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Abstract

The concept of safety barriers has become a main focus in the oil and gas industry in the last decade. Accordingly, many efforts are being spent from the risk decision makers to improve the understanding of the different aspects in that context. One of the main challenges is how to integrate the quantitative risk analysis (QRA) with safety barrier management (SBM). The integration of both concepts will result in better management of major accident hazards (MAH) on board the production facilities. However, the integration of QRA with SBM can take several forms when it comes to the operations phase. Condition monitoring of safety barriers' performance can be a good solution for bridging the gap between both tools.

The objective of the thesis is to introduce a methodology for monitoring the performance of safety barriers continuously in daily operations on offshore production platforms. The safety barriers are monitored through indicators. The indicators are representing the critical human, technical and organisational (MTO) factors that could influence the performance of safety barriers dramatically during operations. Further, the critical MTO factors are identified through independent uncertainty and sensitivity assessments of the performance of safety barriers as provided in the QRA results. Afterwards, the different indicators of each factors are linked with a risk barometer in order to indicate the status of the particular safety barrier. Such status, as indicated on the barometer, is providing the concerned parties with early warning signals about the performance degradation of the barrier of interest. Accordingly, the operation personnel and management can take the proper precautionary actions to maintain the performance of the safety barrier within the safe limit.

In order to produce the proposed methodology, the thesis has covered different aspects of safety barriers and risk assessment on its context. At the beginning, a literature review of the concepts of risk, risk assessment, and safety barriers is introduced. In particular, this part has introduced the scientific foundation of these concepts, in addition to, their different types and methods of classification. Furthermore, the thesis has introduced a brief description of the relevant regulatory requirements and standards in the Norwegian Continental Shelf (NCS). Subsequently, the thesis has also described the methodologies used for including the performance of safety barriers into QRA model. In this part, it has been recommended that the influence of MTO factors on safety barriers performance should be considered when performing QRA. Moreover, the methods of uncertainty and sensitivity analyses have been described and discussed to identify the most applicable approach for criticality assessment of

MTO factors. Finally, the thesis has concluded with a case study and discussion to illustrate the possibility of implementing the proposed methodology for monitoring the safety barriers continuously in operations phase.

Acknowledgement

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Stavanger, 15th June 2015.

Mohamed Abdulmalek

Abbreviations

AFS	Active Fire System
BBD	Barrier Block Diagram
BBN	Bayesian Belief Network
BORA	Barriers and Operational Risk Analysis
CCR	Central Control Room
DALs	Dynamic Accidental Loads
ESD	Emergency Shutdown
ETA	Event Tree Analysis
FTA	Fault Tree Analysis
FW	Fresh Water
HC	Hydrocarbon
HEP	Human Error Probability
HOFs	Human and Organisational Factors
HRA	Human Reliability Analysis
HSE	Health, Safety and Environment
IE	Initiating Event
ISC	Ignition Sources Control
ISO	International Organization for Standardization
MAH	Major Accident Hazards
MTO	Man, Technology, and Organization
NCS	Norwegian Continental Shelf
PFD	Probability of Failure on Demand
PFS	Passive Fire System
PIFs	Performance Influencing Factors
PSA	Petroleum Safety Authority
QRA	Quantitative Risk Assessment
RAC	Risk Acceptance Criteria
RBI	Risk Based Inspection
RIFs	Risk Influencing Factors
SBM	Safety Barriers Management
SIF	Safety Instrumented Function
SIL	Safety Integrity Level
SIS	Safety Instrumented System
UiS	The University of Stavanger
WP	Work Permit

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Definitions

- **Barrier:** A physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents (Sklet, 2006).
- **Barrier element:** Technical, operational or organisational measures which alone or together realize one or more barrier functions (DNV GL, 2014).
- **Barrier Function**: The purpose or the role of the barrier (DNV GL, 2014).
- **Hazard**: Potential source of harm (NORSOK, 2010).
- **Hazardous Event**: The first event in a sequence of events that, if not controlled, will lead to undesired consequences (harm) to some assets (Rausand, 2011).
- **Initiating Event**: An identified event that upsets the normal operations of the system and may require a response to avoid undesirable outcomes (Rausand, 2010).
- **Major Accident**: Acute occurrence of an event such as a major emission, fire, or explosion, which immediately or delayed, leads to serious consequences to human health and/or fatalities and/or environmental damage and/or larger economical losses (NORSOK, 2010).
- **Operational barrier element**: A task performed by an operator, or team of operators, which realizes one or several barrier functions (DNV GL, 2014)
- **Organizational Barrier element**: Personnel responsible for, and directly involved in realising one or several barrier functions (DNV GL, 2014).
- **Risk:** Uncertainty about and severity of the consequences (or outcomes) of an activity with respect to something that humans value (Aven and Renn, 2009).
- **Risk Influencing Factors**: conditions which are significant for the ability of barrier functions and elements to function as intended (PSA, 2013)
- **Safety function:** physical measure which reduce the probability of a situation of hazard and accident occurring, or which limit the consequences of an accidents (NORSOK, 2008)
- **Safety system:** system which realise one or more active safety functions (NORSOK, 2008).
- **Technical barrier element**: Engineered systems, structures, or other design features which realize on or several barrier functions (DNV GL, 2014).

