University of
Stavanger

Faculty of Science and Technology

MASTER’S THESIS

Study program/ Specialization: Risk Management and Offshore Technical Safety	Spring semester, 2019.. [✓ Open] / Restricted access
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Thesis title:

Review and discussion of current approaches on safety barriers for the Norwegian petroleum activities

Credits (ECTS): 30

Key words: Risk Major accidents DSHAs Safety Barriers Barrier Analysis	Pages: 81 + enclosure: 0 Stavanger, 14 June 2019 Date/year

Universitetet
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Master Thesis
Faculty of Science and Technology

Review and discussion of current approaches on safety barriers for the Norwegian petroleum activities

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Stavanger, 14 June 2019

ABSTRACT

Over the past forty years, hydrocarbon industry is the largest revenue generating industry in Norway. The hydrocarbon activities carried out in the Norwegian continental shelf (NCS) are associated with major accident potential and very high-risk levels. Hence, safety to human life, assets and environment becomes an issue of great significance. Accident investigations show that poor risk assessments and failure of safety barriers are the leading causes of major accidents in the offshore petroleum industry (Johansen & Rausand, 2015). The Petroleum Safety Authority (PSA) is a government supervisory and administrative agency with regulatory responsibility for safety, security, the work environment and emergency preparedness in the hydrocarbon sector of the NCS. PSA has been keen on increasing the competence and understanding of the criticality of the safety barriers in order to prevent and control the propagation of major accidents (PSA, 2017). Management regulations of PSA provide several references to safety barriers. Despite the fact that PSA has clearly signified barriers imminence, few operators in the industry still fail to implement the regulatory requirements regarding the safety barriers (Gustafson, 2014). This is because, various operators in the industry have unclear concepts regarding the key terminologies related to safety barriers and are ambiguous about the link between risk and safety barriers.

This report provides an inclusive review and detailed discussion on safety barriers in the NCS. The objective of this master thesis is to review the existing concepts related to safety barriers in the NCS and suggest a comprehensive workflow for barrier analysis so that better decision making while establishing and implementing safety barriers can be guaranteed. A thorough barrier analysis can also help in ensuring safe and sustainable petroleum activities in the NCS. Moreover, developing a clear link between risk assessment and safety barriers optimization of barrier functionality can be enhanced and major accidents can be significantly reduced in the offshore hydrocarbon industry.

Keywords: Risk, Risk Assessments Major accidents, DSHA, Safety Barriers, Barrier Analysis.

ACKNOWLEDGEMENT

This master thesis has been written to fulfill the graduation requirements for the Risk Management master's program with the specialization in Offshore Technical Safety at the University of Stavanger (UiS). The work was carried out in the spring semester of 2019 under the guidance of Terje Aven as the faculty supervisor. I would like to thank Terje Aven for his time, his guidance and his useful feedback throughout this project. The knowledge and the exposure I gained during my studies at UiS has been extremely beneficial for the completion of this thesis.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

BS	Barrier system
DAE	Dimensioning accident event
DAL	Design Accidental Load
DSHAs	Defined Situation of Hazard and Accidents
EPP	Emergency Preparedness Plan
HSE	Health Safety & Environment
ICT	Information and communications technology
IO	Integrated Operations
KPIs	Key Performance Indicators
NCS	Norwegian Continental Shelf
PSA	Petroleum Safety Authority Norway
PR	Performance Requirement
QRA	Quantitative Risk Assessment
RIF	Risk Influencing Factor
SIF	Safety Instrumented Functions
SIS	Safety Integrated Systems
WIF	Well Integrity Forum

1. INTRODUCTION

1.1 Background

From the early 1970s petroleum activities in Norway have seen tremendous development. To cope up with this rapid progress in the Norwegian Continental Shelf (NCS) the industry has allowed dramatic evolution in its technology and working methodologies. The initial platforms on the NCS were designed for wells within a range of 3 km from the platform. However, the current platforms can reach the targets within the vicinity of 12 km. The evolution exemplified above involves sophisticated technology advancements at all work levels in the industry. These advancements have although brought major financial gains to the stakeholders but have also significantly increased the risk associated with failures. This risk of failure remains and will be the main concern in the future (Torbergsen et al., 2012). To manage and control this upsurge of risk levels, the petroleum industry in Norway does Quantitative Risk Analysis (QRA) to generate numerical values for probabilities and consequences of the undesired events. QRA is a decision support tool that also allows comparison between alternatives in terms of their contribution to risk (Tuset, 2014). Since multifaceted operations are carried out in the NCS, hence there are several elements and sub-elements that have a risk of failure. This makes the execution of QRA a challenging task. Moreover, QRA does not explicitly focus on safety barriers for major accidents and rather aims to focus on certain accident sequences and patterns (Tuset, 2014).

Accident investigations proof that inadequate barrier management, poor risk assessment and failure of safety barriers are the main causes of major accidents in the offshore petroleum industry (Johansen & Rausand, 2015). Acknowledging this concern, the Petroleum Safety Authority (PSA) in 2013 identified barriers as one of their foremost priorities and since than extensive regulations are formulated and published concerning the use of safety barriers in NCS. In 2013, the PSA issued a barrier management framework for the offshore oil and gas industry. The framework describes the principles related to barrier management and is a valuable guide for the entire process industry. Despite the fact that PSA has clearly signified barriers imminence, few operators in the industry still fail to implement the regulatory requirements regarding safety barriers (Gustafson, 2014). One of the several reasons is that various players in the industry have unclear concepts concerning the link between risk and safety barriers. This becomes a big challenge for the analysts to select quality information regarding safety barriers from the performed risk assessments. Another unusual challenge is that different concepts regarding safety barriers prevail in the NCS. Although PSA has established requirements corresponding to safety barriers, they have not precisely defined the individual concepts pertaining to it. A clarification of several terms such as major accidents, safety barriers, barrier analysis and Defined Situations of Hazards and Accidents (DSHAs) will make it easier for the petroleum industry to achieve the requirements developed by PSA. Similarly, clear explanation of key concepts can also make it easier for PSA to manage their regulations (Sklet, 2006).

1.2 Purpose

The purpose of this master thesis is to review current terminology and practice on safety barriers for the NCS and suggest improvements.

The specific aim of this master thesis can be listed as follows:

- Review and discussion of current terminology and practice on safety barriers for the Norwegian petroleum activities in view of the scientific literature on the topic.
- Discuss the link between risk assessment and safety barriers.
- Suggest a structured barrier analysis workflow that can be practically implemented into the offshore industry

1.3 Scope limitations

- The studies carried out for this report are only addressing the hydrocarbon industry and particularly the NCS even though knowledge for some of the presented concepts is very generic and may also be relevant for different industries using similar technologies.
- The guiding documents from the Norwegian authorities such as PSA, SINTEF, DNV GL Norge are the prime literature sources. Besides this, scientific papers and technical literature within this subject area have been used to support the discussions and explain the employed frameworks.
- The writer of this report had limited experience and knowledge about actual offshore settings and work practices on the NCS. This limitation will influence the assumptions made in this report and because of it certain scenarios will be simplified in order to provide an easy understanding to the readers.
- The emphasis in this report has been to design and establish safety barriers for major accidents with consequences to personnel safety. Hence, major accidents with consequences to environment and assets are not included in the scope of this master thesis.
- The report is addressing risk related to major hazards/accidents and will not include HSE related issues, unless they overlap with the characteristics related to major hazard & accidents.
- It is usually argued that during the implementation and maintenance of safety barriers, new risks and failures can be added into a system. An example can be the risks and failures introduced during the maintenance activities such incorrect valve positioning or loose joints etc. This report acknowledges these risks and failures as critical to the barrier functionality but do not include them into the discussion due to scope limitation. This implies that this report treats safety barriers as the means of risk reduction only.
- The focus of this master thesis has been on the design phase of the barrier management cycle. The operational phase of barrier management that includes maintenance and verification of the safety barriers is not included.

- Due to the time and scope limitation of this master thesis, the proposed workflow for barrier analysis has not been tested or verified by regulatory and other concerned authorities. Hence, it should only be treated as a theoretical suggestion and can be worked upon in the future so that it can be employed on an industrial level as well.

1.4 Contents

Chapter 1 gives the background, the purpose of the work carried out and the scope limitations faced while writing this master thesis. Chapter 2 provides knowledge and a strong foundation to critically analyze safety barriers in the offshore industry. In Chapter 2, definitions and explanations of the key terminologies for this thesis are provided keeping Norwegian regulations and scientific literature as its basis. In Chapter 3 a link between risk assessment and barrier management is established that is crucial to ensure the optimization of barrier functionality and reduce major accidents in the hydrocarbon industry. In Chapter 4 a more structured workflow to analyze safety barriers in offshore industry is suggested that can be practically implemented in the industry. In Chapter 5, final remarks, a summary of this master thesis and suggested work for the future are provided.

2. Review and discussion of Key Terminologies

2.1. Introduction

This chapter explains some specific concepts related to safety barriers in the offshore hydrocarbon industry. A coherent set of definitions and explanations will be provided for the key concepts related to major accidents, safety barriers, DSHAs and barrier management.

This chapter is divided into 5 sections and further small sub-sections. Section 1 provides an overview of the petroleum activities in NCS and the different types of regulations issued by the PSA of Norway. According to the PSA regulations, safety barriers in the offshore industry are primarily established for major accidents. Hence section 2 describes the characteristics of these major accidents. Section 2 also includes a comparison between major accidents and occupational accidents. The 3rd section defines and explains the concept of safety barriers in the offshore industry. Section 3 also categorizes the safety barriers being employed in NCS and place them in one block diagram. Finally, in section 3, three barrier models are also briefly explained for the reason as follows. PSA uses the energy barrier model as the foundation while formulating regulations with reference to safety barriers, so it is essential to discuss the fundamentals of this model. Bowtie diagram is the most generic model for safety barriers and helps to locate the proactive and reactive barriers on the accident chain. Section 4 discusses the process of barrier management. Since the aim is to provide a structured workflow for barrier analysis, barrier management in this report is only discussed for the design phase of the project. Hence, the entire cycle of barrier management which also includes follow up, verifications and maintenance of safety barriers is not explained but briefly mentioned. The 5th section reviews DSHAs according to the Norwegian regulations and provides a brief description of the RNNP project. Focus while choosing safety barriers is on the set of DSHAs which through risk assessments are recognized as the largest risk contributors hence it is crucial to understand the existing concept of DSHAs in the industry.

2.2. Overview of Norwegian Petroleum activities and regulatory regimes

Hydrocarbons in the Norway were discovered in late '60s at the Ekofisk field and the production of oil began in 1971. Since then the petroleum activities, mostly carried out in the North Sea, have brought incredible fortunes for the country. On the NCS, different activities like hydrocarbon exploration, well development, hydrocarbon production and decommissioning take place (Midttun,2013a). This process is illustrated in figure 1 below. These activities are associated with high levels of risk to human life, environmental and materialistic assets. Major accidents occur rarely in the offshore industry. However, these accidents are associated with extreme consequences hence to avoid them completely and achieve the desired level of safety, barriers were included in the legislation in 2001 for each of the activities shown in figure 1 (Midttun,2013a).

Figure 1: Main steps showing Petroleum activities in Norway (Gustafson, 2014)

This paragraph discusses the organizational hierarchy in the Norwegian petroleum industry and has been from summarized from Gustafson (2014). The regulations and acts formulated by the Norwegian parliament have legal status and must be followed by the operators in the industry. On the contrary, standards and guidelines are recommendations for understanding the technical terminologies and fulfilling the regulations. These are not legally binding and are considered secondary to the regulations. Figure 2 below is an illustration of the organizational hierarchy in Norway and was presented by Associate Director Anne Cathrine Johnson and senior consultant Pippa Brown, DNV GL, 1/5/2014 and is taken from Gustafson (2014). The role of PSA is linked to technical and operational safety, working environment and the emergency preparedness activities in all the phases shown in figure 1. The PSA had so far issued four sets of regulations which are framework regulations, management regulations, facilities regulations, and activities regulations. The framework regulations are applicable both onshore and offshore. These regulations provide frameworks for the performed activities and includes provision on the scope of regulations, responsible parties, risk reduction principles, etc. The management regulations gather all management requirements for HSE and have specified requirements for risk reduction principles, safety barriers, resources and processes, analysis and measurements, etc. The facility regulations are for offshore only and comprises the design and layout of the facilities. They also include information for physical barriers, emergency preparedness, safety function and loads, etc. Similarly, the activity regulations are for offshore only and they help to govern different events and specify the requirement for different aspects such as condition and monitoring, natural environment, maritime operations, and maintenance, etc. (Gustafson, 2014). For this master thesis, the major focus has been on the management regulations since they provide regulations related to the design and establishment of safety barriers.

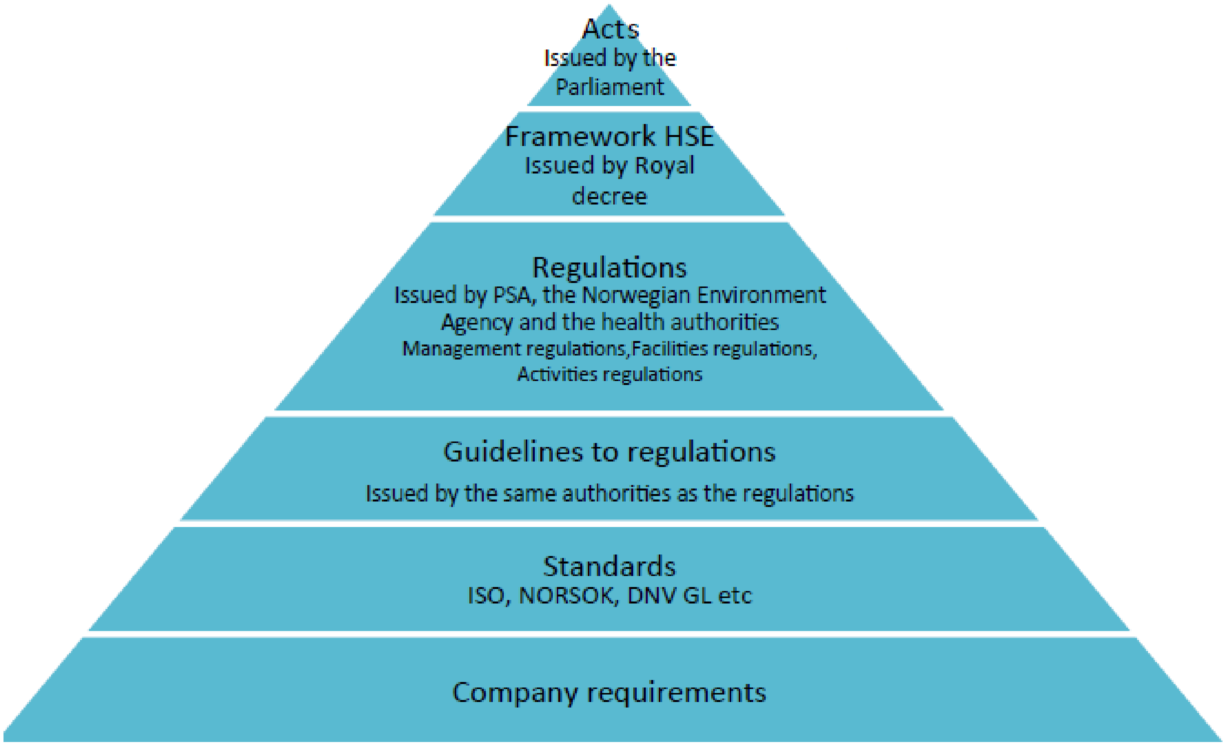


Figure 2: Organizational hierarchy in the Norwegian petroleum industry (Gustafson, 2014)

2.3. Major accidents in the offshore industry

In order to ensure effective emergency preparedness planning, it is very important that the entire organization is aware of the specific characteristics of major accidents. Knowing what to do in case of a major accident is very critical, and safety barriers which avoid or mitigate the consequences of the identified initiating events are a key part of that preparedness plan. The way major accidents are interpreted will have a direct influence on the methodology adopted for design of the safety barriers (Gustafson, 2014). For good barrier management, the link between safety barriers and major accidents needs to be reflected upon. Safety barriers are primarily designed for major hazards and failures (Gustafson, 2014). Therefore, if characteristics of the major accidents are not understood, the identification of barriers and their elements at different stages of the accident chain will be a big challenge.

Preventing the occurrence of major accidents to ensure safe and sustainable operations is the foremost priority of PSA and the offshore industry. Analyses of hazards linked to major accidents is given due attention by PSA which can be seen from separate sections in their regulations, in the form of QRA explicitly addressing this requirement (Skogdalen & Vinnem, 2012).

Major accidents are defined in the guidelines of the management regulations (section 9) alongside the requirements to the acceptance criteria for the major accident risk. The management regulations of PSA define major accidents 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".* Similarly, another definition found in a 2012 report for risk trends in the Norwegian offshore industry describes major accidents as, "*accidents caused by a failure of one or more of the safety barriers or emergency barriers in the systems*" (PSA, 2012).

