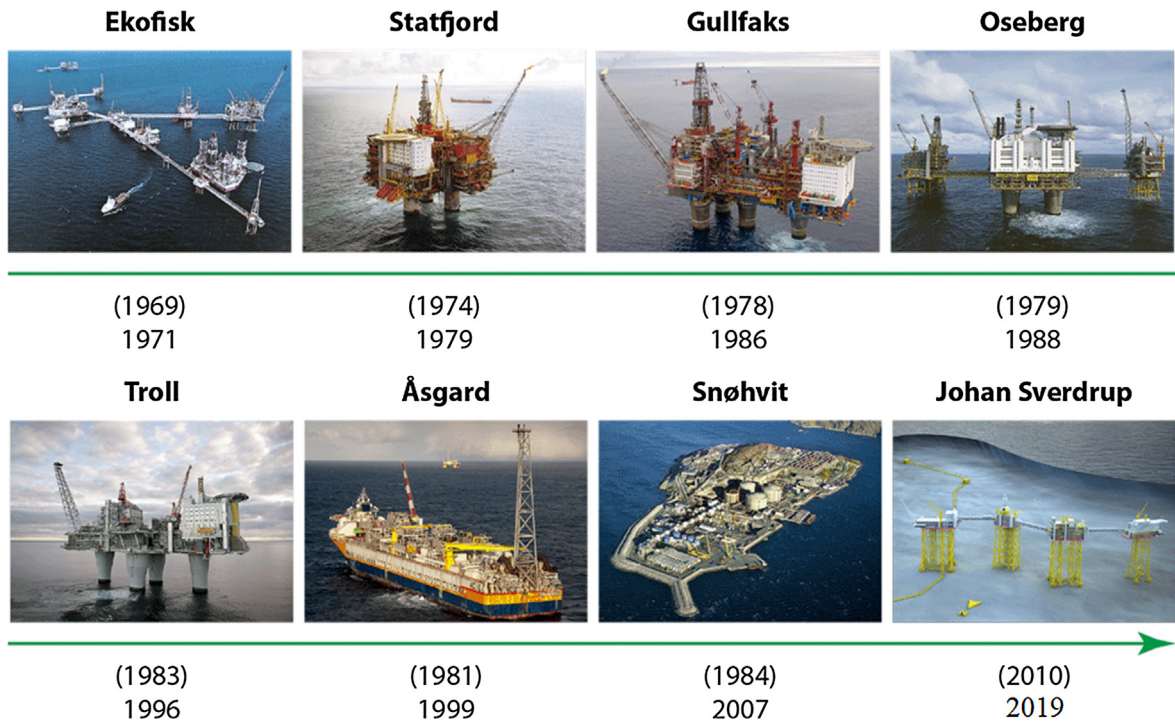


Fig. 3. Examples of marine structures on the Norwegian Continental Shelf (Adapted after Norwegian Petroleum) [29].

the oil and gas “field life-cycle”. Furthermore, in this study, the marine structures refers to the offshore oil and gas structures. According to Moan [6], marine structures are dynamically sensitive structures which are subject to environmental loads. Furthermore, as per the International Ship and Offshore Structures Congress, marine structures are the structures which have an interface with sea.

Fig. 3 illustrate few types of marine structures from the NCS; the first year mentioned under each photo indicates the discovery year for that field, and the second year indicates the beginning of operation for that particular marine structure.

As per PSA [16], generally, the structures in oil and gas industry are divided into two main categories: production structures and mobile structures. Furthermore, according to Odland et al. [30], the production structures are divided into fixed production structures and floating production structures. The fixed production structures include concrete structures or gravity-based structures (GBS) which can have several legs or just a single column, and steel jacket structures. The floating structures or floating production units (FPU) incorporate semi-submersible, tension leg platforms, deep-draft floating platform (Spar platform type), production ships such as FPSO (Floating Production, Storage and Offloading), buoy shaped platform, and floating production systems for liquefied natural gas such as FLNG. Mobile structures include drilling facilities and accommodation facilities which can be moved from one location to another. These structures can be, for example, semi-submersible and jack-up [16].

Production facilities are designed and built for a specific location and a specific purpose, and therefore, are more customized in comparison with mobile facilities where the standardized solutions are highly applied. The design and engineering phase for mobile structures are more standardized and there is less freedom in choice of concept. Moreover, there is also a series production and there are often sister facilities for mobile installations [16].

3. Case studies and Norwegian continental shelf

A total of 296 accidents, major accidents and disasters, over a time span of more than 40 years (from March 1972 until November 2013) was considered. The type of accidents which have been considered for this research study are related to marine structures such as jackets, semi-submersibles, concrete structures, barge (no drilling), loading buoy, jackup, FPSO/FSU, tension leg platforms. Other structures which have an interface with the sea such as drill ships, subsea installation/completion and well support structures were also included. Accidents which involved helicopters (offshore duty) and pipeline accidents were not considered for this study.

Data about the case studies was provided by the World Offshore Accident Database (WOAD) which is a repository of offshore accident data. Since 1975, the WOAD is curated by the Det Norske Veritas (DNV), nowadays, the DNV-GL [31]. Data about the North Sea area is abundant, more precisely, it accounts for 57% of the whole WOAD [32].

All the case studies for this present work are from the Norwegian Continental Shelf (NCS), particularly, from the North Sea and the Norwegian Sea areas, see Fig. 4. The NCS comprises the following areas: the North Sea, the Norwegian Sea, the Barents Sea and areas in the Arctic Ocean, see Fig. 4. The NCS, as shown in Fig. 4, comprises an area of about 2,039,951 square kilometres, and this