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1. Introduction

1.1 Background

The topic of safety barriers in the oil and gas industry has become a main focus in the NCS in the last decade. Accordingly, there are several researches have been performed to present a better understanding of safety barriers on the different levels. Some of these researches were carried out to introduce methods for improving the modelling of safety barriers' performance. For example, the BORA (Aven et al, 2006) and the Risk_OMT projects (Vinnem et al, 2012). In these models, the improvements are acquired by reflecting the impact of the different MTO factors on the performance of safety barriers. In addition, the utilisation of these models in QRA has also introduced a significant improvement in the prediction of the final risk picture.

However, the reflection of the MTO factors on the performance of safety barriers could be a source of uncertainties if some these factors are introduced based on poor background knowledge. Therefore, it is necessary to identify these factors while performing the QRA in the design phase and including them into the operational SBM process. However, at present, there is no clear answer on how to integrate the QRA with SBM to ensure better management of safety during the lifecycle of the asset. Accordingly, an important question has to be raised on how to fill the gap between both disciplines.

The answer of the above question could take several forms. However, the thesis is answering this question by introducing a methodology for monitoring the performance of safety barriers based on the results of QRA. In addition, the use of this monitoring approach is also introducing a solution of how to use QRA in daily operation.

1.2 Objectives

The purpose of the thesis is to introduce a methodology for monitoring the performance of safety barriers continuously in daily operations. The monitoring process is performed by building indicators of the critical MTO factors to the safety barriers. However, the MTO factors are represented with risk influencing factor (RIFs). Furthermore, the input data for the monitoring process are obtained from the QRA that performed in the design phase.

The objectives of this master's thesis are achieved by considering the below tasks.

- Introducing the scientific background about risk assessment and safety barriers, as well as the relevant regulatory requirements in the NCS.
- Describe how the performance of safety barriers can be modelled in the QRA effectively.
- Introduce a description of the proposed methodology for monitoring the performance of safety barriers through RIFs indicators.
- Perform the recommended method on a case study.
- Discussion of the work performed on thesis.

1.3 Limitations

- It is assumed that the reader of this thesis is familiar with safety barriers and risk management in the context of oil and gas industry.
- The focus will be on the major accident risk, so the occupational risk is not accounted in this report. Furthermore, the concentration will be on the process leaks fire and explosion hazards through a selected case study.
- The thesis is restricted to the knowledge-based subjective probability. However, the frequentist probability is also mentioned in some parts for the sake of explanation of probabilistic treatment of uncertainty.

1.4 Report Structure

The report consists of seven Chapters as introduce below:

Chapter 1: starts with the background of the problem of interest and shows the motivation for pursuing the thesis. Also, objectives, scope and limitations are presented to illustrate the boundaries of the report.

Chapter 2: introduces the theoretical background of the thesis. In detail, this chapter provides a brief background of the concept of risk and risk assessment. Furthermore, a brief literature review on the concept of safety barriers and the associated definitions is given in the second section.

Chapter 3: presents a brief revision of the regulatory requirements and standards that relevant to safety barriers in the NSC. In particular, this Chapter involves the petroleum safety authority (PSA) regulations and the NORSOK standards. In addition, the last section introduces a brief summary of one of the documents that is published by DNV GL in 2014.

This publication describes the requirements of managing safety barriers in the operations phase.

Chapter 4: describes the methods used to model the performance of safety barriers in QRA. The Chapter is divided into three sections. These sections answer the following three questions- What are the major accident hazards? How to include the different safety barriers in the QRA model? How to quantify their performance?