Previously in the offshore industry, major accidents were described as those accidents with more widespread consequences than occupational accidents. Accidents were defined and categorized as major by the operating companies in the NCS if they were fulfilling one of the following criteria's: at least 5 fatalities, material damage of more than NOK 30 million or major environmental damage (Andersen & Mostue, 2012). PSA in the updated regulations and through the definition provided in section 9 of the management regulations does not endorse this criterion used by the operators in the industry and tends to avoid any quantification related to loss of lives (e.g. 5 fatalities) or harm to the environment (30 million NOK) and hence only relates major accidents to severe consequences that have a significant impact on environment, human life or material assets. Secondly, PSA has acknowledged major spills as hazards that can lead to major accidents which the operators in the industry previously failed to recognize (Gustafson, 2014). This is a further advancement done by PSA as it helps to realize that major accidents can also be caused by severe harm to the environment. This allows to justify accidents like Montara oil spill in 2009 as a major accident which previously could not be classified as one despite the terrible impact it had on the environment. Therefore, this thesis supports the definition provided by section 9 of the management regulation and will use as its basis to discuss major accidents in the discussions ahead.

According to the available scientific literature, major accidents in the offshore industry are characterized by an intricate interaction of human, technical, organizational and environmental facets. These accidents are not caused by one but a combination of the above-mentioned factors (Sarshar, Haugen, & Skjerve, 2015). Event sequences in the major accidents begin with triggering events causing one or several hazards, resulting in chain of hazardous events which eventually cause large scale consequences. Estimating the potential for escalation also depends whether if the implied consequences are immediate or deferred. To measure the degree of these expected losses, accident categories (e.g. DSHAs) are used that have predefined impact levels and intervals to scale the loss of life, harm to the assets and the environment. For example, loss of life can be measured in terms of the expected number of fatalities, and destruction of the asset in terms of the financial loss incurred (DNV GL, 2014).

2.3.1. Comparison between major accidents and occupational accidents

This section provides the distinction between major accidents and occupational accidents. The idea for this discussion has mainly been taken from the scientific literature DNV GL (2014). Since both major and occupational accidents originate from different hazard sources, it is very important that individuals in the organization acknowledge this distinction and the understand the rationale behind different risk management approaches they need. Major accidents rarely take place in the offshore industry because they are prevented through multiple safety barriers and defense in depth mechanisms (Øien, Hauge, Størseth, & Tinmannsvik, 2015). Accident/incident statistics illustrate that the barrier perspective has been implemented in the design of major accidents with significant success, whereas its application in occupational accident prevention is rather arbitrary (Kjellén, 2007).

In terms of risk, major accidents are low-probability / high-consequence events. Major accidents have intricate risk picture and are hard to predict. Therefore, very high uncertainty is associated with them. Since failure in several safety features is required for a major accident to occur, hence they have a potential for uncontrolled escalation if they take place escalation (DNV GL, 2014). On the contrary, risk of occupational accidents is described in terms of medium to high probability and medium to low consequences. Occupational accidents are single-linear event chains and have relatively low uncertainty associated to them. Due to this they have little or no potential for escalation. Based on the above-mentioned facts it becomes obvious that occupational accidents are less destructive in size and the impact they have on human safety (DNV GL, 2014). Table 1 is a summarized comparison between major and occupational accidents. The distinctive features between major accidents and occupational accidents are not always that evident. For instance, a major accident can also emerge from an occupational accident with personnel injuries and loss of life of one or two people (Andersen & Mostue, 2012).

The Norwegian regulations can be applied to the HSE work on the NCS and these regulations cover both major and occupational accidents (Gustafson, 2014). This master thesis will, however, discuss safety barriers keeping in consideration the major accident risk. According to Norwegian regulations, safety barriers should also be established for risks related to the working environment, security, and production regularity, etc. (Gustafson, 2014). However, this is not included in the scope of this master thesis.

Difference between major accidents and occupational accidents	
Major Accidents	**Occupational Accidents**
Low probability of occurrence	High probability of occurrence
High / Extreme consequences	Medium or low consequences
Large impact	Small Impact
Potential for uncontrolled escalation	Little potential for escalation
More safety systems in place to avoid major accidents	Comparatively fewer safety systems in place for occupational accidents
Multiple failures required to occur	Single failures can be the cause
Very high uncertainty associated	Lower uncertainty associated
A multilinear chain of events	Linear event chain of events
Indicators such as barrier and event indicators	Indicators such as Loss-Time-Injury (LTI)

Table 1: Difference between major accidents and occupational accidents (DNV GL, 2014).

2.4. Safety Barriers

2.4.1. Defining Safety Barriers

Catastrophes like Piper Alpha and Macondo blowout provide clear evidence that offshore petroleum activities are associated with major accident potential and high-risk levels (Røed & Bjerga, 2017). The key role of safety barriers to prevent major accidents has also been verified by investigating these catastrophes. Unsystematic barrier management resulted in failure of multiple safety barriers and caused propagation of these disasters (Johansen & Rausand, 2015).Hence, it becomes crucial to ensure that relevant and adequate safety barriers are established to prevent occurrence of major accidents and to ensure mitigation in case an accident occurs (Røed & Bjerga, 2017).

According to the barrier memorandum published by PSA in 2017, risk shall be managed through safe and robust solutions. As found out by various accident investigations. major accidents occurring in the hydrocarbon industry are of complex nature and have a very high escalation potential. Hence, managing risk only through safe solutions can be hazardous and inadequate. Therefore, additional protection through safety barriers becomes a necessity in order to maintain the desired level of safety. Management regulations (section 5) states that the established safety barriers must detect incipient incidents, avoid propagation of chain of events and limit the damage incurred (PSA, 2017).

Despite being highly critical to safety, no common terminology has been developed in the industry to define the concept of safety barriers (Sklet, 2006). Safety barriers have previously been employed as an expression in the PSA regulations rather than an established concept. This according to PSA is one of the biggest problems while implementing barrier requirements and barrier frameworks in the industry (Midttun, 2013a). Hauge & Øien (2016) have highlighted that in order to overcome this issue barrier definitions must include a logical relationship between its function (role of a barrier) and the respective measures that are vital in realizing the barrier function. Moreover, safety barriers should be directly linked to the event sequence and should not include the RIFs that influence the barrier performance (Sklet, 2006). Safety barriers should be established in such a way that they respond to a definite demand condition and lead to a well-defined condition of success or failure (Duijm, 2009). Section 5 of the management regulations mentions the criteria based on which safety barriers are defined and established. According to Section 5 (management regulations), safety barriers should be established to:

a) Identify conditions that can cause hazard and accident situations.

b) Reduce the probability of hazard and accident situations occurring and developing.

c) Limit possible harm and inconveniences.

With reference to identification and design of safety barriers, management regulations are the foremost classification of the PSA regulations. The following references to the Management Regulations (from different sections) can be employed for mapping of the safety barriers (PSA, 2010):

- *It needs to be realized what safety barriers are established and which functions they are required to perform, (cf. Section 1 on risk reduction, second paragraph), and what performance requirements have been defined in respect of the technical, operational or organizational elements which are essential for each individual safety barrier to be effective. (Second section, second subsection).*

- *It should be distinguished as which safety barriers are not functioning or have been impaired (Second section, third subsection).*
- *The responsible party should take required actions to rectify or compensate for missing or impaired barriers. (Seventh section, second subsection).*

Numerous definitions regarding safety barriers exist. SINTEF proposes safety barriers as, planned measures which are needed to regain control, mitigate development of defined situations of hazard and accident (DSHAs), or mitigate consequences of the occurred event (Øien et al., 2015). In 2010, report published by PSA on the risk levels in the Norwegian petroleum, activities have described safety barriers as measures that influence the progress of a certain accident in the intended direction, hence reducing expected losses (PSA, 2010). However, PSA in the barrier memorandum 2017, has provided a more inclusive definition of safety barriers as "*measures intended to identify conditions that may lead to failure, hazard and accident situations, prevent an actual sequence of events occurring or developing, influence a sequence of events in a deliberate way, or limit damage and/or loss*" (PSA 2017, p.9). Similarly, the scientific literature defines safety barriers as, "*physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents".* (Sklet 2006, p.3). The definitions mentioned above are collective terms that are convenient for explaining the safety barriers and their purpose in a generic manner. However, for analytical purpose, safety barriers should be considered as a series of elements that implement a barrier function, each element consisting of a technical system or a human input/response (Duijm, 2009). Hence, while designing and establishing safety barriers, it is more viable to refer to barrier functions, systems, or elements (Johansen & Rausand, 2015).

2.4.2. Different terminologies for safety barriers

The term “barrier” in the available scientific literature has been used in a broader sense with a slightly diverse meaning. Terms such as countermeasures, safety functions/systems, safety-critical functions/systems, defenses, lines of defense, defense in depth, levels or layers of protection and safeguards are commonly used interchangeably (Sklet, 2006). While all the above-mentioned terms serve a common purpose and are used to describe a similar concept, there are often slight variations in their meanings that can be a source of confusion while implementing safety barriers.

PSA has been using barriers terminology synonymously with safety systems or functions without providing any clear distinction between them. Nevertheless, the definition of safety functions stated by PSA (2010) has an obvious limitation that can allow analysts to develop a contrast between barriers and safety systems/functions. Safety functions according to PSA (2010) only consists of physical measures that reduce the probability of failures and limit the consequence of accidents. Safety systems are those systems which perform one or more active safety functions (PSA, 2010). Similarly, SINTEF describes safety systems as those systems which can be realized as barrier elements (physical) or comprises of several barrier elements (Hauge & Øien, 2016). Safety barriers, on the contrary, are comprised of technical, organizational and administrative elements and not just restricted to physical measures like safety systems (PSA, 2010). Example of safety systems can be, emergency power systems, active fire protection, etc. From the above descriptions, the safety system might apparently overlap with the barrier element and barrier functions. It needs to be clarified that a safety system is not by definition a barrier element since barrier elements are specifically employed to perform a barrier function in preventing major accidents (Hauge & Øien, 2016).

Sometimes, the “*barrier*” term also refers to a larger function or a barrier system (BS) (PSA, 2010). A BS is system designed and is used to execute one or several barrier functions (Sklet, 2006). A barrier system can be comprised of several system elements, such as technical elements, operational activities performed by humans, or a combination of the above (Aven, Sklet, & Vinnem, 2006). PSA does not use the term barrier systems in their recent barrier memorandum (2017) and describes the barrier elements which are combined to execute a barrier function. For this master thesis, safety barrier will be used instead of BS as an organized collection of barrier elements (Røed & Bjerga, 2017)

2.4.3. Categorization of Safety barriers

The idea for categorization of safety barriers has been taken from the scientific literature Johansen & Rausand (2015) and Hollnagel (2006). Categorization of safety barriers may not be a critical task to perform, yet it is very helpful in understanding the fundamental concepts of the safety barriers. There are two ways to categorize safety barriers in the NCS. The first is by their function /role in the accident sequence. Bowtie diagrams (see figure 6) are a popular tool to demonstrate this. Safety barriers influence the accident sequence by prevention, control or mitigation of the accident propagation. The preventive barriers can be also referred to as proactive barriers and will be found on the left side of the bow-tie diagram before the occurrence of the initiating event. Whereas, the mitigative and control barrier can be also be termed as reactive barriers and are located on the right-hand side of the bow-tie diagram. The second categorization of safety barriers is by their "nature". Four sets of barriers can be described in this classification. These are physical/ material barriers, functional barriers, symbolic barriers, and incorporeal barriers. Physical /material barriers are those barriers that physically protect the target from an accident and do not require an acting agent to perform their function. Example for physical/material barriers can be a fire wall. The functional barriers are required to inhibit the accidental chain and need to be activated in order to operate. This activation can be performed by a human operator or by a technological component. Example for functional barriers can be a safety valve. On the contrary, symbolic barrier require a human operator who knows how the barrier works for it to fulfill its purpose, e.g. a warning sign. The incorporeal barriers do not comprise of any material substance in their application (Gustafson, 2014). With reference to the classification done by Hollnagel (2008), technical barriers established by PSA could be described as physical/material barriers or functional barriers that are activated automatically on receiving a signal/intervention. The operational barriers are the tasks and responsibilities performed by the personnel and require manual operationality. These are also a type of functional barriers and can be applied in combination with the symbolic barriers. Finally, the incorporeal barriers are usually synonymous with organizational barriers within the industry. Figure 3 below is a summarized picture of the entire discussion on the categorization of safety barriers.

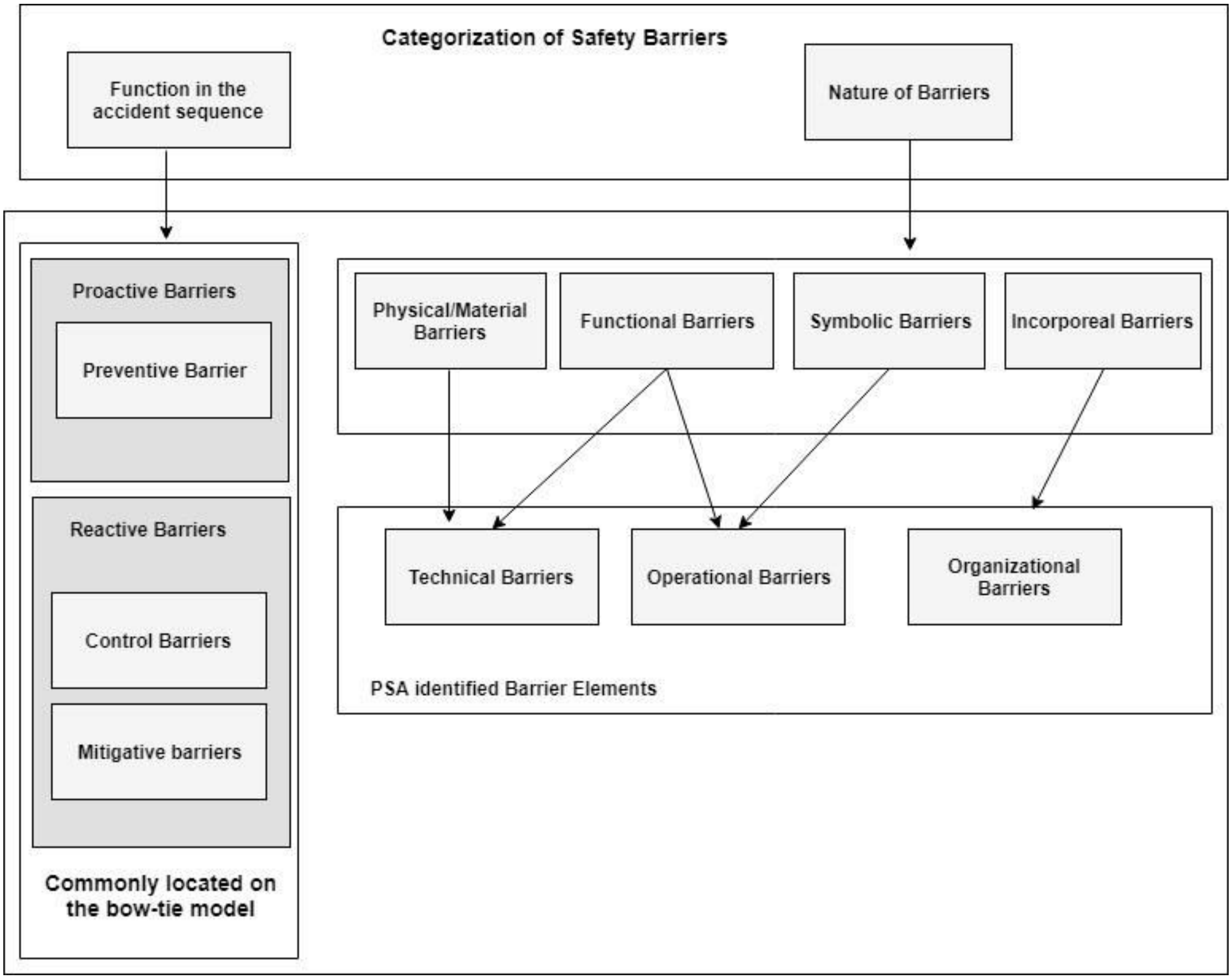


Figure 3: Categorization of safety barriers based on (Hollnagel, 2008; Johansen & Rausand, 2015)

2.4.4. Safety Barrier Models

In this section, three well-known safety barrier models namely energy barrier model, safety diagrams and bow-tie diagrams are discussed. The reason for discussing these models in this master thesis is as explained as follows. From the document "*sikkerhet, status & signaler*" published by PSA in 2013, it is mentioned that PSA has adopted the energy barrier model as the basis of its regulations related to safety barrier. Hence it important to understand the fundamentals of energy barrier model since PSA regulations regarding safety barriers have been extensively used in this report. Safety barrier diagrams and bow tie diagrams are popular methods in risk analysis and safety management. Bow-tie diagrams are among the finest models available to analyze accident sequences and visualize the entire risk picture integrated with safety barriers (Duijm, 2009). In order to illustrate a strong link between risk and safety barriers in Chapter 3 bow-tie diagrams will be used as the basis of the discussion. Therefore, it is vital to have a brief overview of these barrier models here.

Energy Barrier model

Introduction of the term safety barriers is often attributed to the work of Gibson (1961) and Haddon (1970, 1980), who established an accident perspective known as the energy barrier model (Næss, 2012). The general principle of energy barrier model is that accidents take place by lossing control over harmful energy, and that it is necessary to separate this energy from exposed targets by the help of barriers (Gibson, 1961). The model endorses that same accident prevention strategy should be employed for both major and smaller accidents (Gustafson, 2014). This classical barrier concept supposes a hazard (a harmful energy source) and a target (a significant value at risk as mentioned earlier), which is protected by a barrier (Gibson, 1961). The barrier can be physical / non-physical in nature. Distance is also considered a significant factor in this context, and when the energy level is high, the critical distance must be large (Guldenmund, Hale, Goossens, Betten, & Duijm, 2006). Figure 4 below illustrates the concept of an energy barrier model. However, this model has a drawback as it is based on linear causal chains, and poorly explains complex interactions in greater socio-technical systems (Næss, 2012).