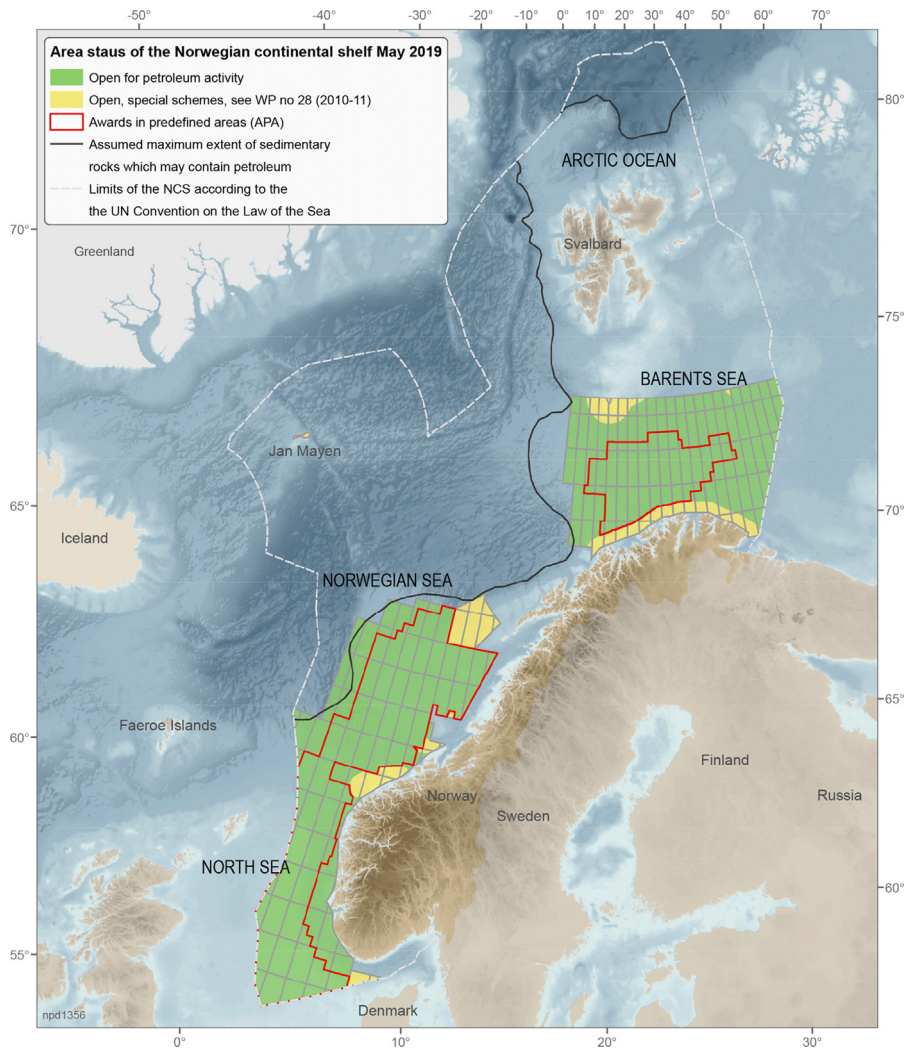


Fig. 4. Map of the Norwegian Continental Shelf by the Norwegian Petroleum Directorate (NPD) and the Norwegian Ministry of Petroleum and Energy [33].

represents almost six times the land area of mainland Norway, Svalbard and Jan Mayen [2].

The North Sea covers an area of 142 000 km² and represents the most explored part of the NCS; from 1971, the petroleum activities started in the Ekofisk field, southern part of the North Sea. In other areas of the NCS, the production started from 1993, in the Norwegian Sea, and in the Barents Sea, from 2007 [34,2]. With regards to the oil and gas fields, the North Sea has about 63 fields in production, the Norwegian Sea has 18 fields in production, and the Barents Sea, just two fields (Snøhvit and Goliat)[34]. The North Sea is the area with the highest number of accidents on the NCS.

4. Analysis & discussions

In this section the data of 296 accidents on the NCS was analyzed. It was identified that the number of accidents per year does not show a trend or tendency towards a steady reduction over the time, but there are registered peaks of accidents, see Fig. 5.

As examples, the highest peaks of accidents were registered in 1985 and 2009. Within the period 1981-1995, a high number of accidents were registered with high peaks in 1984, 1985, and 1993. In 2011, it was still registered a high number of accidents. Possible reasons and explanations about why the number of accidents was high in these years might be linked with fluctuations of oil prices, and with increased pressure to expand exploration/production of oil and gas. Other reasons might be linked to the increased number of old marine structures and necessity to extend the designed life and introduction of new technologies.

It was analyzed which months of the year were linked with a high number of accidents, see Fig. 6.

It was observed that the highest number of accidents occurred during the month of September, followed shortly by the months of November and March. A high number of accidents were also registered in the months of January, May and August. These observations hint to possible correlations between a high occurrence of accidents during particular months and environmental

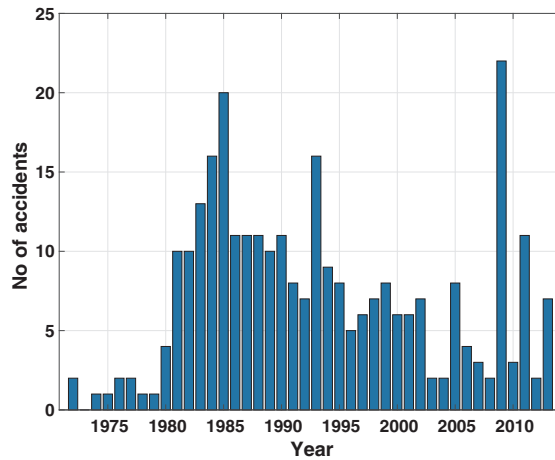


Fig. 5. Accidents on the NCS, over more than 40 years - Year versus Number of accidents.