Chapter 5: introduces a methodology for monitoring the performance of safety barriers continuously in operations phase through RIFs indicators. The Chapter consists of two major tasks. The first task is how to identify the most critical RIFs to the safety barriers based on the information obtained from QRA. Furthermore, the second task introduces a methodology for monitoring the performance of safety barriers in daily activities. This method depends on establishing indicators for the critical RIFs to capture early warnings about the degradation of the safety barriers' performance.

Chapter 6: presents the application of the above methodology through a case study, in addition to, a discussion about the proposed methodology and results of the case study.

Chapter 7: introduces a conclusion of the work performed in the entire thesis, in addition to, recommendations for further work.

2. Theory

Management of MAH is a top priority in the oil and gas industry. Accordingly, the associated hazardous events have to be addressed and identified sufficiently in order to determine the existing risk sources. In addition, a set of protection measures has to be available in order to overcome and minimise the impact of those hazardous events if present. Therefore, it is mandatory to combine both hazardous events and protections in one comprehensive study in order to identify the final risk picture. Such study is called risk assessment. However, it is still a challenge of how to account the protection measures, which is called safety barriers, into the risk assessment and how to represent their performance sufficiently. This Chapter present a brief introduction about the theoretical foundation of risk, risk assessment and the concept of safety barriers.

2.1 Risk and Risk Assessment

Risk assessment has been used for several years as a tool for managing MAH in different industries during the asset's life cycle. In the context of the oil and gas industry, risk assessment can vary from a simple task to a complex detailed analysis. The level of details is relying on several factors, for example, the involved hazards and the risk perspective used in the risk analysis. Therefore, there are several methods and perspectives of risk assessment have been developed in order to suite the wide range of the hazardous activities being performed on board the production facilities.

This section introduces a brief literature survey on the different concepts and perspectives of risk that formulate the foundation of the risk assessment. In addition, an introduction of risk assessment process, methods, and categorisation is presented.

2.1.1. What is Risk?

Definition of the term risk is an area of controversy among the different risk scientists, as risk concept is used in several disciplines. For example, from the economists' point of view, risk is represented by the expected reward of an investment. Whereas, from the safety perspective risk can be seen as the expected losses in human, environment, and assets that occur due to the occurrence of undesired events. As a result, there are a considerable number of risk definitions are available. However, based on Aven (2014), definitions of risk are categorised in the below four groups:

- Risk as the pair of probabilities and consequences

- Risk in uncertainty and objective uncertainty
- Risk as an event or a consequence of an event
- Risk is the two-dimensional combination of consequences and uncertainties.

For the sake of the thesis the first and the last group of risk definitions are addressed in this section.

According to Aven and Vinnem (2007), risk can be commonly defined as a combination of probability and consequences, where consequences are adverse outcomes. This definition reflects the base understanding of the concept of risk. More definitions that following the same idea are:

- *Risk is a measure of the probability and severity of adverse effects* (Lowrance, 1976)
- *Risk is the combination and the extent of consequences* (Ale, 2002)
- *Risk is a measure of possible loss or injury, and is expressed as the combination of the incident's probability and its consequences*(DNV, 2009)

The above definitions are raising three important questions: (1) what can go wrong? (2) what is the likelihood of that happening? (3) What are the consequences? (Rausand, 2011). The answer of these questions are found in the (A, C, P) risk perspective. Where A denotes an initiating event or a hazardous scenario, C is indicating the consequences of that event, and P the associated probabilities (Aven, 2010a). For instance, the event can be a hydrocarbon leak and the consequence can be the loss of human lives or assets. Whereas probability indicates to what extent such event may occur and how severe the consequences will be.

As a tool for risk descriptions, probability has different interpretations. However, the most prevailing interpretations of probability in risk assessment are (a) *Frequentist probability* P_f and (b) *Knowledge-based (subjective) probability* P (Aven, 2003). Based on Aven and Reniers, (2013) both interpretations are defined as:

a) ***Frequentist probability (Relative frequency)*** $\boldsymbol{P_f(A)}$: *The fraction of time the event A occurs if the situation considered were repeated (hypothetically) an infinite number of times.*
b) ***Knowledge-based (subjective) probability*** **P(A)**: *Such probability indicates the degree of belief of the assigner about the occurrence of the event A based on his background knowledge K about the event.*

Subjective probabilities, in that case, are a measure of uncertainty, conditional on the background knowledge (according to the Bayesian approach) (Aven, 2010b). Other interpretations of probability are existing such as classical, logical, and imprecision probabilities, see (Lindley, 2006) and (Aven, 2014). However, they are not considered in the current chapter since they are outside the focus of this project. According to the (A, C, P) risk perspective, risk is described as an expected value based on the assigned probabilities. Therefore, it has to be clarified that, to what extent these values are representing the future events that may occur? Further, have uncertainties been reflected in such risk picture sufficiently? In this risk perspective, uncertainties are accounted as a part of the background knowledge of the assigned probabilities. Moreover, probabilities are based on a number of assumptions and suppositions. That is resulting in an inadequate final risk picture and consequently may lead to surprising events, as uncertainties are camouflaged in probabilities (Selvik, 2012).