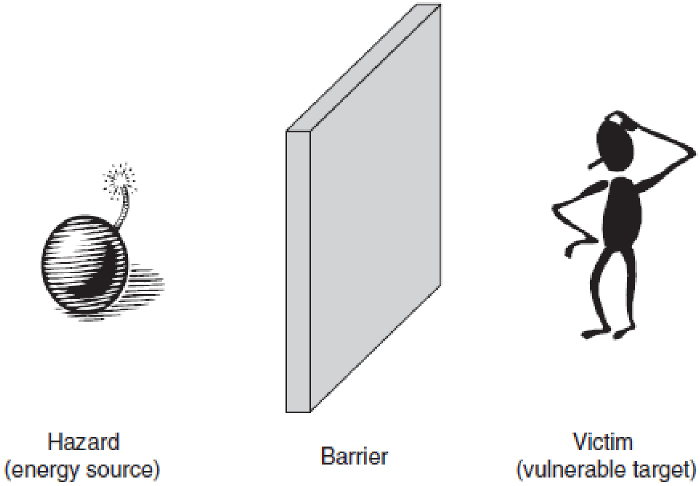


Figure 4: The energy model Haddon (cited by (Sklet, 2006))

Safety barrier diagrams

The following description on the subject of safety barriers diagrams has been taken and summarized from Duijm (2009). A safety barrier diagram illustrates how barriers prevent the buildup and propagation of chain of initiating events into hazards and accidents. Figure 5 below illustrates a possible buildup of an accident scenario. If a specified safety barrier is functioning as desired, the scenario stops at that barrier. However, if that barrier fails, the diagram shows hazard propagation towards the next barrier until the accident occurs when all the safety barriers have failed to function. Safety barrier diagrams employ comparable logic to fault trees and event trees, but the concepts are presented in the way that is less complex and much easier to understand. This is because basic events and judgements linked to functionality of the safety barriers are condensed in a single element, which eliminates all the other symbols in a graph hence resulting in figures that are very easy to comprehend by the analysts. A key advantage of the safety barrier diagrams is that by emphasizing on safeguards deliberately inserted into the system for preventing or mitigating the accidents, the diagram highlights leading concerns of safety management. Bowtie diagram (see figure 6) is a special case of a safety barrier diagram, where all paths (possible scenarios) through the diagram starting from one or more initiating events converge to at least one common event before the diagram diverges to one or several consequences (Duijm, 2009).

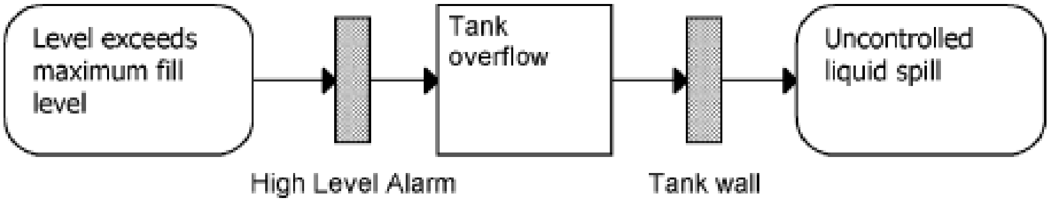


Figure 5: Illustration of a safety barrier diagram showing safety barriers to prevent liquid spillage from a tank (Duijm, 2009).

Bow-tie diagrams

In the offshore industry, safety barriers are selected based on the accident scenarios, which are established with the assistance of so-called bowties (Guldenmund et al., 2006). A Bow-tie diagram is a general model for risk and hazard analysis process. A bow-tie diagram enables identification of the safety barriers which can prevent an accident from occurring. Furthermore, identified integrity statuses of these safety barriers helps operators to understand the entire risk picture as well (Neto, Ribeiro, Ugulino, & Mingrone, 2014).

Figure 6 illustrates a basic bow tie diagram. In figure 6, the left-hand side of the bow-tie represents the threats that can initiate an undesirable event and loss to the ‘values' at stake. The right-hand side shows different scenarios that can propagate from the undesired event resulting in severe consequences (Neto et al., 2014). The left-hand side of an initiating event focuses on preventative barriers and the right-hand side focuses on consequence reduction or mitigation barriers (Røed & Bjerga, 2017). The Bow-tie diagram combines the fault trees (the left-hand side of the bow-tie) and event trees (the right-hand side of the bow-tie) and uses it in the quantitative risk assessments (Neto et al., 2014). Event trees and fault trees are applied to quantify the frequency of initiating events and performance of the safety barriers (Aven et al., 2006). Safety barriers will often correspond to the branching points in the incident trees in a QRA, and will have different functions based on their locations with respect to the fault tree/ event tree (Guldenmund et al., 2006). The idea is to employ safety barriers in such a way that hinders the threats and furhter stop developments that causes severe harm. For ease of analysis, there are bow-tie diagrams related to each top event and its subsequent consequences (Neto et al., 2014)

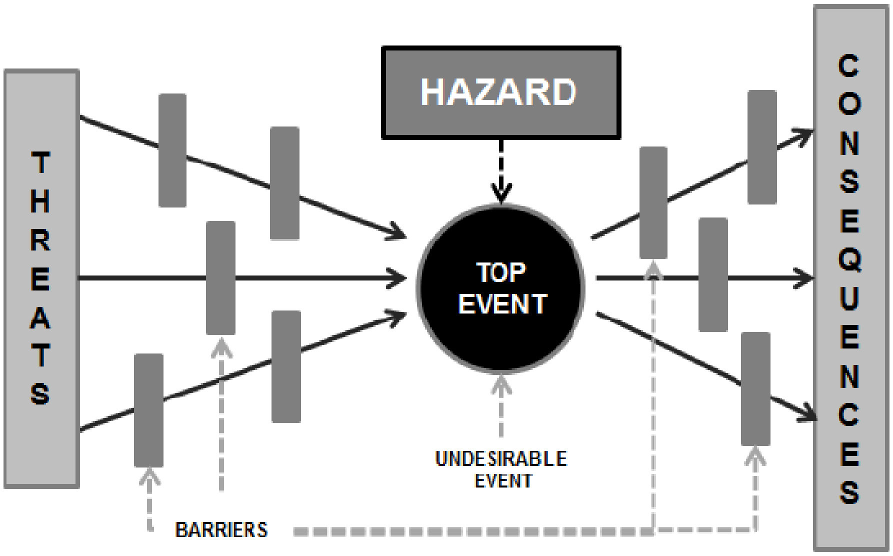


Figure 6: Bow-Tie diagram (Neto et al., 2014)

2.5. Barrier Management

In the offshore hydrocarbon industry barrier management is performed to ensure that adequate safety barriers are identified and established through a systematic and continuous process. This is done to provide protection in failure, hazard and accident situations (PSA, 2017). The foremost objective of barrier management process is to enable operators select the essential safety measures related to design and operations, such that the risk of major accidents can be significantly reduced in the industry (DNV GL, 2014). Below is figure 7, which illustrates the barrier management process proposed by PSA for operating companies in the NCS. As explained by Hauge & Øien (2016) and endorsed by figure 7, barrier management can be divided into two phases which are design/planning phase (brown arrows in figure 7) and operations phase (blue circle in figure 7). The implementation of the barrier management model during the operations phase is strongly dependent on the barrier management in the design/planning phase, hence it becomes crucial to employ sound techniques while implementing the design phase (J.-E. Vinnem, 2014a). The work for this master thesis focusses on the design phase of the barrier management process. Maintenance and follow up of safety barriers and fabrication of barrier indicators for the operational phase is not included in the scope for this thesis

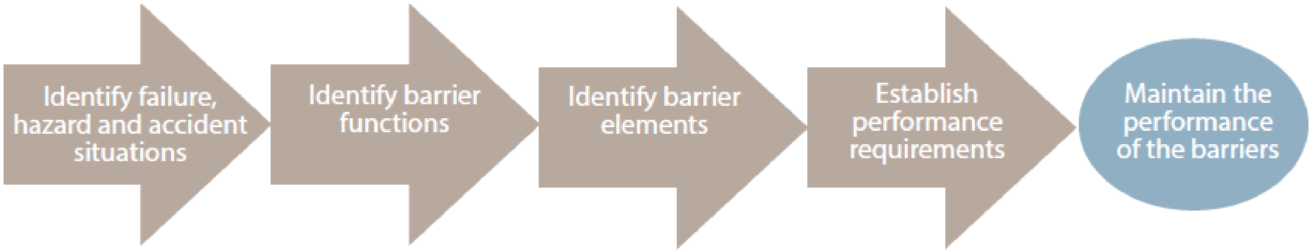


Figure 7: Barrier management process (PSA, 2017)

Safety barriers are identified and established in the design / planning phase of a project. Barrier analysis is subpart of the design phase and includes all the activities from identifying barrier functions till developing performance requirements for the safety barriers. Focus during the design phase is to detect and design safety barriers to ensure that required risk reduction is attained during the operations phase. Barrier strategies and specific performance requirements are developed and defined in the design phase, and consistently followed up in the operations phase through monitoring, evaluation, and implementation of the suggested improvements in a typical control loop (Hauge & Øien, 2016). Figure 9 presents the PSA model for barrier management in the design/planning phase. It is evident that the model is based on the ISO 31000 model for risk assessment and management. The upper part of the model is consistent with risk assessment and risk management, whereas the two lowest boxes are explicitly focusing on the barrier management process (J.-E. Vinnem, 2014a). The need for an effective barrier management process persists throughout the life cycle of the onshore/offshore facilities which includes execution of individual activities and operations. This is because even after the design phase, many conditions need to be monitored and continuously followed up during the second phase (operations) of the barrier management. The operations phase ensures the status of the safety barriers is maintained and followed-up. This is done to verify that the barriers are available at all times, and to implement alternative measures if barriers are impaired (Hauge & Øien, 2016).

Figure 8 illustrates that barrier management is a continuous process. The process is not only restricted to the selection of technical, organizational and operational elements and solutions during the planning/design phases. It also requires to ensure that the solutions maintain their desired properties during the operational period. (PSA, 2017). Apart from scheduled operational and maintenance activities, systems must functions as required to ensure efficient communication, expertise management, monitoring of results, changes in context and change management. Maintaining the functionality of individual barriers, making barriers more independent, focusing on various barrier elements are all important factors in an effective barrier management (Hauge & Øien, 2016).

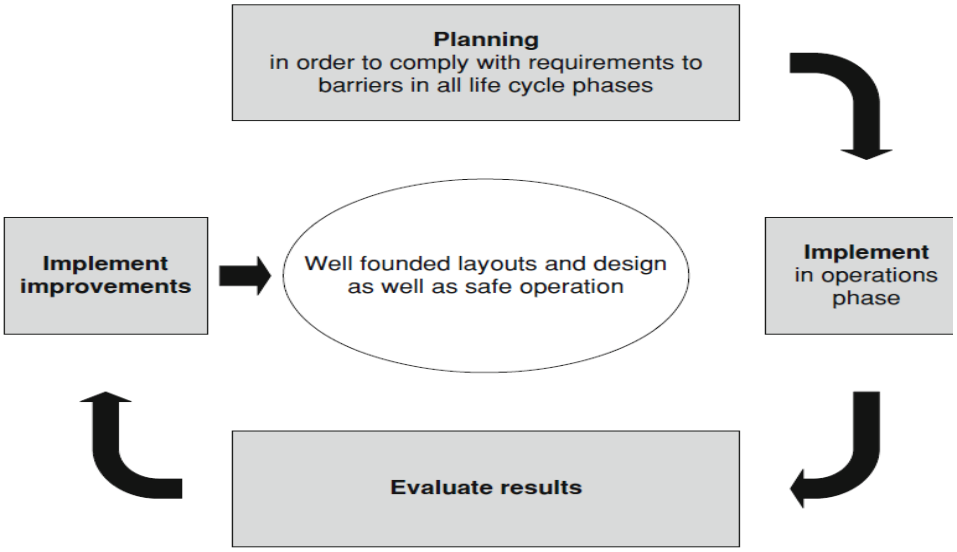


Figure 8: PSA model for barrier management (J.-E. Vinnem, 2014a)

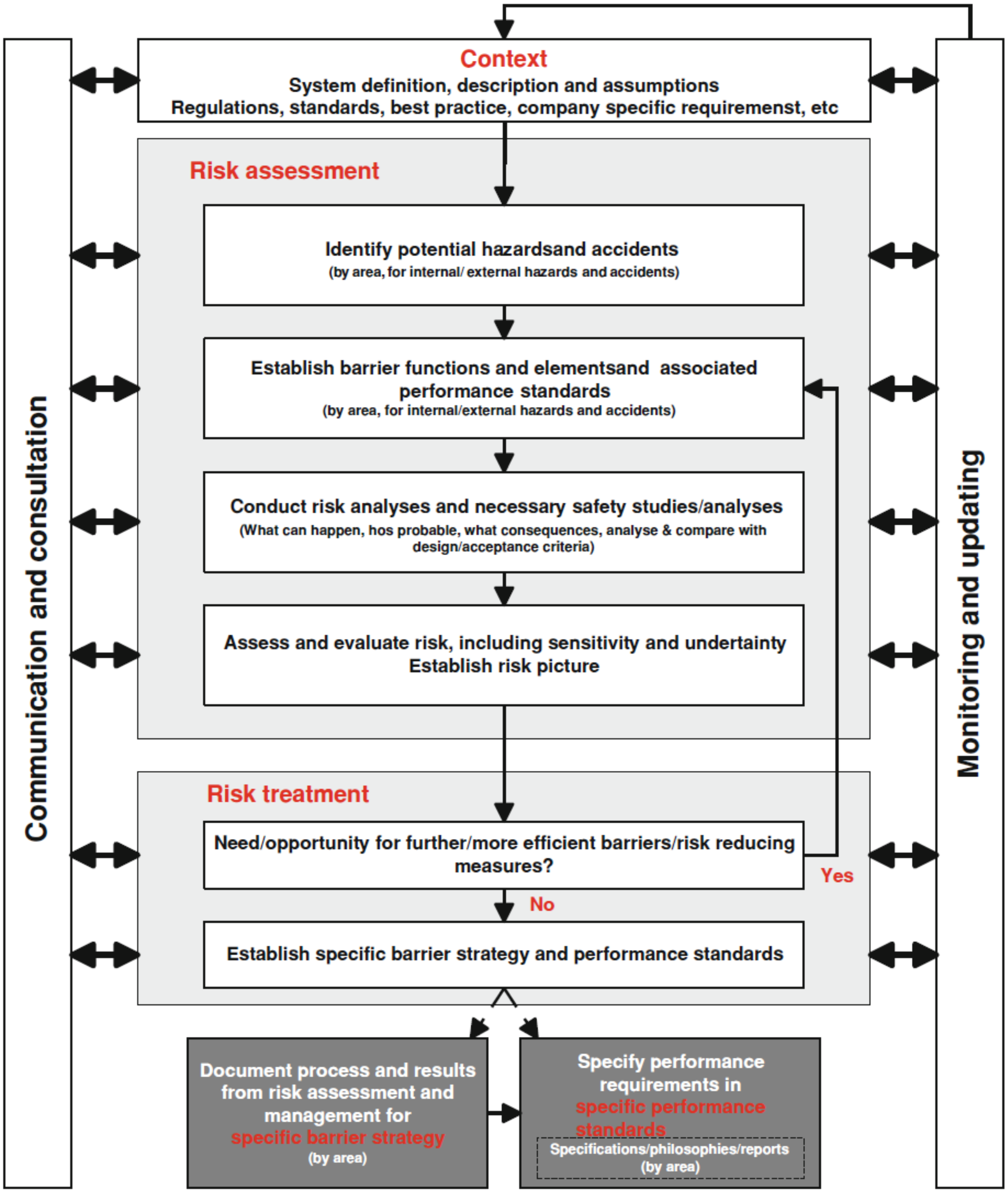


Figure 9: PSA model for barrier management in the design/ planning phase (J.-E. Vinnem, 2014a)

2.6. Defined Situations of Hazard and Accidents (DSHAs)

2.6.1.Defining DSHAs

According to NORSOK Z-013, Defined Situations of Hazard and Accidents (DSHAs) can be defined as, *"Selection of hazardous and accidental events that will be used for the dimensioning of the emergency preparedness for the activity"* (NORSOK Z-013 2010, p.9). The idea of DSHA/DFUs is effectively used by the hydrocarbon companies operating in the NCS. The concept is applied to specify a range of hazardous and accidental events based on which emergency preparedness procedures could be carried out (Wilhelmsen, 2011). Commonly known DSHAs currently being used in the offshore industry are, e.g., hydrocarbon leaks, well kick/blowouts, fire/explosions, and man, etc. (Skjerve et al., 2008). DSHAs are primarily aimed to prevent recurrences of scenarios that can negatively influence safety. The idea here is that accidental risk in the hydrocarbon industry will be significantly lowered down if protection against occurrence of the DSHAs is developed. Moreover, the companies safely act against the harmful effects that may follow given that the DSHAs takes place in reality (Skjerve et al., 2008).