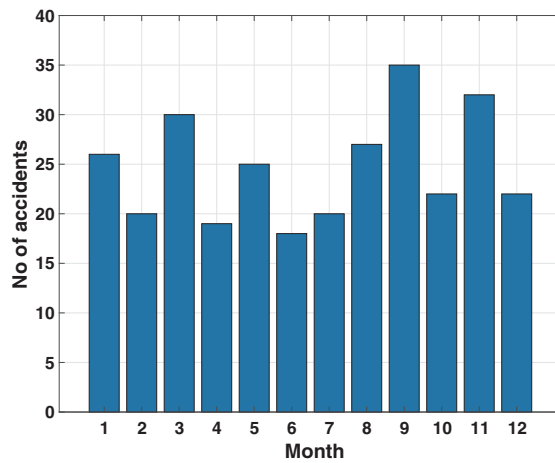


Fig. 6. Accidents on the NCS, over more than 40 years - Month versus Number of accidents.

conditions such as wind, waves, current, in particular fields/locations of the North Sea and the Norwegian Sea. In order to observe a possible contribution of environmental loads to accidents, the waves and wind at the time of accident were analyzed versus month, see Fig. 7 and Fig. 8. As a note, WOAD database does not provide for all accidents data specific environmental conditions like for

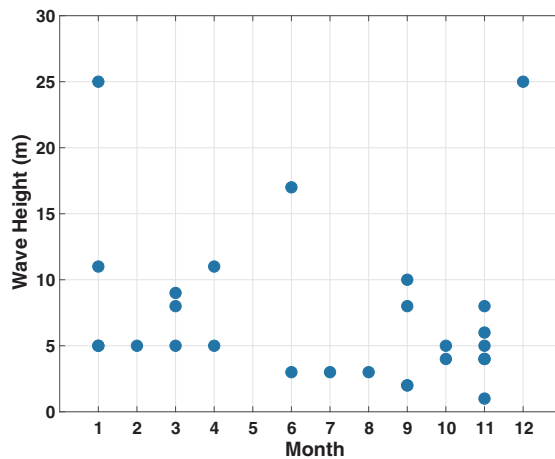


Fig. 7. Wave heights versus months during accidents on NCS over more than 40 years.

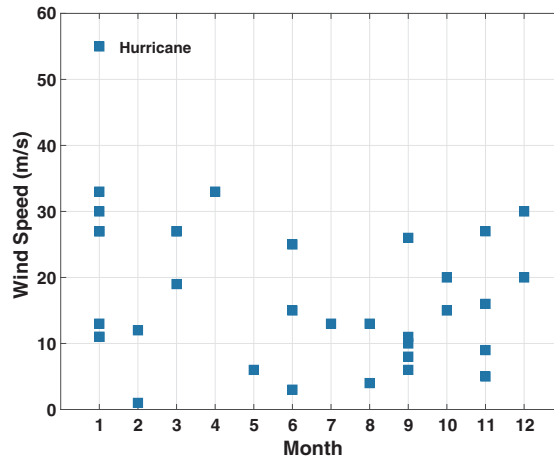


Fig. 8. Wind speeds versus months during accidents on NCS over more than 40 years.

example, wind and wave at the time of accident; in WOAD database, it has been mentioned just the value of zero for many accidents. However, the existing environmental data provided by WOAD is valuable and can offer interesting insights over a period of more than 40 years.

With regards to waves versus months, over more than 40 years, see Fig. 7, it can be observed that the highest waves - 25 metres (m) - extreme values - were registered in the months of January and December. It was identified which marine structures were affected by such high waves. It was found out that the same marine structure within a period of almost 6 years was affected two times by high waves of 25 m. This particular marine structure was designed for 30 m waves occurring within a 100 period years, and it suffered significant damages on both occasions. In the months of June, waves higher than 15 m were also registered. High waves of around or more than 10 m there were registered in the months of January, March, April, and September; in March, September and November were registered waves of 8 m.

In connection to wind versus months, over more than 40 years, see Fig. 8, it can be observed that the highest wind of 55 metres/second (m/s) was registered in the month of January. It was identified that was a hurricane which produced significant damages to the marine structure. High winds between 30-34 m/s were registered in the months of January, April, and December. In the months of January, March, June, September, and November were registered high winds between 25 and 28 m/s. In the months of March, October and December, high winds of 20 m/s were also registered.

Based on the data presented by Fig. 6, Fig. 7 and Fig. 8, some possible correlations can be established among accidents and environmental loads from waves and wind for some months, for instance, for months of January, March, September, November, and December. Nevertheless, more environmental conditions data is required as WOAD does not provided it for all the accidents, and the operational activities in those specific months need to be analyzed.

Fig. 9 presents the type of marine structures versus total number of accidents (296 case studies) on the NCS, over a time span of more than 40 years. In this figure, it can be observed that the highest number of accidents is linked with jackets and semi-submersibles. Moreover, a high number of accidents is also linked to concrete structures. The WOAD's White paper issued by DNV-GL brought also to attention that worldwide, the highest number of accidents is linked to jackets. As a note, the highest number of marine structures which exist in the world is represented by jackets [32].

Furthermore, an analysis was performed to identify the number of accidents per marine structure type, more precisely, the number of accidents per each type of structure was divided to the number of structures, see Fig. 10.

Fig. 10 shows that over a time span of more than 40 years on the NCS, the highest rate of accidents per marine structure type is linked to concrete structures as 5.5 accidents occurred per each concrete structure. Furthermore, a high rate is also linked to loading buoy, jacket and TLP. It was identified, for example, that a concrete structure was linked with a total of 17 accidents over 40 years. The main event of accidents was identified to be linked with fire, and for one accident case, explosion also occurred. Another concrete structure encountered a total number of 12 accidents. In this case, the main event of accidents was identified to be linked with fire, explosion, release of fluid or gas, falling load or dropped object, blowout, and collision offshore units. The third place is shared by a concrete structure and a jacket, both of them linked with 8 accidents. In case of concrete structure, the main event of accidents was linked with fire, explosion, release of fluid or gas, and falling load or dropped object. With concerns to jacket, the main event of accidents was linked with fire, explosion, and falling load or dropped object. All these three concrete structures which encountered such high number of accidents are located in the fields of the North Sea.

Worldwide, the highest rate of accidents per marine structure type is also linked to concrete structures [32].

The case studies were investigated in order to capture aspects about the impact of accidents on people and assets. The number of fatalities versus number of accidents on the NCS are shown in Fig. 11. The number of fatalities includes both the fatalities for crew and for third party personnel.

Fig. 11 shows that the year 1980 is linked with the highest number of fatalities on the NCS within more than 40 years time span.