2.6.2. Emergency Preparedness Process according to Norwegian standards

In the guidance document for the management regulations it is stated, that for obliging by the PSA regulations regarding quantitative risk assessments and emergency preparedness analysis, the standard NORSOK Z-013 shall be used (Skjerve et al., 2008). NORSOK Z-013 (2010) illustrates and defines the elementary parameters, sets the scope and criteria for the entire process risk assessment process, and includes both the internal and external context.

Figure 10 shows the risk and emergency preparedness assessment process, such that both processes are executed concurrently or during the same phase of a project (NORSOK Z-013, 2010). During the project both the risk and emergency preparedness processes should be effectively coordinated and communicated. Input used and results generated from one process will in certain circumstances be employed as input to the other process. Thus, the two processes are practically integrated (NORSOK Z-013, 2010). The emergency preparedness assessment in figure 10 consists of the following main steps (NORSOK Z-013, 2010):

1. Establish context of the assessment carried out.
2. HAZID.
3. Define and create DSHA and analyze the course of events.
4. Recognize the governing performance requirements for emergency preparedness.
5. Identify and assess.

- Explicit performance requirements.
- Explicit emergency response strategies.

Measures and solutions.

6. Documenting process and results

The emergency preparedness assessment is ought to be conducted for each individual phase of the facility's life cycle along with consistent references to the QRA (NORSOK Z-013, 2010). During an emergency preparedness assessment, the following characteristics should be considered from the risk analyses (NORSOK Z-013, 2010):

a) DAEs need to be identified and explained. Further, information from QRA concerning major accidents shall also be identified and described. The content for this sort of information can be as: possible consequences of every initial event, variation in consequences and course of events, etc.

b) Assumptions and scope shall be documented as a basis to create performance requirements for emergency preparedness process and for defining range of operations.

c) Recommendations from the QRA shall be included while formalizing performance requirements for the emergency preparedness process.

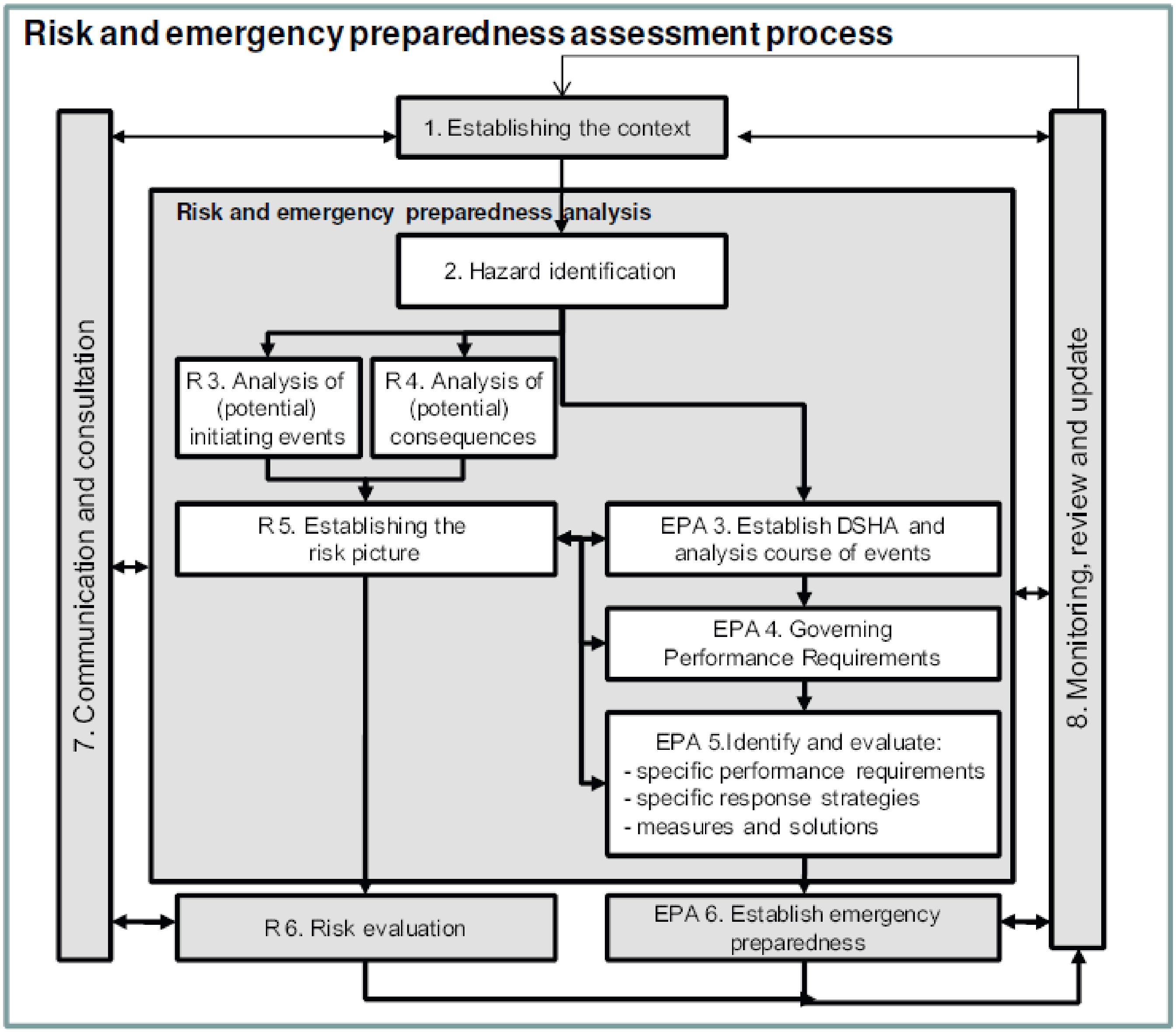


Figure 10: The process of risk and emergency preparedness assessment (NORSOK Z-013, 2010)

2.6.3. DSHAs according to the Norwegian standards

It is essential to mention here that the PSA regulations are articulated in a functional form. This means that the regulations do state what goals the responsible party (e.g. operators) should achieve, but do not explicitly mention how to achieve them. The management regulations of PSA very concretely and in detail explain the concept of ‘party responsible' to ensure safe operations in the NCS (Skjerve et al., 2008). Section 15 of the management regulations states that *“The responsible party shall identify the necessary information to plan and carry out the activities and improve health, safety, and the environment*”. Referring it to the DSHAs, it means that the responsible/ concerned party (usually the operator) shall perform quantitative risk analysis related to all kind of activities including the identification of DSHAs. According to the regulations, it also means that it is up to the operators to govern the actual count and content of the DSHAs (Basharat, 2012).

The description of an individual DSHA shall be comprised of at least the following (NORSOK Z-013, 2010):

a) Relevant scenarios to demonstrate the variability of each individual DSHA.

b) Situations with respect to duration and extent.

c) Both, number of people and environmental resources /assets that can be threatened or harmed.

d) Both, operational and environmental settings that prevail when the DSHAs takes place.

e) Account of establishment of each scenario as well as the escalation potential.

f) All related safety barriers.

NORSOK Z-013 suggests that the selection of each DSHA should at least include: the description of that DSHA, selection criteria of that specific DSHA and the types of events/scenarios that are listed below (NORSOK Z-013, 2010) (Basharat, 2012) :

- Dimensioning accident event (DAE), which is mostly defined based on the dimensioning accidental load (DAL) studies from the QRA. This also covers the major accidental events. Note: Refer to NORSOK Z-013 (2010) for the definitions of DAE and DAL.

- Accidental events that are present in QRA but are not recognized as major accidents. These events should be included only when they pose further challenges to the emergency preparedness.

- Minor accidental events (e.g. acute pollution).

- Events for which emergency preparedness exists according to normal practice.
- Scenarios related to the momentary surge of risk such as drifting objects, man-over-board, hot-work, etc.

Besides the above-mentioned scenarios, DSHAs can also include events which are similar to the accidental events recognized in the QRA but not identified typically as DAE which causes further challenges while developing emergency preparedness procedures (NORSOK Z-013, 2010).

2.6.4.RNNP Project & DSHAs

The project regarding trends in risk levels in the NCS was originated to monitor the variations in risk levels within the petroleum industry. Monitoring risk is crucial as it allows to highlight the negative trends beforehand to respond proactively and successfully to avoid undesirable incidents and lower the overall risk levels (Årstad, Kristensen, & Vinnem, 2010). However, it is equally important to ensure that the reduced risk is not undermining the attention given to sustain the measures in order to stay at that level. For achieving low risk levels, a fundamental recognition of uncertainty, complexity, and a deep understanding of the system dynamics is required. (Årstad, Kristensen, & Vinnem, 2010).

The RNNP project helps to recognize the development of negative trends at an early stage so that government and other stakeholders could ensure appropriate accident prevention procedures (Årstad, Kristensen, & Vinnem, 2010). The RNNP project covers the PSA regulations for safety and the working environment and also includes major accidents, occupational accidents and other work-related accidents. However the main focus of the RNNP projects is dedicated to major accidents and risks to human life (Årstad, Kristensen, & Vinnem, 2010).

To provide a broad set of DSHAs that can be used in the Norwegian petroleum industry, a company independent set of DSHAs by RNNP was introduced (Skjerve et al., 2008). The fundamental purpose of this set was to offer a basis for scheming data of incidents/accidents occurring on the NCS (Basharat, 2012). DSHAs developed by RNNP mostly comprises of events that are similar to the DSHAs used by the offshore companies. This makes the RNNP established

DSHAs as a standard set of DSHAs that is easy implement in the offshore industry (Basharat, 2012). It is interesting to mention that both RNNP and the offshore hydrocarbon companies employ DSHAs differently. Through RNNP, the DSHAs are used as reactive indicators to ensure the desired level of safety in the industry. The number of events/accidents in relevance to every DSHA are informed to the authorities. The authorities then analyze statistics for each DSHA and bring the outcomes into for assessing the safety levels in the NCS (Skjerve et al., 2008). On the other side, in addition to using DSHAs as risk indicators, the companies use the established set of DSHA as a way to strengthen the emergency preparedness procedures. Different companies adapt RNNP set of DSHAs distinctively, according to the work performed on the specific installations (Skjerve et al., 2008).

The RNNP set of DSHA is created on the following two basic principles (Skjerve et al., 2008):

1) The DSHAs are framed to cover all the identified events that can trigger accidents leading to loss of lives. Occupational accidents/incidents come down on the priority list are also covered. Therefore, all chain of events that potentially can cause loss of lives will usually have one or more of the DSHAs. Safety barriers hold immense significance here. The degree to which a DSHA will cause severe consequences in terms of fatalities will vastly depend on the barriers that influence the event chain.

2) Availability and quality of applicable data for each DSHA is very important and hence must be available. The DSHAs established for the RNNP project comprises of major accidents indicators, occupational accidents indicators and also includes indicators for temporary risk surge.

Table 2 and Table 3 below are taken from the RNNP report (2016). Table 2 shows the list of identified DSHAs in relevance for the occurrence of major accidents. Table 3 shows DSHAs from the RNNP that are significant but are not dimensioned for the occurrence of major accidents in NCS. Table 4 shows the DSHAs not mentioned in the RNNP report but are generally employed in the offshore industry.

DSHAs for Major Accidents
1. Un-ignited hydrocarbon leaks
2. Ignited hydrocarbon leaks
3. Well incidents/blowouts/ loss of well control
4. Fire/explosion in other areas, combustible liquids
5. Ship on a collision course
6. Drifting object
7. Collision with field-related vessel/installation/shuttle tanker
8. Structural damage to platform/stability/anchoring/ positioning failure.
9. Leaking from subsea production facilities, pipelines, and risers.
10. Damage to subsea production, pipelines, and risers.
11. Evacuation
12. Helicopter crash/emergency landing on/near the installation

Table 2: List of identified DSHAs for major accidents in RNNP (NORWAY(PSA), 2016)

DSHAs for other accidents
1.Man overboard
2. Personal injury
3. Work-related illness
4. Full loss of power
5. Diving accident
6. H2S emission
7. Crane and lifting operations
8. Falling objects

Table 3: DSHAs for accidents other than major accidents. (NORWAY(PSA), 2016)

DSHA other than RNNP
1.Acute pollution.
2.Production Halt
3.Transport system halt
4. Lost control of the radioactive source.
5. Control room out of service.

Table 4: DSHA other than from RNNP (Wilhelmsen, 2011).

3. Reviewing link between Risk and Safety Barriers

3.1. Introduction

The bow-tie diagram (see figure 6) mentioned earlier in Chapter 2 helps to illustrate how a critical initiating event may have various precursors and /or various consequences. The event sequence propagating from left to right as shown in the figure 6 suggests there are at least three different ways of achieving safety for the operations carried out in the offshore industry (Hollnagel, 2008). The 1st option is to prevent the critical initiating event from occurring. This can be achieved by hindering initiating factors from having an such an influence that could transform the critical event from a potential threat into a reality. The 2nd way is to eradicate the hazard, either directly or by substitution, depending on the accident scenario. The 3rd option is to mitigate consequences of the critical event or develop protection against them if they take place (Hollnagel, 2008). It is thought-provoking to see that the first two options (prevention and elimination) attempt to maintain functionality of the system, whereas the third option (protection) might not necessarily do that. In most of the cases, protection while ensuring safety may cause the system to shut down or reduce systems functionality until the conditions have returned to normal (Hollnagel, 2008).

Prevention and protection as mentioned above, are the commonly used safety methods in the offshore industry. Both these methods employ safety barriers in one way or another (Hollnagel, 2008). It needs to be emphasized that despite being so pertinent to safety, barriers often represent a reactive approach which is insufficient on its own to guarantee complete safety in the offshore settings. Safety cannot be guaranteed only by reacting to a hazard or an accident. It is equally important to look ahead, identify potential risks, and then devise barriers to counter them (Hollnagel, 2008). In order to design and establish safety barriers in a way that ensures safety both in a proactive and reactive manner risk and barriers need to be linked both conceptually and rationally (Hollnagel, 2008).

PSA has identified several shortfalls from the operating companies while implementing regulatory requirements for barrier management. Among the several shortfalls, one common issue is that there is a limited connection between risk management and in the design and establishment of safety barriers (J.-E. Vinnem, 2014a). Acknowledging the importance of this issue, Chapter 3 was included in this report to explain how and to what extent risk assessments and QRA studies are vital for an effective barrier analysis in the offshore industry. Chapter 3 is divided into two major sections. 1st section explains the prevailing concept of risk in the NCS. Section 1 includes: brief description of the risk assessment process, how to establish a risk picture and the worth of uncertainty assessments carried out in the offshore industry. Section 2 illustrates how the two processes of risk and barrier management overlap and how vital inputs from risk assessments and risk picture are utilized in the development of barrier functions, performance requirements and an overall barrier strategy.

3.2. Concept of Risk in the NCS

According to the risk management memorandum published by PSA in 2018, understanding the risk concept is crucial to manage, prevent and minimize the risk exposure. The risk concept in the offshore industry not only refers to consequences of the individual activities on the facility but encompasses consequences of the overall enterprise. Due to complexity of the operations carried out in the offshore industry, the level of risk related to an explicit activity is not limited to that activity alone. Rather, it influences the devised strategy, influencing factors and the entire context in which those and other similar activities are planned (PSA, 2018).

Uncertainty is a crucial component of the risk concept. Norwegian regulatory requirements emphasize that the impact of associated uncertainties must be considered while selecting suitable solutions and measures (PSA, 2018). Uncertainty in the offshore industry can be of several forms and is linked to the incidents that may take place in the future. Frequency of occurrence, causal factors, consequences and the impact of those incidents are all subject to uncertainty (PSA, 2018). The Management regulations suggest use of important measures associated to risk and uncertainty such as quantitative risk analyses to identify major hazard risks and further balancing the results to formulate a comprehensible risk picture (Skogdalen & Vinnem, 2011). Section 17 of the management regulations addresses the uncertainty factor and is dedicated to risk analysis and emergency preparedness assessments carried out in the offshore industry. According to the management regulations (section 17), the responsible authority should conduct risk assessment and an inclusive risk picture should be established which can further support decision making. The performed risk analyses should also be able out to identify and assess the contributing factors towards. i.e. major accident risk and environmental risk. Section 18 states that the operator shall carry out analyses that can ensure a comprehensive working environment and provide desired support for the technical, operational and organizational solutions, such that safety is ensured and measures to enhance the risk are addressed for: (i) mistakes that can result in hazards and accident situations, (ii) exposure and physical or physiological effects, are addressed. (Skogdalen & Vinnem, 2011).

3.2.1. Risk Assessments

In the offshore industry, focus of risk assessment is associated to safety of the installation and the crew, prevention of environmental damage, production regularity and other safety aspects (Brandsæter, 2002). Initially, the role of risk assessment was to document the risk level to be in line with the acceptance criteria formulated by the authorities. However, due to its imminence, the central role of risk assessment has extended and is now to support decisions related to design, construction, operation and maintenance of the offshore installations (Brandsæter, 2002). Providing decision support refers to providing all the concerned stakeholders awareness of the inherent risks and hazards pertaining to the activities under emphasis, and further providing the basis to plan and prioritize over the risk reducing measures (Funnemark and Engebø 2005).

The process of risk assessment includes risk identification, risk analysis and risk evaluation (PSA, 2018). A risk assessment performed in the offshore industry will include assessment of risk to the people, risk to environment, risk to material assets, failure frequency of safety functions and impairment of barrier functions and its respective elements (NORSOK Z-013, 2010). Depending on context of the risk management process and the methods being employed (qualitative or quantitative), the structure of the assessment differs considerably. Moreover, the quality of available data and the regulations for specified applications also dimension the type of risk assessment that should be carried out (Derempouka, 2017). There are certain circumstances where a total quantification of risk is considered more viable. In these cases, a certain level of caution must be placed as of not attributing a level of accuracy and precision more than it derives from the analysis (Derempouka, 2017).