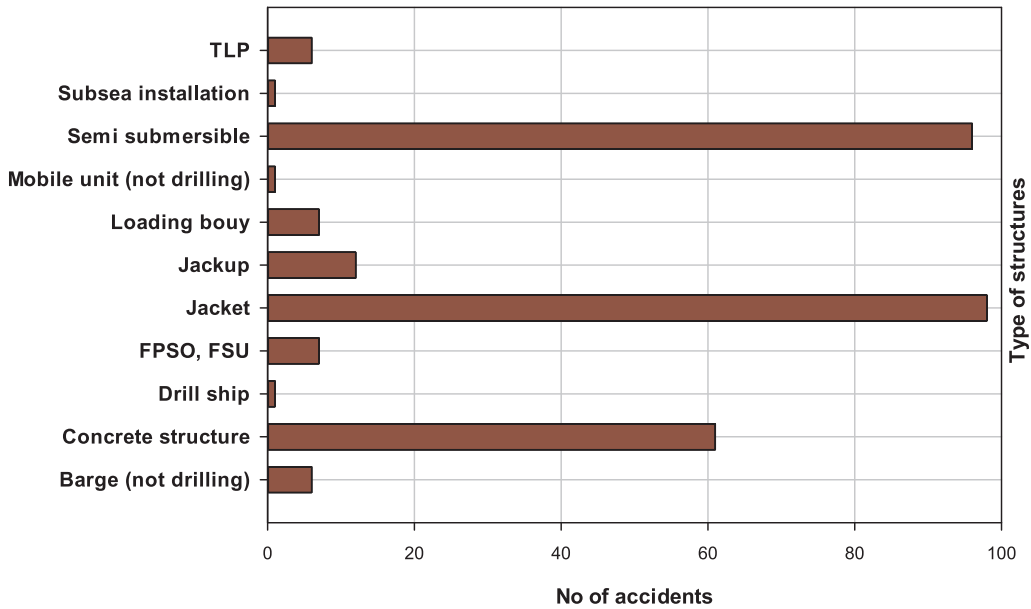


Fig. 9. Types of marine structures versus number of accidents on the NCS, over more than 40 years.

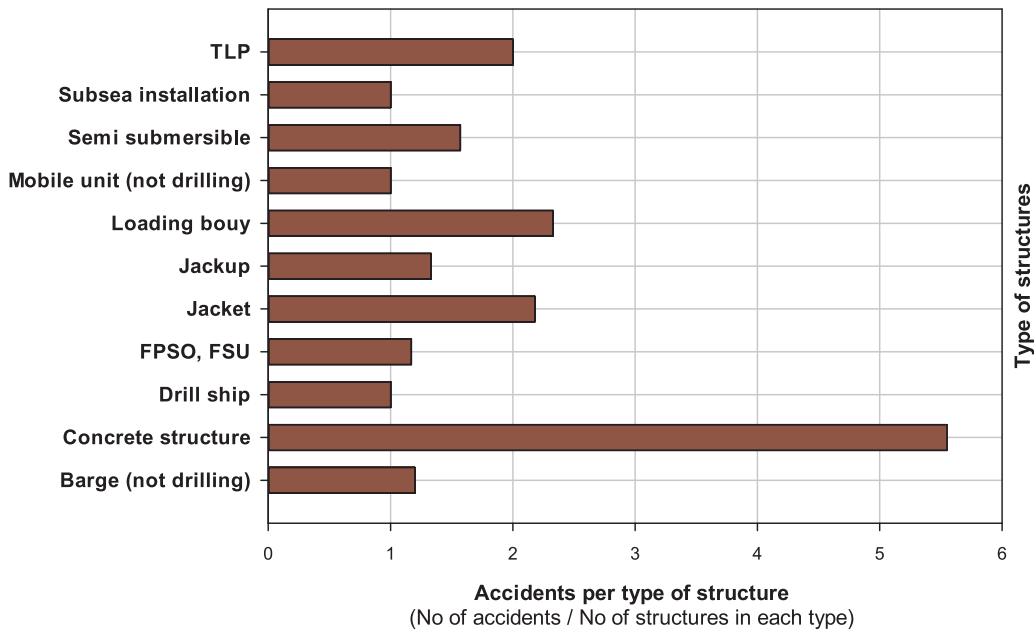


Fig. 10. Number of accidents per marine structure type on the NCS, over more than 40 years.

This is the year when the disaster of Alexander L. Kielland took place, on 27 March 1980, in Ecofisk area, North Sea. Around 18.30, the semi-submersible flotel Al. L Kielland capsized, and from a total of 212 people on board, 123 people lost their lives. This major accident was the worst accident which occurred on the NCS and was immediately followed by the appointment of an official commission of inquiry. This disaster had a big impact for the safety developments on the NCS, including division of regulatory responsibilities, regulatory regime and regulations. There has been a reduction of number of fatalities over the years, however, it can be seen that in 1985, 15 fatalities occurred, and still there are registered fatalities on the NCS until 2010.

Faber [24] emphasized that a society is less tolerant to events with a high number of fatalities than a series of events which cumulative kill the same amount of people, but over a longer period of time. Magne Ognedal, from NPD and later Norwegian PSA, brought to attention that the driving force, all along his career, after 1980, it was that Norway shall never experience again anything like the Alexander L. Kielland disaster [13].

The number of injuries versus accidents on the NCS over 40 years time span is presented in the Fig. 12. The number of injuries