ISO 31000 and NORSOK Z-013 are the two guiding documents for performing thorough risk assessments in the offshore industry (Andersen & Mostue, 2012). Anderson & Mostue (2012) conducted surveys and interviews from experienced employees in the NCS and concluded that, FMEA/FMECA, FTA, ETA, HAZOP, HAZID and JSA are the commonly used risk analysis methods, all of which are described in the NORSKOK Z-013 (2010). As discussed in chapter 3, For hazard identification the risk analysis process uses various approaches. However, a widely used approach for failure identification is the FMECA. The objective of this method is to identify all the failure modes, their causes, and effects for each of the barrier elements of a safety barrier (Torbergsen et al., 2012). Most risk analysis methods are carried out in the design and modification phase of the projects and hold less impetus in the daily operations. The reason for not using these formal methods during operations is their inadequate potential to give valuable safety information for operational procedures (Andersen & Mostue, 2012). Rather, in the operational phase other approaches are used to generate knowledge for decision making on risk. Examples of these approaches are formal procedures, plant specific knowledge and informal processes without use of systematic risk assessment methods (Andersen & Mostue, 2012).

In traditional risk assessments performed in the NCS, technical safety functions, technical design, layout and construction of the installation are studied in detail. Operational factors such as organizational design, work processes and actual work execution in daily operation are poorly reflected upon. (Andersen & Mostue, 2012).

3.2.2. Risk Picture

QRA is the commonly used term for the risk assessments performed in offshore operations (Madsen, 2013).QRA helps to determine future risks in a given context. QRA provides a descriptive risk picture with necessary sensitivity calculations and evaluation of uncertainty which provides information about initiating events, factors that lead to those events, possible consequences and preventative actions to avoid serious consequences (Aven, 2015). A better way to formulate a risk picture which is in accordance to the Norwegian regulations is explained by DNV GL (2014). It mentions to divide the risk into two levels which is, basic risk level and variable risk level. The basic risk level is governed by a specific activity and signifies inherent risks that are managed during design phase of the project and are associated to the nature of the business (e.g. production of hydrocarbons, offshore environment). In this several safety studies are carried out such as, FMEA and HAZOP etc. to ensure that the design contains necessary safety functions. Variable risk levels represent risks related to the technical operational and organizational conditions, activity levels and the impact factors etc. that affect the risk levels DNV GL (2014). This is shown in the figure 11 below.

Figure 11: Description of the risk picture (DNV GL, 2014)

3.2.3. Uncertainty Assessments

Uncertainty is the event with either positive or negative impact on the future developments. (Perminova, Gustafsson, & Wikström, 2008). In the context of risk analysis, uncertainty is characterized into two different types. The first type is uncertainty due to randomness. The uncertainty due to randomness occurs because of systems inherent variability. The second type of uncertainty is due to limited understanding and weak knowledge for the phenomena or the observable quantities (Aven & Zio, 2011).

Uncertainty is a fundamental and integral element of risk analysis (Aven & Zio, 2011). The objective of risk and uncertainty analysis is to forecast future performance of uncertain quantities or events which are unknown at the time of analysis (Madsen, 2013). Uncertainty assessments performed in the offshore industry are based on technical feasibility (facility design, engineering judgment, development review) and economic measures (expected NPV, IRR and cost benefit analysis) (Supriyadi, 2013).

Sensitivity analysis is used to verify variations of final output relative to changes in the systems input. Hence it is essential to configure uncertainty underlying the input parameters and assessments on which the analysis is based (Supriyadi, 2013). As specified in Section 17 of the Management Regulations, sensitivity and uncertainty assessments must be carried out as an integral component of risk analysis. This is to provide analysts a firm basis for understanding strengths, weaknesses, and limitations of the system, and to identify all significant assumptions related to final outcome of the analysis (J.-E. Vinnem, 2014a). Sensitivity and uncertainty must be assessed and employed in the work of risk handling, whether it involves communicating the need for risk-reducing measures in barrier strategies or specifying the performance requirements (J.-E. Vinnem, 2014a).

The current approach and framework for uncertainty assessment in the offshore industry still lacks a firm basis. The commonly used tool to express uncertainties in risk analysis are subjective probabilities which alone are inadequate to work with. This is because risk and uncertainties are not incorporated representatively, and it possesses certain level of arbitrariness (Aven & Zio, 2011). Researchers find this framework for assessing risk and uncertainties to be very narrow and recommend to look beyond the probabilistic values (Aven & Zio, 2011). Several scientific papers have been written to address the need to see beyond the probabilistic values. The 2018 memorandum, "*Integrated and unified risk management in the petroleum industry*" issued by PSA also suggests the operating companies in NCS to concentrate systematically on this problem and seeking out potential surprises rather than completely relying of probabilistic assessments. The concept of risk is more than the assigned subjective probabilities by the analysts. The knowledge on which the probabilities are assigned could be weak or based on wrong and deviated assumptions, which can result in poor prediction of the observable quantities. If uncertainty is not properly treated in risk assessment, the risk assessment tool fails to perform as intended (Aven & Zio, 2011).

3.3. Integration of Risk and Barrier Management process

Figure 12: Barrier management illustrated as an integral part of risk management and corporate governance (PSA, 2017)

Figure 12 illustrates how barrier management is an integral part of the enterprise risk management process which in turn forms an integrated component of its entire management system. As a result, management standards such as ISO:9000 and ISO:31000 can also serve as the basis to establish the model for barrier management as shown in figure 13 (PSA, 2017).

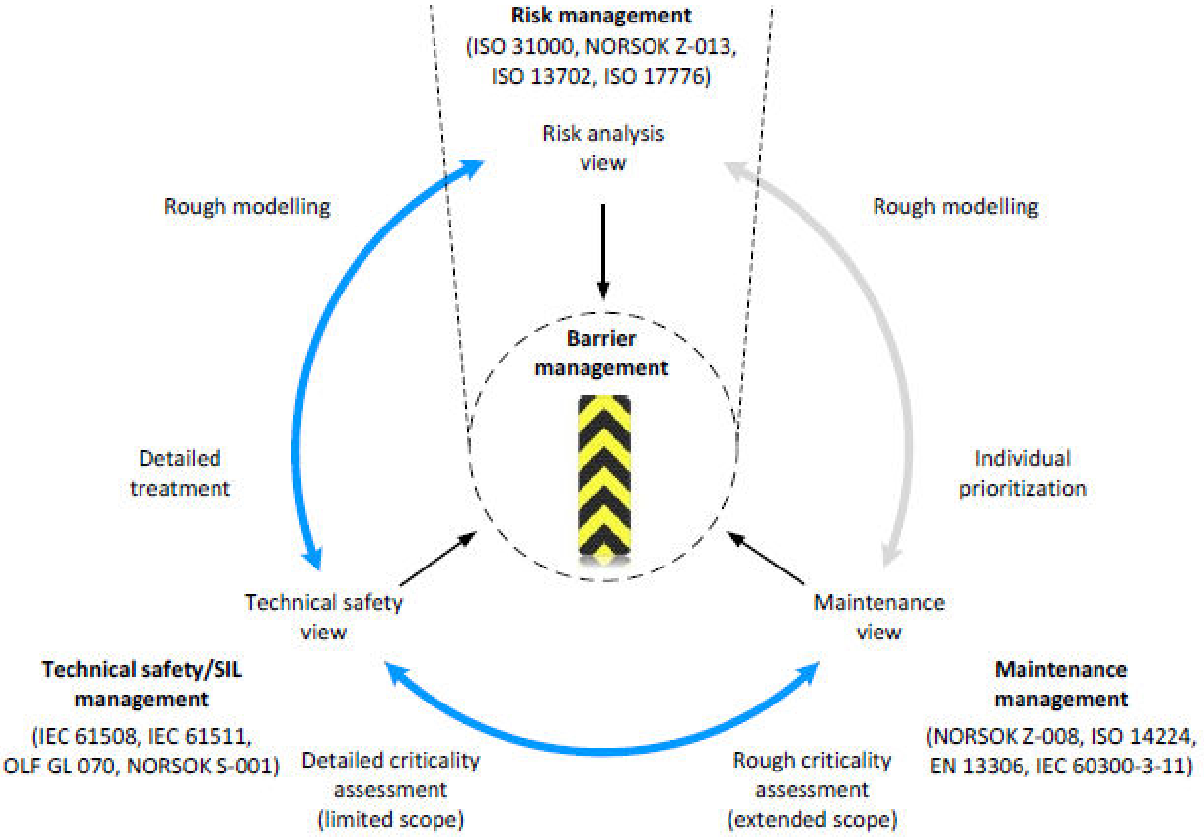


Figure 13: Key management process and related stakeholders in barrier management (Øien et al., 2015)

The risk management process which comprises of several critical aspects like hazard identification and formation of the entire risk picture, has an extensive scope in covering all the hazards and risks for offshore facilities (Øien et al., 2015). Safety barriers are established when the risk management process detects failure, hazard and accident situations for which an added source of protection is necessary (PSA, 2017).

The barrier management process begins with establishing the context and setting the scope for functionality of the safety barriers (PSA, 2017). The primary purpose of barrier management is to establish and maintain barriers to manage the risks faced (PSA, 2017). As explained by Hauge & Øien (2016) and mentioned earlier in this master thesis, barrier management can be divided into two phases which are design phase and operations phase. In the design phases safety barriers are formulated and established. The focus is on identifying and designing safety barriers to ensure that the required risk reduction is attained during operations. During the operations phase the status of the safety barriers is maintained and followed-up. This is done to verify that the barriers are available at all time, and to implement alternative measures if barriers are impaired. This implies that it is crucial in the design phase to have a complete understanding of the installation explicit risk picture so that the necessary safety barriers could be specified. If associated risks are not assessed and neglected, the result can be that inadequate safety barriers are identified and implemented in the design phase of the project (Hauge & Øien, 2016).

3.3.1. Risk Assessment a valuable input for safety barriers

Risk assessment performed with reference to the barrier management process involves four main tasks which are: hazard identification, barrier analysis, risk analysis, and risk evaluation. These processes must be integrated and iterated throughout the assessment (Johansen & Rausand, 2015). The basic risk models devised through the risk assessments are used for both qualitative and quantitative analyses of risk and the established safety barriers (Aven et al., 2006). From the risk assessments, barrier functions that are necessary to prevent or mitigate the hazards are identified. A barrier function is realized during the risk assessments and then specified with respect to the position on the fault tree or an event tree (Guldenmund et al., 2006). It is essential to define concrete role of a barrier function in the accident scenario instead of just handling them as an aid to lower down the overall risk (Johansen & Rausand, 2015).

After identification of the barrier functions, work related to performance requirements (PRs) begins (Gustafson, 2014). The results are subsequently compared to the decision criteria which can be based on enterprise goals and internal/external context. This decision criteria can also be obtained from the standards and regulations. To optimize the performance requirements they must be updated at regular intervals (Gustafson, 2014). It is impossible to verify that all future incidents have been identified, or that failure/hazards and accident scenarios will develop as planned in the risk assessments (PSA, 2017). There may be situations where unpredicted scenarios may arise. The risk picture, assumptions, and condition of technical elements vary as operations proceed, triggering a need for new or altered risk-reducing measures (PSA, 2017). In these situations, safety barriers planned in the design phase may become inadequate and hence it is important to iterate them regularly and take the uncertainty and other relevant factors into account (Øien et al., 2015).

3.3.2. Risk Picture vital baseline for Barrier Strategy

Barrier strategy is a scheme to establish safety barriers in an individual facility or a plant. According to PSA (2011), a barrier strategy should always be based on risk analysis and hazard identification during the initial risk assessments. Hence, detailed and updated risk assessments are very important for a strong and valid barrier strategy. Barrier strategy describes a logical relationship between the unique risk picture and the selected barriers (PSA, 2017). Safety barriers for individual areas of the facility and for different plant operations are designed keeping an explicit risk picture as its basis (PSA, 2017). The risk picture is necessary to determine the required barrier functions and to verify that the barrier elements have the required properties (J.-E. Vinnem, 2014a). It is important that risk picture is established, presented and evaluated in terms of what it practically will be used for (Gustafson, 2014).

Barrier strategy for an individual facility is based on the unique characteristics of that facility. A suitable division of the facility areas hence becomes imperative. Brief description of different facility areas is incorporated in the barrier strategy document (Andersen & Mostue, 2012). Therefore, the devised barrier strategy is area specific, addressing the explicit needs (barriers against hazards/accidents) in each area of the facility. The area division methodology in the barrier strategy document is based on a preestablished risk picture. By keeping the risk picture as its basis, area risk charts are designed for each facility area (Andersen & Mostue, 2012). The area risk charts signify important premises and limitations for each plant area, and are aimed at communicating results from the risk analyses (Andersen & Mostue, 2012). Risk levels within a defined area should not vary a lot while establishing risk charts. If risk levels and the barrier elements significantly vary within an area, they should be further divided into various sub-areas in the barrier strategy document (Hauge & Øien, 2016).

The next step is to treat the risk according to the defined areas of the facility. According to Gustafson (2014), risk treatment is the phase in which more effective barriers or risk reducing measures are evaluated. If there is no need for it, specific strategies and performance requirements can then be established. The barrier strategy shall provide a common understanding of why a specified barrier has certain set of performance requirements and how can it help to reduce the overall level of risk. The requirements are established for all technical, operational and organizational barrier elements (Gustafson, 2014). Meanwhile, during the process, monitoring and evaluation of the safety barriers is done, and a proper communication channel is maintained throughout the organization. The monitoring and review of the safety barriers is crucial since it also comprises of steps like maintenance and verification of these barriers (Gustafson, 2014). The entire process is iterative and continuously updated and that the status of the barriers is monitored to ensure that conforms to their desired purpose. It is essential that the personnel that effect the risk picture directly or indirectly are thoroughly involved and have a complete understanding of the consequences of their selections. Therefore, the organizational aspect is of same value as the technical aspect and to enable good barrier management, the processes should be implemented in the maintenance program (Gustafson, 2014). Devising barrier management in the maintenance program means that the maintenance activities are connected to the performance requirements from the design phase. The results when testing the barriers shall be associated to the requirements that are set and followed up to assure the status of the barrier. If required, improvements can be suggested, and the maintenance program restructured (Gustafson, 2014).

3.3.3. QRA’s crucial role in development of safety barriers

As discussed by Vinnem (1998), in the NCS, QRA is often employed for the design of new installations as well as for improving the existing platforms. For the latter, since improvements in platform is the main concern hence accuracy and robustness of the QRA become extremely crucial which can have an impact on extensive upgrading developments. On the other hand, new installations have limitations towards size and function, therefore, new installations rely on QRA to direct the desired level of protection required from the potential accident scenarios on the installations. Using risk analysis for these projects can be suitable to reach a profitable development concept (J. E. Vinnem, 1998). In the recent times, authorities are basing their regulations and operators their design on the use of risk analysis to determine the preventive and mitigative systems required, as well as to dimension the loads and requirements. It is therefore critical to recognize what the QRA can be effectively used for and the areas where this approach is not appropriate (Skogdalen & Vinnem, 2012) .

Input from QRA is essential for managing major accidental risk in both the design and operational phases of the barrier management process. QRA can be used to identify main risk drivers for a given activity or an explicit area of the installation (Næss, 2012). The risk in these cases is usually determined based on the probability of barrier functions being fulfilled by the safety barriers, for instance by using a certain set of performance measures. Eventually, these probabilities form the basis of a QRA (Næss, 2012). This makes QRA a key document and base point while striving to manage risk associated to safety barriers (DNV GL, 2014). The enhanced knowledge about existing and non-existing safety barriers, and improved understanding of the PIFs/RIFs are vital outcomes in addition to the quantitative results obtained the QRA studies (Aven et al., 2006).

QRA plays a critical role in design process and dimensioning of the safety barriers, particularly the consequence mitigating and emergency preparedness barriers (NORSOK Z-013, 2010). While conducting QRAs, offshore companies in the NCS define a risk acceptance criterion, which is used and referred to on regular basis in the design of safety barriers. During the feasibility phase of a project, it is necessary to validate that the considered concept alternatives can meet the predefined risk acceptance criteria. This is achieved through delta analyses, where specified conditions are evaluated with reference to the identified risks for standard platform alternatives. Safety personnel involved in the project specify requirements for barriers based on these analyses (Kjellén, 2007). During the operations/execution phase of the project, basic layout and process design are evaluated with respect to the barrier integrity concept developed in the QRA (Kjellén, 2007). The regulations use a joint strategy of inherent safety and safety through barriers. There are regulations to design solutions that eliminate or significantly lower the risk at the source or isolate the hazard from the personnel. Hence, only residual risks are treated through the use of personnel protective equipment or other operational solutions (Kjellén, 2007).

Limitations of QRA studies for safety barriers development

As mentioned earlier, PSA has published several requirements for risk analysis and safety barriers. In their regulations it is stated that QRAs are performed to identify RIFs for major accidents and provide a complete risk picture for further analysis. However, there are some limitations while utilizing QRA as an input to the barrier management. Existing QRAs in the offshore hydrocarbon industry are largely targeting the consequence mitigating barriers and primarily focus on the right side of the bowtie diagrams. Traditional QRAs give very less attention to containment of the causal factors or left side of the bow tie diagram. Hence in certain circumstances, QRAs alone are not enough to analyze the impact of safety measures for avoiding the initiating events (Aven et al., 2006).