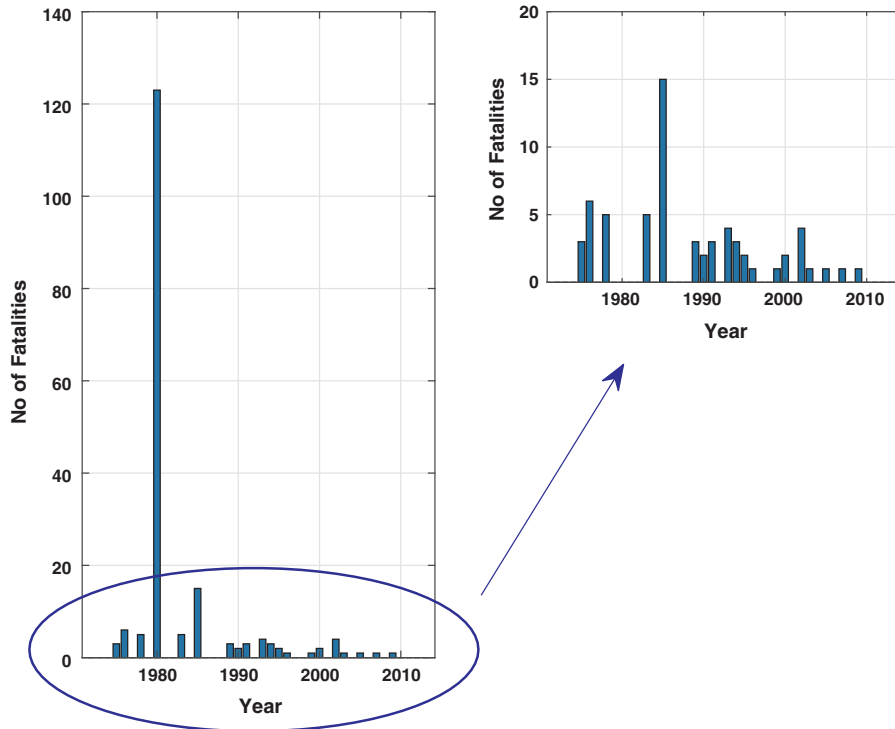


Fig. 11. Fatalities versus no of accidents on the NCS for more than 40 years time span (right figure excludes the 1980's record).

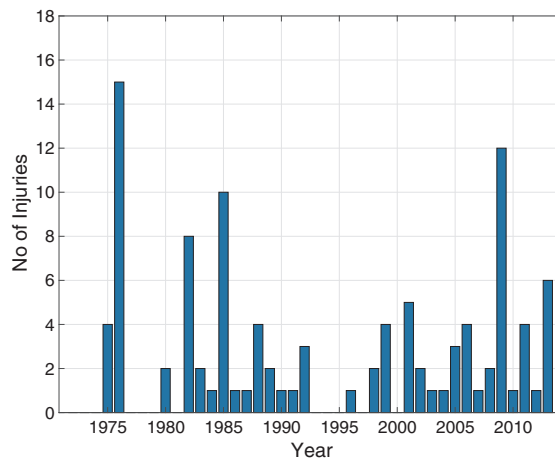


Fig. 12. Injuries vs. no. of accidents, on the NCS, over 40 years time span.

includes both the injuries for crew and for third party personnel.

Fig. 12 shows that the highest number of injuries were registered in 1976. Moreover, the trend of injuries on the NCS, over more than 40 years, shows peaks of injuries in 1982, 1985 and 2009. The injuries are continuously present on the NCS; even, in 2013, there were registered 6 injuries.

It is important to find out which type of failure occurs in order to reduce the downtime, to improve design, to tailor condition monitoring or bring forward other solutions and strategies of risk reduction [9]. Fig. 13 shows various degree of damage severity to the marine structures on the NCS, over 40 years time interval: insignificant or no damage, minor damage, significant damage, severe damage, and total loss.

Fig. 14, Fig. 15, and Fig. 16 present the categories of the main events and their percentage linked with total loss, severe damage and significant damage of marine structures on NCS over 40 years. In Fig. 14 it can be observed that breakage or fatigue, capsizing, overturning or toppling and grounding represent together 75% of all main events linked with total loss. Fig. 15 shows that collision, falling load, dropped object and fire account together for more than 75% of all main events linked with severe damage. Fig. 16

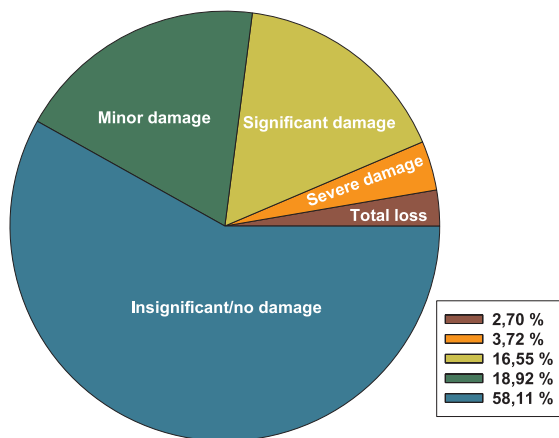


Fig. 13. Accidents on the NCS, over more than 40 years - Damage severity.

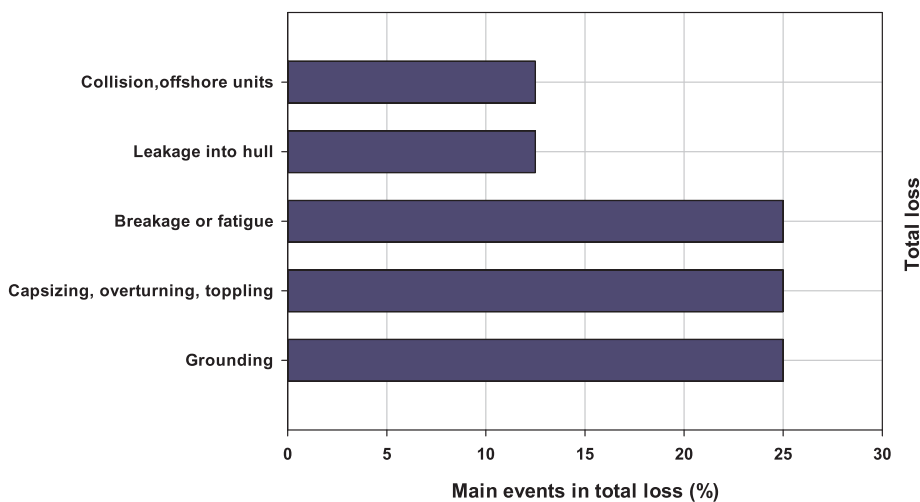


Fig. 14. Main events in total loss (in percentages).