It is a challenge to make QRAs operational. QRA cannot be used extensively in the daily work routine since they are to a certain extent static and incomprehensible for daily work activities (Andersen & Mostue, 2012). QRAs are infrequently updated and important changes in the safety functions or technical conditions usually get omitted even if it is crucial for risk management. (Andersen & Mostue, 2012).

Often it is inadequate to exclusively use QRA as the basis to conclude whether certain barrier elements are required or not and while developing specific PRs for individual barrier elements (J.-E. Vinnem, 2014a). The outcomes of risk analysis at times indicate that some barrier elements are not needed, as they do not contribute positively to the quantitative results generated in a traditional QRA. An example could be of the fire protection of certain rooms on the platforms. This should not be interpreted to denote that the rooms do not need to withstand fires, but it refers to the fact that the risk analysis in this case is not a suitable tool to provide input to the applied performance standards (PSs) (J.-E. Vinnem, 2014a).

Another challenge that should be addressed is over emphasis of QRA studies on certain tolerance criteria's and various risk indices (e.g. FAR or AIR values) (J.-E. Vinnem, 2014a). This is very unsuitable for developing safety barriers PRs. It is often argued that improvement in a barrier performance would have very limited effect on overall FAR values. This holds true for certain safety barriers and can be a limitation of QRA studies as the models for escalation or accident sequence development are too coarse. When these models are coarse, the ability to reflect differences in safety barriers performance may get limited. It is hence argued that QRA studies in certain circumstances fail to highlight what is important in order to provide a suitable basis for the effective management of safety barriers and its elements (J.-E. Vinnem, 2014a).

4. Suggested workflow to analyze safety barriers in the offshore industry

4.1. Introduction

So far in this report two objectives have been achieved. The first objective was to present the existing concepts and the current practices of safety barriers prevailing in the NCS. The next objective was to review and illustrate a relationship between risk assessment and safety barriers in such a way that overall barrier functionality could be enhanced. In this section of the report, employing concepts presented in the previous chapters, a structured workflow to analyze safety barriers in the offshore industry is suggested and discussed. Figure 14 as shown below is an illustration of the entire work process to analyze safety barriers in the offshore industry. Each phase in figure 14 acts as an input to the next phase of the workflow and all phases are strongly integrated to each other. Workflow to analyze safety barriers has been divided into four phases that begins with the initial risk assessment phase through which accidental scenarios are classified. Furthermore, safety barriers for the specified accidental scenarios (DSHAs) are established and implemented, and functions of all those barriers are recognized accordingly. After identifying all the barrier functions, next step is to conduct a functional breakdown to identify the technical, operational and organizational barrier elements needed to implement and realize each of the sub-functions till all the individual barrier elements are established and their respective PIFs are identified (Hauge & Øien, 2016). Chapter 4 provides the description and explanation of the four phases for barrier analysis workflow as illustrated in figure 14. The chapter will be divided into four sections, with each section dedicated to the individual phases illustrated in figure 14. The core of the barrier analysis process begins in phase 4, after suitable safety barriers are identified. However, this chapter aims to provide a detailed description beginning from the hazard identification process until individual barrier elements are established and their Performance standards (PSs) developed. This is done in order to improve the decision making while improvising the safety barriers and also provide readers an integrated picture of the overall work procedure followed during establishing safety barriers in the offshore hydrocarbon industry.

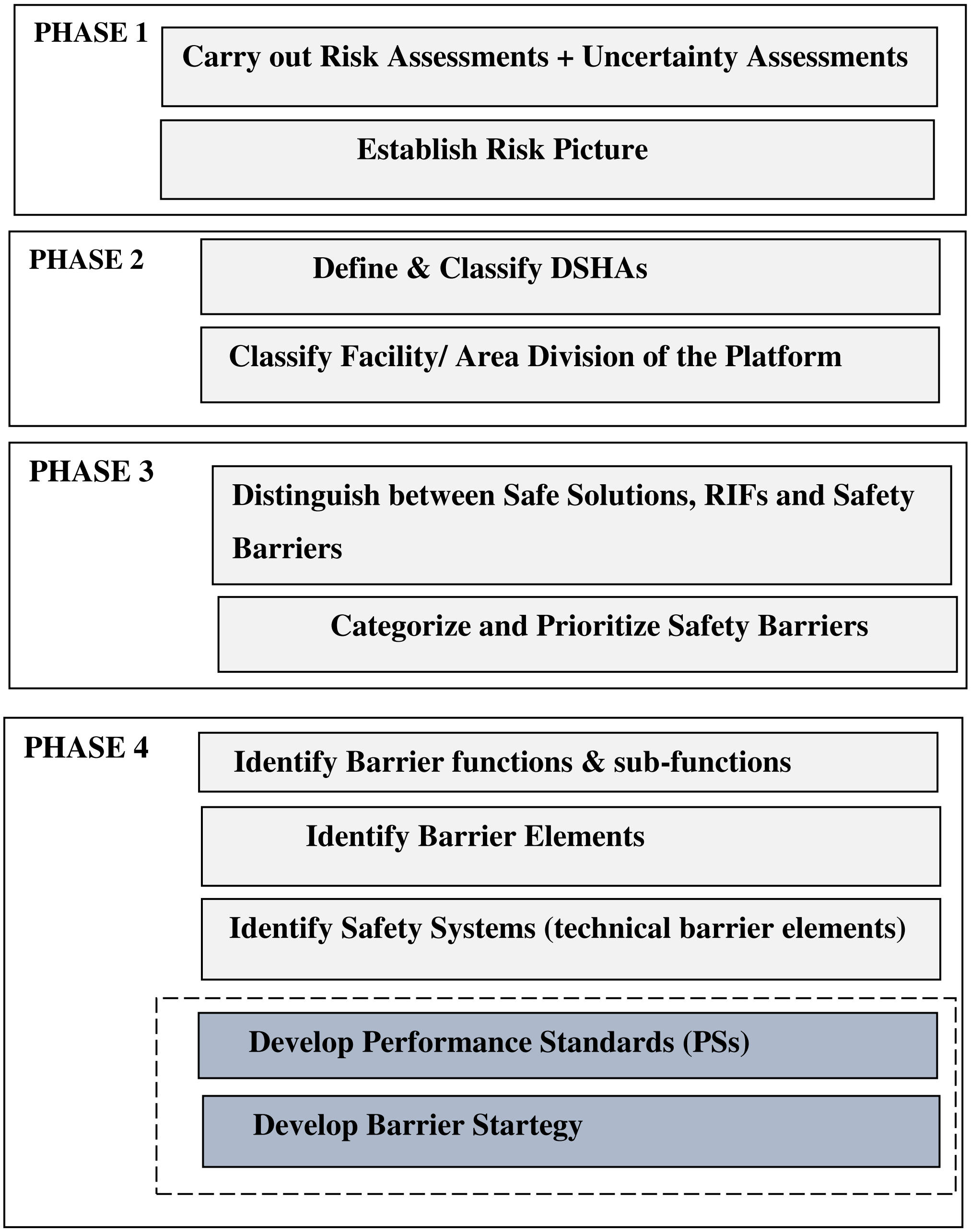


Figure 14: Suggested workflow for barrier analysis

4.2. PHASE 1: Analyzing Risk and Uncertainties

According to NORSOK Z-013 (2010), the risk assessment performed in the offshore industry helps to recognize and classify the potential accidental scenarios. The process of risk assessment includes identification of the initiating events that can cause hazards and accidents. Furthermore, performing causal analysis and consequence modelling of the identified initiating events is also the part of risk assessment process. Scope of the risk assessment performed in the offshore industry includes identification and establishment of; the accidental loads, requirements for barrier functions and its respective elements, operational boundaries, DSHAs, classifying area, system categorization and equipment classification (NORSOK Z-013, 2010). The performed risk assessment facilitates in formulating a comprehensive risk picture, that provides vital and detailed information for the decision makers and relevant users regarding risk and implications of the main results. With reference to safety barriers, the established risk picture offers a clear description of the methodology, risk models, employed tools and justification of their use in the analysis being carried ahead (NORSOK Z-013, 2010). Furthermore, the risk picture provides a comprehensive representation of the risk exposure, main risk contributing factors and list of the assumptions used while identifying the barrier functions. These assumptions and presuppositions should be explicitly documented and categorized in analytical, technical, organizational and operational groups. The risk picture also includes a discussion on the effect of uncertainty and the methodology used for uncertainty assessments (NORSOK Z-013, 2010).

In the offshore industry high level of uncertainty prevails regarding frequency of occurrence of hazardous events and severity of its consequences for the personnel, environment or assets. The uncertainty depicts insufficient information and knowledge available during the risk analysis process and also while establishing the risk picture (J.-E. Vinnem, 2014b). The level of uncertainty will be lowered down as the field development project progresses but there will always be some uncertainty about consequences of the accidental events even after the installation has been put in operation. Hence, to aid decision making, the NORSOK Z–013 standard mentions to use the best possible results and risk levels from risk analysis rather than using the optimistic or pessimistic results (J.-E. Vinnem, 2014b).

4.3. PHASE 2: Platform area division and defining of DSHAs

Phase 2 begins with classification of the platform facility or area division based on the established risk picture in phase 1. As discussed earlier in chapter 2, while defining and documenting are area division in the barrier strategy, the risk levels within a defined area (facility) should not vary significantly. If the risk level varies considerably within an area, the area should be further divided into several sub-areas (Hauge & Øien, 2016). A common practice in the industry is to generalize the number of main areas to avoid intricate barrier management process and to reduce the complexity of the barrier strategy document (Hauge & Øien, 2016). To serve as an example, main areas on an offshore platform are broadly categorized as follows (Hauge & Øien, 2016) :

- Process area
- Riser area
- Utility area
- Living Quarter
- Shafts
- General functions

A traditional way to protect a system against the uncertainty of its failure scenarios is to first recognize the group of failure event sequences leading to worst case accidental scenarios (Aven & Zio, 2011). Moreover, foresee and estimate the consequences of those accidental scenarios (DSHAs) and establish suitable safety barriers for preventing occurrence of such accidental scenarios or reducing their associated consequences. The underlying principle has been that if a system is designed to withstand all the worst case accidental scenarios, then it is certainly protected against all the other type of possible accidents that can take place on an offshore platform (Aven & Zio, 2011). Therefore, protection of the offshore systems is ensured by establishing safety barriers for the pre-defined DSHAs. It is very important to understand that safety barriers are supplement to normal operations, and they only come into play when an abnormal situation with some type of nonconformity, failure or malfunction have already occurred (Hauge & Øien, 2016). Hence, safety barriers are only required after loss of control; first to regain control, then to prevent further propagation, and finally to reduce the consequences. The phase after losing control will often correspond to the DSHAs (Hauge & Øien, 2016). Emphasis while selecting the safety barriers is on those set of DSHAs which are highly prioritized by risk assessments and pose biggest threat to overall safety of the system. This shows how important it is to get affiliated to the concept of DSHAs while analyzing safety barriers. There is a strong link between the major accidents identified in the QRA and the DSHAs identified during the Emergency Preparedness Plan (EPP). Since EPP is usually known amongst the personnel onboard, the DSHA numbers and names from EPP should preferably be used in the barrier strategy. These major DSHAs, which are part of the QRA are reviewed at various stages throughout the safety barrier design phases (Hauge & Øien, 2016).

4.4. PHASE 3: Identify and categorize Safety Barriers

Before moving into core of the barrier analysis process, it is necessary to list all the safety barriers of a system. When listing safety barriers, it is extremely important to use a structured approach so that all the relevant safety barriers and their defined roles are known. As discussed earlier, this can only be possible if all relevant DSHAs are identified (Hauge & Øien, 2016). Moreover, to reduce complexity of the safety systems, barriers are only designed for the DSHAs with extreme consequences and not for all kinds of hazards that can take place on an offshore platforms (Hauge & Øien, 2016)(Kjellén, 2007).

While designing and establishing safety barriers it is crucial to differentiate between safety barriers and other types of measures that are employed to reduce the risk levels, such as inherent safe designs or safe operations (Hauge & Øien, 2016). An important concept that is often misunderstood is how to differentiate between normal operations measures /safe solutions, safety barriers and other risk influencing factors (RIFs). Some experts contemplate normal process control measures as safety barriers. This is not correct since barriers only come into action after certain deviation from normal process has taken place (Kjellén, 2007). Similarly, safety measures like maintenance, training/ audits etc. which can lower possibility of an error or a failure to occur are also not barriers as they do not have any direct influence on the accident sequence (Hauge & Øien, 2016). Safety barriers should only be considered as explicit safety measures having a direct impact on an event sequence leading to an undesired event or accident (Næss, 2012). In order to clearly illustrate the difference between normal operations, RIFs and safety barriers, a comparison between them has been provided in the next section.

4.4.1. Comparison between safety barriers, normal operations and RIFs

Normal Operations and Safety Barriers

A normal state is a phase in which the system functions in accordance to the design specifications without significant process hitches or direct intrusions into the processing plant (Aven et al., 2006).

Hauge & Øien (2016) have concluded that the following set of points can be considered while describing a system operating at normal conditions:

- Operations, maintenance and monitoring is conducted within the design envelope.
- Keeping overview, logging and control of procedures
- Scheduled reporting of safety critical failures and non-conformities.
- Management of non-conformities.
- Realizing the need for modifications and changes.

The Norwegian regulations have distinguished between normal operations and safety barriers. According to the management regulations of PSA, normal operations are solutions that are optimal for avoiding or getting into failure and dangerous conditions On the contrary, Section 5 of the management regulations describes safety barriers as measures established to prevent/avoid failure and hazard situations emerging into incidents and damage, loss and disruption (PSA, 2017). Figure 15 below shows how normal operations are distinguished from safe solutions. It is evident from figure 15 that safe solutions adapted during normal operations are measures that are employed before the accident event sequence is triggered. On the other hand, safety barriers operate after the conditions deviate from normal operations and the accident sequence is already triggered.

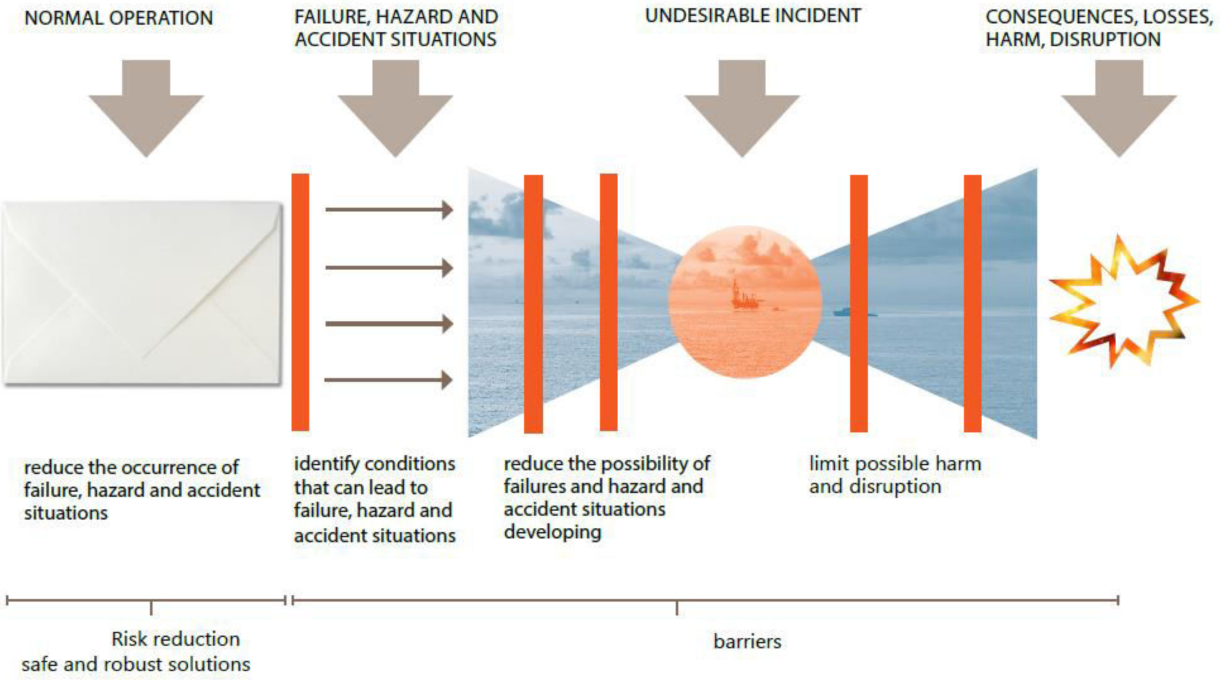


Figure 15: Normal operations and safety barriers (PSA, 2017)

RIFs/PIFs and Safety Barriers

A Risk Influencing Factor (RIF) can be defined as, "*an aspect (event/condition) of a system or an activity that effects the risk level of that system or that activity*" (Øien, 2001, p.130). RIFs are identified and created based on a sensitivity analysis. It is important to integrate the effect of process specified conditions of operational, organizational and technical RIFs on the occurrences of the initiating events and the barrier performance (Aven et al., 2006).

Performance influencing factors (PIFs) are set of conditions that are vital for barrier functions and barrier elements to perform as required (PSA, 2013). PIFs are thought to be a set of factors /conditions that have an impact on the performance of both technical systems and the involved personnel (Hauge & Øien, 2016). With reference to safety barriers, the PIFs can also be referred to as RIFs (Johansen & Rausand, 2015). PSA while carrying out studies for barrier analysis has not specifically drawn a line between PIFs and RIFs which also seems reasonable since going into depth with these details will only make barrier analysis more complex and difficult to comprehend. Hence in this report both PIFs and RIFs should be considered as serving a similar purpose.

The key difference between safety barriers and RIFs/PIFs is that excluding barrier element of a safety, the barrier function cannot be accomplished. On the contrary, if a PIF is missed the barrier function may still be realized, but its performance is reduced (Johansen & Rausand, 2015). An example here can help to understand the difference between barrier (elements/functions/systems) and PIFs/RIFs. Assume an inspection test to detect leakage as a basis for isolation of leaking segment signifies a barrier (sub)function. On the other side, a proof test of a detection device is a PIF since it verifies whether the barrier function is achieved or not (Johansen & Rausand, 2015). Hence it can be deducted that PIFs/RIFs have only an indirect influence on the accident event chain as compared to safety barrier which are directly associated to the accident scenarios.

4.4.2. Categorization and prioritization of Safety Barriers

The identified safety barriers can further be categorized and prioritized for an efficient barrier analysis. In NCS, safety barriers can be categorized in two ways. The first is influence of safety barriers on the accident sequence and secondly genre of those safety barriers. This categorization of barriers has been discussed in Chapter 2 and will not be repeated in this section.

While prioritizing safety barriers several aspects need to be taken care of. For instance, proactive barriers need more attention than the reactive safety barriers. This is because proactive safety barriers can stop a chain of events from developing in the initial phase (PSA, 2010). Furthermore, proactive barriers get very less attention during the QRA studies so additional emphasis is required to establish them. Similarly, passive barrier elements are prioritized over the active barrier elements. Since, passive barrier elements are more independent and do not require much human interaction, so they are above the priority list.

Moving on, after all the relevant operational conditions have been defined and required safety barriers identified, listing of barrier functions and sub-functions is done which is core of the barrier analysis process and is described in phase 4 of the suggested work procedure.

4.5. PHASE 4: Core of Barrier Analysis

Phase 4 of the suggested work procedure presents core of the barrier analysis process. The process begins after the safety barriers have been identified and categorized. The core of the barrier analysis process can be listed as follows:

1. Identification of barrier functions and barrier sub-functions.
2. Recognize the safety systems (e.g. technical barrier elements)
3. Identify the barrier elements
4. Establish performance requirements.

It is very critical to document all the findings, including assumptions and delimitations that have been encountered. Recommendations and suggestions that need further follow-up, with regards to redesigning or to update planning, operating, or maintenance procedures need to be adequately emphasized. Recommendations and suggestions for improvements should always be assigned to concerned persons or departments (Torbergsen et al., 2012).

4.5.1. Barrier Functions

According to section 5 of the management regulations, function of the safety barriers must be defined and realized. In the offshore industry, a common practice is to describe safety barriers in terms of the function they perform. A suitable example can be of a flare system that is established in order to perform the function of relieving the process pressure (Størseth, Hauge, & Tinmannsvik, 2014). Every barrier function is established to avoid or mitigate the consequences of a failure or a hazardous event (DNV GL, 2014). A simple way to define barrier function is through recognizing two basic facts about a safety barrier, which is the purpose and role of a safety barrier (DNV GL, 2014). An example here can be about a drilling fluid which is used to maintain appropriate pressure and prevent well kicks. Preventing well kick is the purpose of the barrier. It achieves this by exerting hydrostatic pressure and that is the role of this specific safety barrier (DNV GL, 2014). Individual barrier functions can be further divided into several barrier sub-functions, for example to detect, verify, and relieve high pressure (DNV GL, 2014). A barrier sub-function cannot accomplish the barrier function by itself, but is an essential component of the barrier function. (Johansen & Rausand, 2015). If one or several of the barrier sub-functions fail, the barrier function can be weakened or at worst totally lost. From the example, it may be useless to close the well if the kick is detected too late (DNV GL, 2014).

Barrier functions are organized at several levels. The division of barrier functions and sub functions is carried out until the barrier function is broken down into a simplest barrier element (Hauge & Øien, 2016).

According to the PSA requirements, the identified barrier functions must be applicable for each area of the facility. For the definition of barrier functions and areas, the following are the main objectives (J.-E. Vinnem, 2014a):

- Be very specific while using the wording as it expresses a relevant function.
- Cover all pertinent hazards according to the regulations including the hazards related to the major accidents.
- Barrier functions and number of areas should be kept as low as possible.

It is very important to model the impact of barrier functions on the accident scenarios (e.g. reliability modelling). Several models are available to be used in the industry. However, preference should be given to the type of systems under investigation and the quality of data that is available (Torbergsen et al., 2012). For better illustration of certain safety barriers (e.g. well barriers), barrier block diagrams can be used. Barrier block diagrams are easily converted to event trees, and fault trees can be later employed to model all the failure pathways (Duijm, 2009). A fault tree is a graphical modelling technique to represent all the possible combinations of failure events that may cause a system to fail. The fault tree is easy to develop from the well barrier diagrams (Torbergsen et al., 2012). Bowtie diagrams are also suitable to obtain an outline of the barriers and their influence in the accident scenario. While using bowtie diagrams it is needed to ensure that they are being used as a basis for quantitative analysis and requirement specification to maintain the distinction between barrier functions, systems, and elements (Johansen & Rausand, 2015).

4.5.2. Identify safety systems

It is essential to identify safety systems while doing the breakdown of barrier functions and sub-functions into barrier elements. As defined previously, safety systems are physical measures that reduce likelihood of hazards and accidents. Hence, identification of safety systems will generally aid the technical barrier elements only. When the barrier (sub)functions are carried out by technical safety systems, they are referred to as safety functions. Similarly, if the sub-functions are executed by safety instrumented systems (SIS) they are named safety instrumented functions (SIFs) (Hauge & Øien, 2016). Technical systems can also be further categorized into SIS, safety systems without integrated logic (e.g. pure mechanical devices), and external risk reduction facilities (e.g. evacuation means). A SIS consists of input items (e.g. detectors), one or more logic solvers, and actuating items (e.g. valves). This is an active barrier and can be contrasted with passive barriers that do not require any action to perform their function, such as a fire wall (Hauge & Øien, 2016). The standard IEC 61508 (2010) is the guiding document for these safety systems and provides special requirements for SIFs. According to IEC61508 (2010), each SIF should be allocated a safety integrity level (SIL), which is calculated by the average probability of failure on demand (PFD_{avg}) for low demand systems and deterministic requirements are given for the treatment of systematic faults. It can be quite complex to define requirements for operational and organizational elements, but a task analysis can provide relevant assistance for this (DNV, 2014).

4.5.3. Barrier Elements

The barrier function is performed and maintained by its barrier elements. A barrier function can include several barrier elements. The barrier elements are established to enable safety barriers perform as anticipated (Størseth, Hauge, & Tinmannsvik, 2014). Barrier elements are classified as technical, operational and organizational elements and will be individually described in this section (PSA, 2017). Operational barrier element is the task accomplished by personnel which realizes one or several barrier functions. On the other hand, organizational barrier elements are the personnel responsible for or directly involved in realizing one or various barrier functions. Hollnagel (2006) also describes the concept of organizational barrier elements and concludes that an organizational element cannot be a barrier element itself. Barriers are procedures that are carried out by people working in the organization, therefore only the tasks should be classified as operational barriers elements. Due to a strong overlap between the operational and organizational barriers elements, operators in the industry consider it futile to distinguish between both these elements and treat the organizational barrier elements as a performance requirement for the operational barrier elements (Gustafson, 2014). However, PSA in the barrier memorandum 2017 have defined them separately and hence this master thesis will also keep the distinction between these two barrier elements.

One key aspect while formulating barrier elements is that reference to standards is crucial. Majority of barrier elements will be essential if for instance ISO13702 is held valid. Hence, it will be wrong to infer that decisions about barrier elements are only dependent on barrier management in the design phase. The application of standards (e.g. ISO or NORSOK) and company documents may suggest that the most of the barrier elements have to be provided for, and that PRs may also partially come from these sources (J.-E. Vinnem, 2014a).

Technical Elements

Technical barrier elements are *"equipment and systems involved in realization of a barrier function*" (PSA 2017, p.9). Technical barrier elements can also be classified into two further categories (DNV GL, 2014). The first category is of passive barrier elements. Passive barrier elements are not dependent on operational control to achieve its function in accident scenarios. The second category is of active barrier elements. These elements need to be activated by the operators or by a technical control system (or a combination of both). A fire and explosion wall is an example of a passive barrier. A sprinkler system is an example of an active barrier. Ideally the technical barriers elements should be more robust by minimizing or excluding the dependence on the operators (Kjellén, 2007). This is the reason why passive barrier elements are prioritized more over the active barrier elements.

Operational Elements

As discussed above, some barrier functions when triggered are automatically realized by technical barrier elements (e.g. passive barrier elements). The rest are partially automatic or completely manual (e.g. active barrier elements) and need involvement of operating personnel. Such tasks that required to fulfill a barrier functions are denoted as operational barrier elements (DNV GL, 2014).

It is not necessary that all operational barrier elements should be combined with the technical barrier elements to achieve barrier functions. Some operational barrier elements, like the one associated to emergency preparedness are almost solely performed by operating personnel. A good example can be of activities such as search and rescue which are an important part of emergency procedures performed in the industry (DNV GL, 2014).

Operational barrier elements should not be overlapped with tasks having an indirect impact on technical barrier elements. These are the tasks associated with testing, inspection and maintenance of barrier elements. Although these tasks are critical to safety and environment, they are not directly required to achieve barrier functions. Hence, only procedures that are required during the realization of the barrier function are operational barrier elements (DNV GL, 2014).

For operational barrier elements the specific set of performance requirements can be the response times and methodology of operations that are to be executed (PSA, 2017).

Organizational Elements

The organizational barrier elements are the personnel (roles) directly involved to accomplish safety critical tasks. Example can be a central control room operator (Hauge & Øien, 2016). The concept of organizational barrier elements can be extracted from the Performance requirements (PRs) for the operational barrier elements. This can be illustrated through an example illustrated here. For an event X, personnel Z and Y shall be present and responsible, due to their required competence and level of authority described by the operational element (DNV GL, 2014).

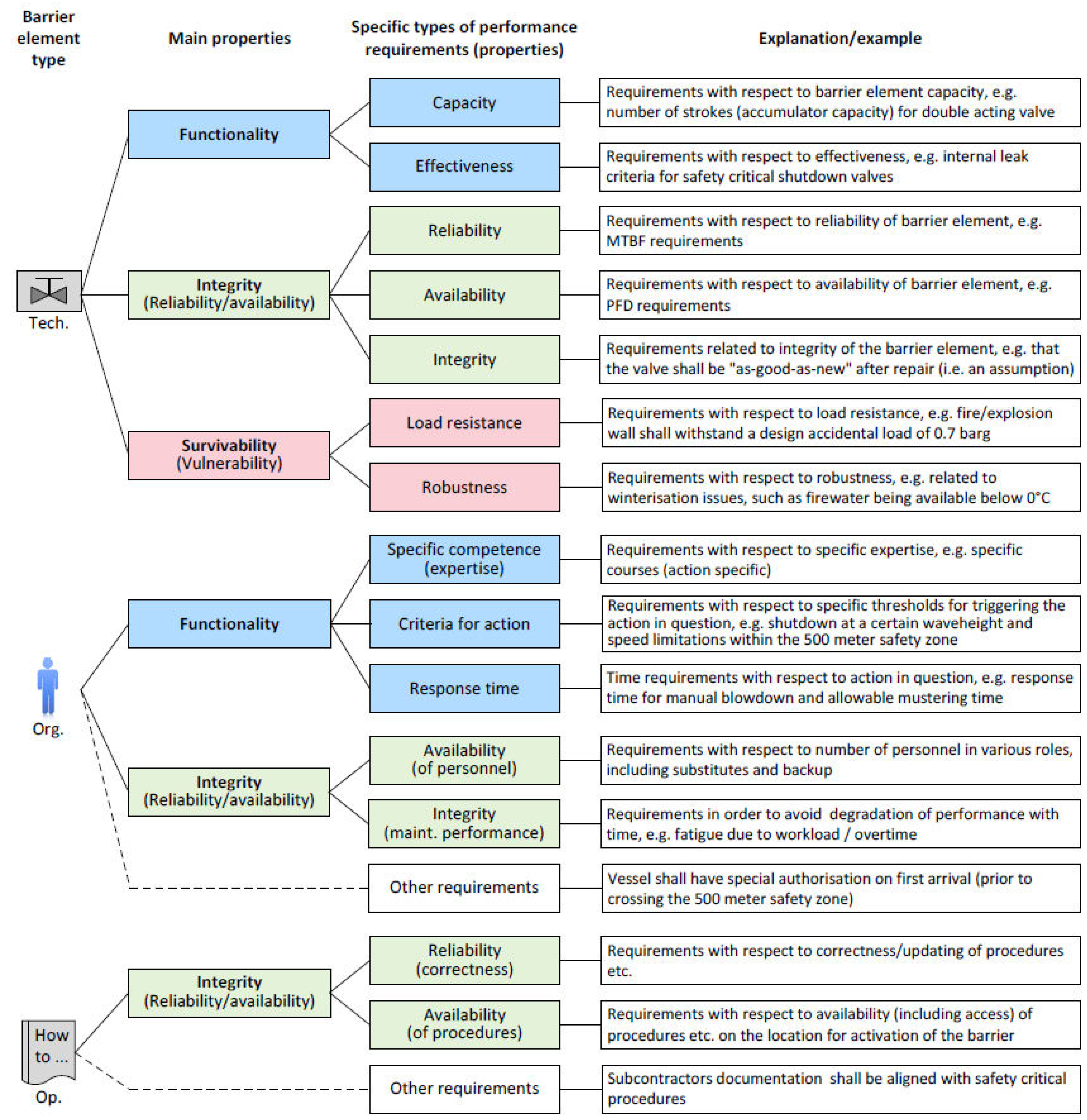
4.5.4. Performance Requirements (PRs)

There is a requirement to performance as mentioned in the management regulation section 5. The term performance according to PSA is described as the qualities a barrier function or barrier element must have to enable barrier functionality. Barrier functions shall be broken down into barrier elements and performance requirements (PRs) shall be established for the individual barrier elements. Specified PRs for these barrier elements allow the safety barriers to fulfil its function. The performance requirements cover various aspects of the barrier elements. These can be for example, accessibility, efficiency, specificity, functionality, reliability, response time, capacity, durability, robustness, audit-ability, and independence (PSA, 2010) (Johansen & Rausand, 2015). However, according to PSA these performance requirements can be condensed to three general categories which are (PSA, 2017):

- Functionality: Impact elements have on the event chain
- Integrity: Ability to be in place and intact during accident scenarios
- Robustness: Ability to endure and survive situations that are different from the planned DSHAs.

An overview of PRs is beneficial especially in situations where the barrier element are expected not to function (DNV GL, 2014). Figure 9 below is a very useful categorization of all the different types of performance requirements into the three main categories as mentioned above. The figure also distinguishes how these performance requirements vary with reference to the technical, operational and organizational barrier elements.

It is very important that the risk analysis studies are sufficiently detailed, in order to provide the basis for comprehensive PRs. The PRs should be updated as more detailed assessments and information gets accessible. The performance requirements must highlight the characteristics that are pertinent for each barrier element. These requirements can be qualitative/ quantitative or deterministic/probabilistic (DNV, 2014). Deterministic requirements are built on best practices, technical standards, and design and dimensioning loads. The probabilistic requirements are established in various ways. Semi qualitative risk assessments method is the commonly used approach for the probabilistic requirements (DNV, 2014). Alternatively, comparison between the results of a quantitative risk analysis with overall risk acceptance criteria can also be done. This allows to allocate the required risk reduction to barrier functions, systems, and elements as stated in IEC 61508 (2010).



Barrier element type	Main properties	Specific types of performance requirements (properties)	Explanation/example
Tech.	Functionality	Capacity	Requirements with respect to barrier element capacity, e.g. number of strokes (accumulator capacity) for double acting valve
		Effectiveness	Requirements with respect to effectiveness, e.g. internal leak criteria for safety critical shutdown valves
	Integrity (Reliability/availability)	Reliability	Requirements with respect to reliability of barrier element, e.g. MTBF requirements
		Availability	Requirements with respect to availability of barrier element, e.g. PFD requirements
		Integrity	Requirements related to integrity of the barrier element, e.g. that the valve shall be "as-good-as-new" after repair (i.e. an assumption)
	Survivability (Vulnerability)	Load resistance	Requirements with respect to load resistance, e.g. fire/explosion wall shall withstand a design accidental load of 0.7 barg
		Robustness	Requirements with respect to robustness, e.g. related to winterisation issues, such as firewater being available below 0°C
Org.	Functionality	Specific competence (expertise)	Requirements with respect to specific expertise, e.g. specific courses (action specific)
		Criteria for action	Requirements with respect to specific thresholds for triggering the action in question, e.g. shutdown at a certain waveheight and speed limitations within the 500 meter safety zone
		Response time	Time requirements with respect to action in question, e.g. response time for manual blowdown and allowable mustering time
	Integrity (Reliability/availability)	Availability (of personnel)	Requirements with respect to number of personnel in various roles, including substitutes and backup
		Integrity (maint. performance)	Requirements in order to avoid degradation of performance with time, e.g. fatigue due to workload / overtime
		Other requirements	Vessel shall have special authorisation on first arrival (prior to crossing the 500 meter safety zone)
Op.	Integrity (Reliability/availability)	Reliability (correctness)	Requirements with respect to correctness/updating of procedures etc.
		Availability (of procedures)	Requirements with respect to availability (including access) of procedures etc. on the location for activation of the barrier
		Other requirements	Subcontractors documentation shall be aligned with safety critical procedures

Figure 16: Categorization of performance requirements for barrier elements (Hauge & Øien, 2016)

4.5.5. Performance Standards

The PSA emphasizes upon two main aspects when it comes to establishing, updating, and maintaining an adequate set of safety barriers. These two aspects are specified barrier strategy and performance requirements for the barrier elements. When the performance requirements are identified, they are gathered and listed in the performance standards (PSs) on a system level or the functional level. The PSs developed for barrier functions help to clarify what other systems or functions it borders. Operational and organizational PSs are also established when these factors are critical for implementation of different barrier functions (Madsen, 2013) (Ptil, 2011).