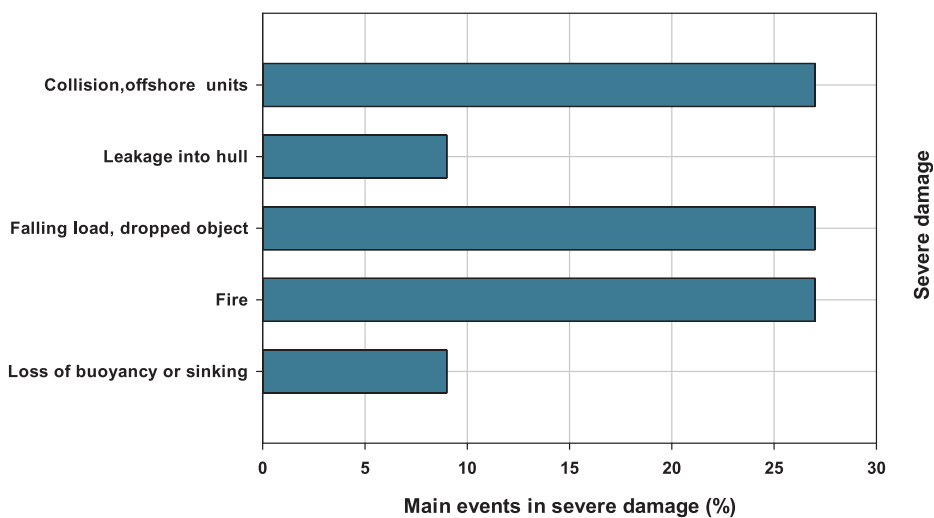


Fig. 15. Main events in severe damage (in percentages).

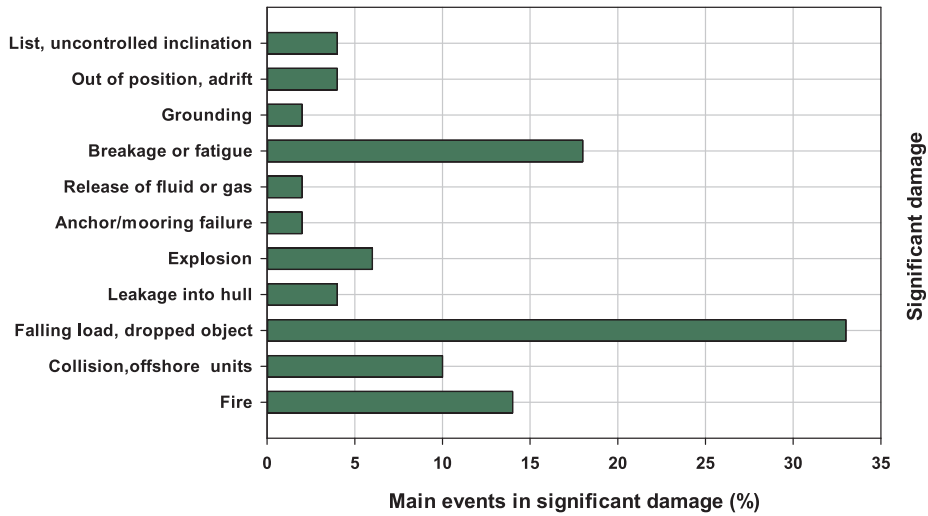


Fig. 16. Main events in significant damage (in percentages).

presents that falling load, dropped object represents more than 30% of all main events linked with significant damage. Moreover, breakage or fatigue accounts for more than 15% , and fire accounts for more than 10% all main events linked with significant damage.

According to Vicente [35], the failures in the oil and gas industry can occur over all the life cycle of a system and the failure/s is mainly connected with one or more from the following causes: faults in design, material defects, manufacturing deficiencies, installation defects, maintenance deficiencies, improper operation. Moreover, a failure can be directly or indirectly caused by following external stressors: mechanical, environmental, electrochemical, thermal exposure and radiation. Corrosion failures, fatigue failures and ductile and brittle metal failures are among the most common root causes for failures in oil and gas industry [10]. In addition to technical root causes, there are human and organizational causes for failures [35].

After employing the life-cycle investigation approach to the 296 accidents on the NCS, it was found out that the accident occurrence is mainly linked with the operation (in-service) stage of life-cycle and represents 96%. Furthermore, the accident occurrence is linked to the installation stage and represents 4% , see Fig. 17. Moreover, it can be observed in Fig. 17 that a significant percentage of accidents occurred during marine operations linked to operation (in-service) and installation stage, more precisely, 12% and 40% respectively.

The study of Ibrion et al. [23] identified also that major accidents occurred mainly in the operation (in-service) stage. Moreover, the marine operations linked to operation (in-service) stage was found to be on second place with reference to accident occurrence.

Various reasons can be connected with this high risk linked with the operation (in-service) stage and marine operations. A fundamental matter is that the operation (in-service) stage is the longest stage for the life-cycle of a marine structure and also is very complex stage. The marine operations are always required during the installation and the operation (in-service) stages. A marine structure shall fulfill a set of functions during its designed life while is in the operation (in-service) stage. The design is carried out based on the existing knowledge and design codes with the aim to address or account for known uncertainties. However, when a

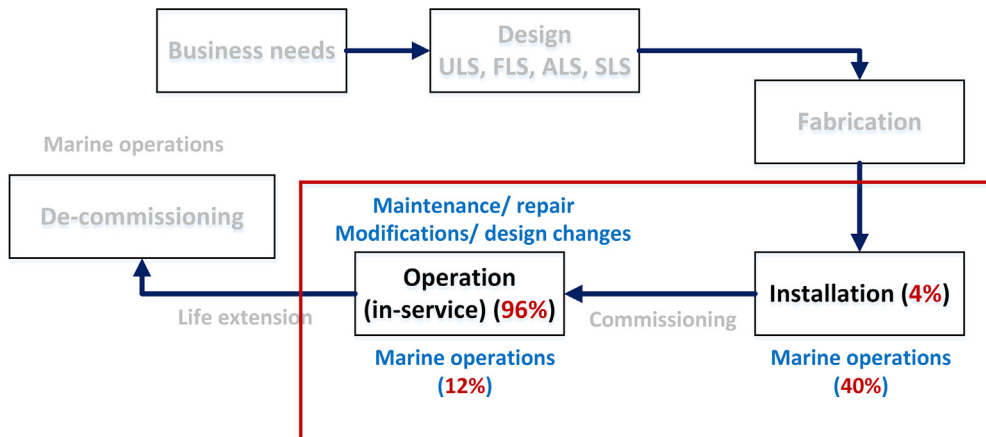


Fig. 17. Accidents occurrence on the NCS over 40 years time span and the stages of life-cycle.

marine structure reaches to the operation (in-service) stage, then it is exposed to several uncertainties which either have been underestimated or even may have not been accounted for. These uncertainties might be associated with the field conditions, changes in environmental conditions (higher wave and wind loads than what were considered), the equipment used in operation, maintenance work, risk management, human factors, safety culture, a complex regulatory structure, or even new type of hazards can be among new challenges [23].

Vinnem [18] drew attention about the subjective values of risk assessments and influence of uncertainty in oil and gas industry. According to Nadim [36], uncertainty can be classified into aleatory and epistemic. Aleatory uncertainty makes reference to the variability of physical environment and represents the natural randomness of a variable. The temporal variation for the peak acceleration of an earthquake with a given return period, the variation in wind forces, and the height of sea waves are just few examples of aleatory or inherent uncertainty. The aleatory uncertainty cannot be reduced or eliminated. Epistemic uncertainty represents the uncertainty which is due to lack of knowledge on a variable. Measurement uncertainty, statistical uncertainty, and model uncertainty are examples of epistemic uncertainty. Measurement uncertainty is linked for instance to imperfections of an instrument, or of a method to register a quantity. Statistical uncertainty is due to limited information and data, like for example, a limited number of observations. Model uncertainty refers to idealizations made for physical formulation of a problem. Epistemic uncertainty can be continuously reduced, for example, by collection of more data and information, improvement of the measurement method(s), calibration of instruments, by improving the calculation method(s) [36]. Furthermore, Nadim [36], proposed a second possible categorization of uncertainty, the objective and subjective uncertainty. The objective quantification of uncertainty is based on usage of statistical and probabilistic methods for processing available data. Subjective modelling of uncertainty refers to the analyst's experience or expert judgement, existing information, beliefs, necessity, and other factors.

Investigations done in the Norwegian industry and abroad has shown that major accidents very often have a complex and complicated course of events [1]. Leveson [37] warned that an accident is a complex process and in order to have a broader understanding of an accident and to learn from it and to prevent its future occurrence, the identification of all causal factors is required together with a comprehensive analysis of the technical and social system levels. Moreover, the foundation for an accident is laid years before accident occurrence. Therefore a broad view of accident mechanisms which expand the investigation beyond the proximate events needs to be encouraged [37]. According to PSA [7], a number of technical, operational, human and organizational factors can individually or collectively cause an accident and influence its development. With regards to human factors, Moan [38] emphasized that one of the lessons to be remembered from the Alexander L. Kielland disaster is that the human factors play a decisive role in safety, and a proper safety culture and safety management are required in the involved organizations. A deficient expertise and experience, a lack of awareness with reference to expertise, deficient transfer of experience among various stages of facilities were also seen among the causes of accidents in Norwegian petroleum industry [16].

Another cause of a high number of accidents during the operation (in-service) stage is represented by the deficient maintenance. Ibrion et al. [23] brought to attention that the high risk in the operation (in-service) stage highlights the importance of preventive maintenance and condition monitoring. PSA [12,16] warned that a defective or deficient maintenance, particularly for safety-critical equipment, has often proved to be a contributory cause of major accidents in the petroleum activities. This was also emphasized by the Norwegian Ministry of Labour and Social Affairs [1]. PSA [12] identified high levels for the backlog of the preventive and corrective maintenance, for a period of almost 10 years, from 2011 until 2018, for both fixed and mobile offshore structures.

About maintenance/repair, Faber [24] drew attention to the risk-based inspection and maintenance planning. In case of the Alexander L. Kielland, the initial fatigue failure of a brace was due to lack of fatigue design checks, fabrication defects and an inadequate inspection of structure [6]. Moreover, Moan [6] have recommended also Reliability or Risk based Inspections (RBI) as an alternative to traditional prescriptive and time-based programs. RBI relies on a predictive and preventive maintenance strategy.

Moan [6] have highlighted the importance of dedicated Inspection, Maintenance, Monitoring, and Repair (IMMR) to each individual marine structure. IMMR should address all kinds of damages and all conditions which might lead to damages. On general basis, annual and intermediate inspections are less extensive and major inspections of offshore structures are carried out every 4 or 5 years. Moan [6] recommends to shift from the traditional maintenance management to the integrity maintenance management. The traditional approach to maintenance focus on maintaining conditions according to design and is done to detect any failures and degradation which are not in accordance with the design. The integrity management incorporates the operational observations, results of inspections, history of design modifications, and focus on potential need for structural improvements of a design in order to fulfill its functions. Furthermore, Moan [6] emphasizes importance of the structural integrity management approach which include an adequate design based on FLS, ULS, ALS, a follow-up during fabrication, and the IMMR during operation, and a modification and repair history. Structural reliability methods can provide an improved basis for ULS and FLS design and for inspection and repair planning.

As per the white paper issued by the Norwegian Ministry of Labour and Social Affairs [1], many facilities and associated infrastructure on the NCS were normally designed and built with an estimated lifetime of approximately 15–30 years. As per PSA [11], according to rough estimations, it can be claimed that approximately one third of the structures on the NCS are in various degrees of late life. Nowadays, about half of the fixed facilities are more than 20 years old, and the oldest facilities on the NCS are more than 40 years old. New discoveries and improved recovery measures have led to extended lifetime for various structures and have postponed submission of cessation plans on the NCS. Inspections for life extension and a continuous status monitoring are required as risk reduction measures [16].

Concerning the old structures, it was identified that the combination between new and old equipment and systems, and different modifications and changes often pose many challenges. The PSA have already identified incidents which are linked to a deficient understanding of interaction between old and new. Therefore, it is important that technical conditions on old structures and

structures with extended life time are good and that the involved personnel have good competence and understand the systems and new equipment on the facility [11,16]. Furthermore, it was identified that maintenance on late-phase structures is characterised by being more corrective than preventive, and this can affect the safety over time [1].

With regards to the high risk linked to the marine operations, various reasons can be brought to attention, such as human errors, complex relationship between humans and automation, a low culture of safety and prioritizing business profits over safety, emerging hazards, changing environmental conditions, reduced ability and willingness to learn from past events. Errors and faults can easily happen during operations and marine operations. Aspects of risk and challenges associated with the digital twin implementation in marine industry needs also to be considered [39]. Therefore an increased focus on safety of marine operations is required, particularly as various challenges have to be settled in time such as hydrodynamic modelling of motions, automatic control, reliability and safety of human factors, simulator training for crew [38].