The safety performance standards for a specified system shall verify that barriers, safety systems or safety functions (Standards Norway, 2008, s. 12):

- *are suitable and fully operative for the identified hazards.*
- *have sufficient capacity for the time frame of the hazard or the time needed to provide evacuation of the installation.*
- *have adequate availability to counter the frequency of the initiating event.*
- *have appropriate response time to achieve its role.*
- *are fit for all operating conditions.*

4.5.6. Barrier Strategy

The barrier strategy is an outcome of the barrier management process (see figure 7). The major steps to form a barrier strategy are as listed below (Hauge & Øien, 2016):

1. Facility description and area division.
2. DSHAs and barrier functions per area (based on the risk picture).
3. Barrier elements for individual areas (or globally).
4. Performance requirements.
5. PIFs.

6. Verification activities for monitoring of barrier performance.

The starting point for developing a barrier strategy document is the risk picture. Although there are many approaches to obtain a risk picture, in the offshore industry it is based on the QRA studies. The principal contributions to the risk level should be affirmed as part of the risk picture presentation, for the following mentioned below (J.-E. Vinnem, 2014a):

- Potential hazards.
- Distinct areas on installations.

The overview of hazards is split into hazards inside and outside a specific area. It is of value to focus on certain hazard aspects that are unique to the installation under consideration compared with other similar offshore installations. This is essential as certain specific hazards will require additional barrier functions or elements. If no specified aspects exist, then an industry standard solution with respect to barrier functions will be applicable and sufficient (Næss, 2012).

A large installation may consist of several main areas which are subsequently divided into many subareas and rooms with special protection needs. Barrier strategies should follow the separation of main areas since they are not applicable to all individual subsea and rooms (J.-E. Vinnem, 2014a). Barrier strategies must illustrate the link between hazards, areas, barrier functions and barrier elements. Furthermore, effective barrier strategy must be able to present these links in a manner that can be utilized by installations personnel during operations. It is therefore vital that the barrier strategy provides a comprehensive overview (J.-E. Vinnem, 2014a)

5. Summary, Remarks and Future work

5.1. Introduction

In the previous chapters of this report, several aspects of safety barriers in the offshore industry have been presented and discussed, that also includes a structured workflow to analyze the safety barriers. Moreover, a strong link between risk and safety barriers was also reviewed. The final chapter of this master thesis provides a concise summary and some final remarks. Furthermore, based on the safety barriers concepts discussed earlier, future work related to the field of safety barriers is also presented.

5.2. Summary

In chapter 2, a brief overview of Norwegian petroleum activities and regulatory regimes was presented. This was done to give readers a basic idea of major hydrocarbon activities, legislation hierarchy and the set of regulations issued by PSA in the NCS. The concept of safety barriers was introduced and discussed based on the PSA regulations and important scientific literature available for this subject. Since the concept of safety barriers is often vaguely defined and used interchangeably with similar terminologies, there is need for a common understanding of the term within the NCS. Various methods for categorizing safety barriers exist. In this report, safety barriers were categorized by their *'function in the accident scenario'* and by the *'nature/genre'* of those barriers. Furthermore, three important safety barrier models were discussed namely bow-tie model, safety barrier diagrams and energy barrier model. PSA uses the energy barrier model as its foundation to formulate regulations for safety barriers despite the fact that this model has some serious drawbacks. Energy barrier model is based on linear causal chains and therefore poorly illustrates complex interactions in larger socio-technical systems (Næss, 2012). In the offshore industry, barrier management process is performed to ensure suitable safety barriers are identified and established by means of a systematic and continuous process. In this report, two phases of barrier management process namely design, and operational phase were described respectively with emphasis on the former phase.

Safety barriers are primarily established to avoid major hazards and accidents. Hence, the term 'major accidents' was explained and the different viewpoints prevailing in the offshore industry regarding major accidents were also discussed. Furthermore, a comparison between major accidents and occupational accidents was also presented.

DSHAs and the process of emergency preparedness was explained in this master thesis. DSHAs are commonly known terms in the offshore industry. This facilitates strong communication of the barrier management process among the platform personnel. DSHAs are aimed to prevent recurrences of scenarios that can cause hazards and failure of safety systems. Risk of major accidents occurring in the industry can be significantly brought down if protection against the DSHAs is adequately established (Skjerve et al., 2008). The report also includes a brief description of the RNNP project. Gathered data from the RNNP project helps to get an overview of risk trends within the offshore industry. Besides this, the RNNP data also helps to assess general developments even though significant discrepancies in risk trends prevail between different offshore facilities (Årstad et al., 2010).

In the offshore industry, safety barriers primarily serve as reactive safety measures (Hollnagel, 2008). To provide proactiveness in the approach and ensure that desired goals for safety barriers are achieved, it is extremely crucial to demonstrate a strong linkage between risk and safety barriers. Over the past years, PSA has put a lot of efforts to consolidate a clear link between risk assessment and safety barriers. Hence chapter 3 was based on reviewing this relationship in detail. Chapter 3 began with an overview of the risk concept in the offshore industry which was in accordance with the PSA and its management regulations. Norwegian regulations strongly emphasize that both risk and uncertainty should be contemplated while prioritizing suitable solutions and safety measures. The idea of risk assessment and the commonly used methods for doing the assessment in the offshore industry were also part of this report. Furthermore, a simplified way to formulate a risk picture that is suitable to be used in the NCS was also described. According to the management regulations, uncertainty assessments must be regarded as an inherent part of risk analysis. However, in the offshore industry these uncertainty assessments face serious limitations in the adapted approach which was also briefly mentioned in this report

While drawing a relationship between risk and safety barriers in chapter 3, various aspects were highlighted and reviewed. Means by which risk management process can serve as a basis to establish barrier management model was presented. Identification of barrier functions and formulating performance requirements based on the risk assessment was also described. The discussion also incorporated the way barrier strategy develops a logical relationship between the barrier functions and barrier elements. Barrier strategy, which is based on the risk picture for the installation, provides an overview of all the barrier functions in the system (J.-E. Vinnem, 2014a).. Furthermore, a comprehensive review demonstrating the extent of QRA utility as an input to safety barriers was encompassed. QRA play a critical role in the design process and dimensioning of the safety barriers. However, the QRA studies have certain limitations as there is focus is more biased towards consequence mitigating barriers and certain tolerance criterions. Furthermore, due to the complexities of data analysis and representation, they are less operational (Andersen & Mostue, 2012).

Chapter 4 suggests a structured workflow to analyze safety barriers in the offshore industry. The process is divided into four phases. The first phase is analyzing risk and uncertainties. Risks and possible hazards are identified, analyzed and evaluated in this initial phase of the suggested work procedure. This technique produces tables (event, consequences and measures) and hazard barrier matrices (Torbergsen et al., 2012). Through these event-consequence pairs, safety barriers can be identified. In phase 2, area classification is done, based on the different risk levels obtained from the risk picture. Furthermore, worst-case accidental scenarios are drawn, and safety barriers are established for those worst-case accidental scenarios which are also commonly known as DSHAs in the offshore industry. To allow efficient identification of barrier elements while performing barrier analysis, it is extremely crucial to differentiate between safe solutions, PIFs/RIFs, and safety barriers. This is done in phase 3 of the suggested work procedure. After adequate set of safety barriers are identified and listed, they are categorized and prioritized based on their impact on the accidental scenario and the genre of those safety barriers. Phase 4 comprises of the main sequence for barrier analysis process that begins from identification of the barrier functions till performance requirements for each barrier element has been defined. A barrier function is a function designed to prevent, control, or mitigate the propagation of an undesired condition or event into a hazard or a major accident scenario (Duijm, 2009). The reason for employing least number of barrier functions is to obtain a simplified overview and understanding of the entire safety system. The barrier function is performed and maintained by its barrier elements. These barrier elements are typically classified as technical, operational, or organizational elements (PSA 2017). To summarize all the three barrier elements a quote from PSA barrier memorandum 2017 is taken which is, "*Who does what with which equipment in failure, hazard and accident situations*" (PSA 2017, p.13). This is an instructional phrase for clarifying the interaction between organizational, operational and technical elements. Operational and organizational elements are tasks that personnel perform in order for a safety barrier to function as planned (PSA, 2017). The PSA in their document from 2017 on barrier management principles, expressed a need for a higher focus on operational and organizational barrier elements since they get very limited focus while performing risk analysis as compared to the technical barrier elements. These may need to be made visible and known, if they have implications for barrier performance, and therefore need to be stated as PRs. With regards to barrier functionality, it is not the label associated to various barrier elements that is of high imminence rather identification and establishment of PRs for all these barrier elements is more significant (Madsen, 2013). The PRs are usually developed for barrier elements, but sometimes they can also be stated for barrier systems and barrier functions or subfunctions. When the PRs are recognized, they are gathered and listed in the PSs on a system or the functional level.

5.3. Concluding Remarks

After reviewing the available scientific literature, this report has highlighted the following aspects that should be identified and improved in order to effectively implement safety barriers in the offshore industry.

This report tries to condense the gap between different interpretations devised by PSA and operators so that a mutual set of goals can be achieved in the Norwegian petroleum industry. It is of value to present a clear picture of how the offshore industry is commonly using the safety barriers concepts and ensure that it correlates and conforms with the PSA regulations. In order to do this, it is extremely important to have an understanding of how the Norwegian regulations related to safety barrier are practically applied and brought into use. Furthermore, how various entities like PSA Norge, DNV GL and SINTEF can effectively work in collaboration and implement these regulations and identify crucial areas for improvement.

In this report safety barriers were defined in various ways. However for analytical purposes, a safety barrier should always be considered as a series of elements that implement a barrier function, in which each element consists of a technical system or a human input/response (Duijm, 2009). Hence, it is more precise and relevant to refer to barrier functions and elements while explaining the concept of safety barriers (Johansen & Rausand, 2015).

Among the distinct characteristics of offshore hydrocarbon operations is the potential for catastrophic consequences if an accident takes place. Major accidents on the offshore platforms can cause severe losses to human life, assets and the environment. Focus while establishing safety barriers in the offshore industry is on major accidents and their associated risk. Hence understanding the generic characteristics of major accidents and distinguishing them from occupational hazards is extremely important so that effective use of available resources can be ensured.

In general, every attribute associated to safety barriers will have a direct or an indirect impact on the risk levels. The risk assessments performed in the offshore industry aim to identify, illustrate, and explain the accidental scenarios (Aven et al., 2006). An efficient risk assessment system is required to define scenarios and devise barrier solutions for those scenarios. Safety barriers need to be designed, built, installed and used according to particular specifications from the risk assessments (Guldenmund et al., 2006).

A common trend in the industry is to perform uncertainty assessments and relevant sensitivity calculations while establishing the risk picture. However, it is suggested that the uncertainty assessments should be carried out at all individual steps especially when the final set of safety barriers are identified. Hence, after identifying the safety barriers a comparison must be drawn with the already performed risk assessments such that it could be verified that adequate safety barriers are established for all the identified risk and hazards in the risk assessments. Hence, the outcomes from the initial phase of risk analysis phase 1 should be used as a reference in all the upcoming phases of the suggested work procedure (as shown in figure 14).

PSA in the barrier memorandum published in 2017 seemed concerned about a very wide definition of safety barriers being used in the offshore industry which if wrongly interpreted will include every safety measure as a barrier. Hence, PSA is very keen to ensure that the companies operating in NCS clearly differentiate between safety barriers, RIFs/PIFs and normal operations process (safe solutions). This will aid in classifying and evidently differentiating safety measures which on their own practically avert an accident from happening and the others which assist those safety measures to fulfill their task.

It is suggested that only elements which have a direct impact on the accident scenario should be categorized as safety barriers. Functions or elements which have an indirect impact on the accident scenario should be either be considered as safe solutions or RIFs/PIFs. This suggestion is also supported by Sklet (2006). It suggests that a barrier function must have a direct and substantial impact on risk. Hence functions or elements which have an indirect impact should not be categorized as barrier functions and rather should be termed as RIFs/PIFs (Sklet,2006).

It is also important to maintain a clear distinction between barrier function and barrier systems. Sometimes, the "barrier" term also refers to a larger function or a barrier system (BS) (PSA, 2010). A BS is system designed and is used to execute one or several barrier functions (Sklet, 2006). A BS can be comprised of several system elements, such as technical elements, operational activities performed by humans, or a combination of the above (Aven, Sklet, & Vinnem, 2006). PSA does not use the term barrier systems in their recent barrier memorandum (2017) and describes the barrier elements which are combined to execute a barrier function. Hence it is suggested that to avoid confusion the term barrier system (BS) should not be used in the offshore industry.

There are requirements set by PSA and operators in the offshore hydrocarbon industry that the condition and status of both technical and organizational barriers elements on installations must be demonstrated in risk analyses. However, implementing this in a way that supports appropriate analysis and decision-making processes has proved to be difficult. The performance of organizational barrier elements and associated details not clearly addressed in the risk analyses (Næss, 2012). The impact of organizational barrier element is a critical issue that currently receives very little attention in the safety barrier concepts. Within a system, the organizational barrier elements impact several corresponding safety barriers and thus significantly contribute to risk transfer, and dependence between other barrier elements. For an active barrier management, it is very important to emphasize more on treating these barrier elements with same significance as the technical barrier elements (Størseth, Hauge, & Tinmannsvik, 2014). Several methods have been developed over the years to cater this problem. One such method is Risk OMT (Risk modelling – Integration of Organizational, Man, and Technical factors). The method provides both a qualitative and quantitative analysis and intends to consider the organizational elements during project execution. It also has a high focus on proactive barriers as well as reactive barriers

(Madsen, 2013). Moreover, value of broadening the scope of organizational barrier elements as part of barrier management should also be emphasized. Broadening the scope can also refer to rethink and let go the traditional approach of dictating a finite and static formula to outline and establish organizational barrier elements. Rethinking involves recognizing the effect of several other human traits like decision making, confirmation bias, groupthink, as well as other social influences. Organizational barrier elements are crucial in maintaining the overall barrier functionality and in avoiding the propagation of major accidents. Organizational barrier elements should be included in the barrier analysis as crucial factors that influence several barrier elements, and hence contribute to overall risk levels (Størseth, Hauge, & Tinmannsvik, 2014).

5.4. Future Work

This master thesis had a delimitation that it was addressing major accidents and its consequences were restricted to personnel safety only. The reason for this was that the regulations issued by PSA for barrier management in the hydrocarbon industry are primarily focused on personnel safety and fatality prevention (Gustafson, 2014). Therefore, environmental safety barriers are in practice not emphasized in the same manner, and this can surely hamper good communication and management of safety barriers (Røed & Bjerga, 2017). It is very essential to combine safety and working environment considerations along with the concern for natural environment (Årstad et al., 2010). After Macondo blowout, a growing concern about oil spills can be seen in the society. An acute oil spill can have severe consequences on fish, marine mammals, seabirds and beach zones. Along with the environmental losses these types of accidents also have high financial repercussions. The northern parts of the North Sea and the Arctic are exposed to high-risk levels and extreme challenges. Darkness, ice and long distances from onshore facilities create difficulties for the industry and the concerned authorities. To increase safety and avoid major accidents in these situations, barriers play a critical role. In Norway, particularly in the Arctic regions, it is extremely important to prevent oil spills and to ensure adequate emergency preparedness resources. Hence, future work related to environmental safety barrier management can be very beneficial in preventing major environmental accidents (Gustafson, 2014).

The issue pertaining to barrier management for environmental accidents begins right from the hazard identification phase. Risk assessments conducted for environmental factors is centered towards a chain of events happening after the discharge has reached to the sea. Research projects need to be carried out in order to design safety barriers that not only assist in consequence mitigation given an oil spill occurs in the sea but also for designing safety barriers that can prevent an oil spill from occurring in the first place (Røed & Bjerga, 2017). There are some studies being conducted such as by Røed & Bjerga (2017) which states that the safety barriers established for personnel risk are also to a certain extent suitable for environmental risk. However, work needs to be done to address particular characteristics in the Arctic such as polar lows, icing, and extremely low temperatures. Due to such characteristics, barrier elements and performance requirements in the Arctic may not be the same to the ones being relevant to the rest of the NCS. (Røed & Bjerga, 2017). Hence, similar studies like this master thesis can be carried out in which the entire focus along with the application domain should be based on environmental risk and major accidents that can incur environmental losses.

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