Maritime accidents for mobile facilities include, but are not limited to anchor line breakage, uncontrolled deployment of anchor lines, stability and buoyancy accidents. The anchoring system, particularly, is not sufficiently perceived as a safety-critical system. With regards to accident investigations, the rig owners mainly focus on proximate causes, particularly the technical causes [16].

With reference to the marine operations, PSA [16] based on an analysis of maritime accidents over almost 15 years period, from 2000 until 2014, brought to attention the most important causal factors leading to accidents: a lack of and deficient maritime competence and experience among personnel on board, deficient procedures and deficient compliance with procedures and requirements on board, failure in anchoring systems. The operating companies have given less importance to maritime training and expertise. With reference to accidents related to anchoring, a deficient maintenance, inspections and conditions monitoring of the anchoring system and a lack of experience and expertise with relation to usage of equipment are emphasized. Furthermore, concerning the marine operations, regulatory regimes and interface between petroleum regulations and maritime regulations can bring various challenges. More knowledge, cooperation and risk-reducing measures are recommended about the interface among maritime and petroleum regulations, and among experts within the oil and gas industry and marine industry. There is a need for improvement of knowledge and practice, cooperation, communication and teamwork with regards to marine systems, particularly with regards to anchoring systems and human-machine interfaces. Additionally in maritime activities, a more holistic approach with regard to interactions among technical factors, human and organizational factors is recommended [16].

Vinnem [18] brought also to attention the particularities of the regulatory regime in the Norwegian oil and gas. The regulations concerning Health, Safety and Environment (HSE) in the Norwegian petroleum industry contain risk- and performance-based requirements and are not following a prescriptive approach. According to the performance-based requirements the companies involved in the oil and gas industry on the NCS are solely responsible for complying with legislation. The regulations specify which level of safety shall be achieved, but now how. The companies have both the responsibility and a high degree of freedom in selecting the solutions which fulfil the safety requirements. They have flexibility in choosing the right methods, approaches, technological solutions, in their planning and execution [40]. In the Norwegian petroleum industry, the operators are responsible for maintaining an effective accident preparedness and for handling the hazards and accidents; the PSA supervises these activities of operators [1]. The regulatory regime in Norway shifted from an approval regime to a consent regime. The approval regulatory regime means that the authorities are the guarantors that the companies activities are acceptable. The consent regime means that the regulator express confidence that operators are acting in compliance with regulations [41]. However, Vinnem [18] warned that this approach can be sometimes fragile, particularly with regards to the prevention of major accidents.

The accidents in the oil and gas industry shows that this industry has become more cost focused and the right balance among safety and costs has not been properly kept and maintained. A safety culture is not only comprising the operational personnel, but also the safety culture of organizations [16]. Knowledge and new technology are rapidly developing in the petroleum industry. Technological development contributes to a higher level of safety and efficiency in the petroleum activities, but can also bring new challenges that the industry must manage in time [1].

5. Conclusions

In this article a total of 296 accidents from the oil and gas industry were analyzed over more than 40 years time interval, and over space – the Norwegian Continental Shelf – through a life-cycle perspective. Data provided by the World Offshore Accident Database (WOAD) was used. Based on the analysis of case studies on the NCS and over more than 40 years time interval, the 96% of accidents occurrence is placed in the operation (in-service) stage of the life-cycle, and 4% is linked to the installation stage with marine operations responsible for 13% of the accidents in both operation and installation. A wide range of factors might be linked with this situation which include and are not limited to complexity and length of operation (in-service) stage, uncertainties associated with load and load effect estimations for decision making in operation, the safety culture among stakeholders involved, organizational and human factors, particularities of regulatory regime, and inadequate maintenance or inspection planning. Moreover, a high number of old marine structures on NCS which are subject to life extension, poses challenges to safety in terms of interactions among new and old systems, and usage of corrective rather than preventive maintenance. The importance of dedicated RBI which relies on a predictive and preventive maintenance has been promoted. A required shift from a traditional maintenance to the integrity maintenance management for each individual marine structure which was highly emphasized by Moan [6] needs also to be encouraged.

It was also identified that the number of accidents per year on the NCS over more than 40 years time does not show a trend or tendency towards a steady reduction. The analysis also indicates possible correlations between accident occurrence and the environmental loads, waves and wind, however for instance, the highest number of accidents is found to be in September, while the wind and wave height are not the highest values in this month. This may imply that the environmental conditions are not necessarily

the cause of majority of accidents. It also can indicate that the implemented reliability-based design of marine structures on NCS has been relatively successful in addressing the uncertainties related to environmental load estimations, considering the limited data available. In addition, the type of marine structures versus total number of accidents was analyzed and found that the highest number of accidents in NCS is linked with jackets and semi-submersibles followed by concrete structures. With regards to the highest rate of accidents per marine structure type, the concrete structures are on top of list, followed by loading buoy, jackets and TLP.

The number of fatalities versus number of accidents shows that 1980 is the year with the highest number of fatalities on the NCS with the disaster of Alexander L. Kielland, when 123 people lost their lives. There has been a reduction of number of fatalities over the years, but still there are registered fatalities on the NCS until 2010 (the WOAD data was analyzed until November 2013). With regards to degree of damage to marine structures, the significant damages represented about 17%, severe damages almost 4% and total loss near 3%.

Learning from accidents is an important input to risk assessment and contributes to improvement of risk management, and to a reduction of accidents in the future. It requires among other factors, time in order to be implemented, promoted and supported. Moreover, learning from accidents on the NCS needs to be continuously monitored over the time. It is vital to learn to be prepared for the future as the risk for the marine structures is never static on the NCS. The oil and gas industry in Norway is a mature industry, but the number of aging marine structures is increasing which posing new challenges. Fundamentally, this calls that a reactive learning from accidents needs to be continuously supported by a proactive learning and development of a dynamic risk culture, as the uncertainty in the operations can only be reduced until some extent.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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