As a solution for the above challenge, an extended risk concept that is seeing beyond the assigned probabilities and the expected values is required. In particular, it is necessary to implement further uncertainty assessments on these values in order to get a better expression of the parameters of interest (Aven, 2008). Accordingly, in the last few years the (A, C, P) risk perspective has been replaced with the (A, C, U) risk perspective; see (Figure, 2.1).

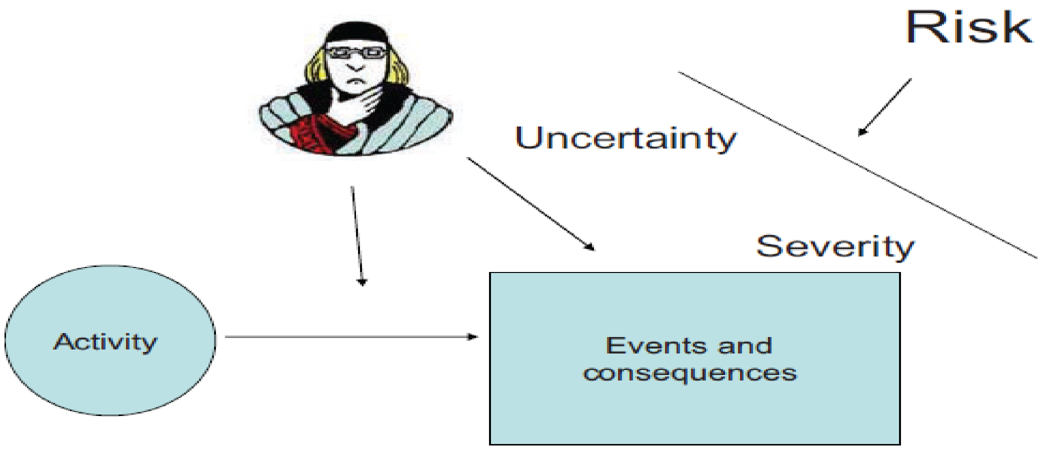


Figure 2.1: Illustration of the (A, C, U) risk perspective (Abrahamsen et al, 2010 p98)

Similar to the preceding concept, A denotes the undesired events or scenarios, and C represents consequences. U, in this context, includes the associated probabilities of occurrence of this event and the level of severity of the outcomes, based on the background knowledge. In addition, it represents the assessor's degree of belief about the underlying parameters that influencing the event and consequences beyond the assigned numbers. Such perspective can also denoted as (C, U) where C represents the event and the consequences (Aven, 2014). However, the assessor’s opinion about the quantities of interest is known as the epistemic uncertainty.

Based on (Rausand, 2011), “*Epistemic uncertainty is caused by lack of knowledge*”. Such uncertainty can be reduced by increasing the knowledge about the element of concern. That can be discerned from the meaning of the word epistemic that is derived from the Greek *episteme*, which means knowledge. Furthermore, epistemic uncertainty is expressed with subjective probability P.

Another type of uncertainty is called aleatory uncertainty. The word aleatory is derived from the Latin *alea*, which means the rolling of dice. Rausand (2011) has also described such uncertainty as “*the uncertainty is caused by natural variation and randomness”*. This type of uncertainty is irreducible due to the idea of randomness. However, this type of uncertainty is not discussed any further according to the thesis limitations.

2.1.2. What is Risk Assessment?

Risk assessment is a systematic process that is used to establish and to provide judgement on a risk picture of the undesired events that may occur in the future. The process comprises several activities as shown in, (Figure, 2.2).The first step is to establish the context of the risk assessment. Afterwards, risk analysis is used to utilise the available data and information in order to identify hazards and describe risk (NORSOK, 2010).Whereas, risk evaluation is used to compare the risk picture against the risk acceptance criteria (RAC) in order to identify, whether the risk is tolerable or not.

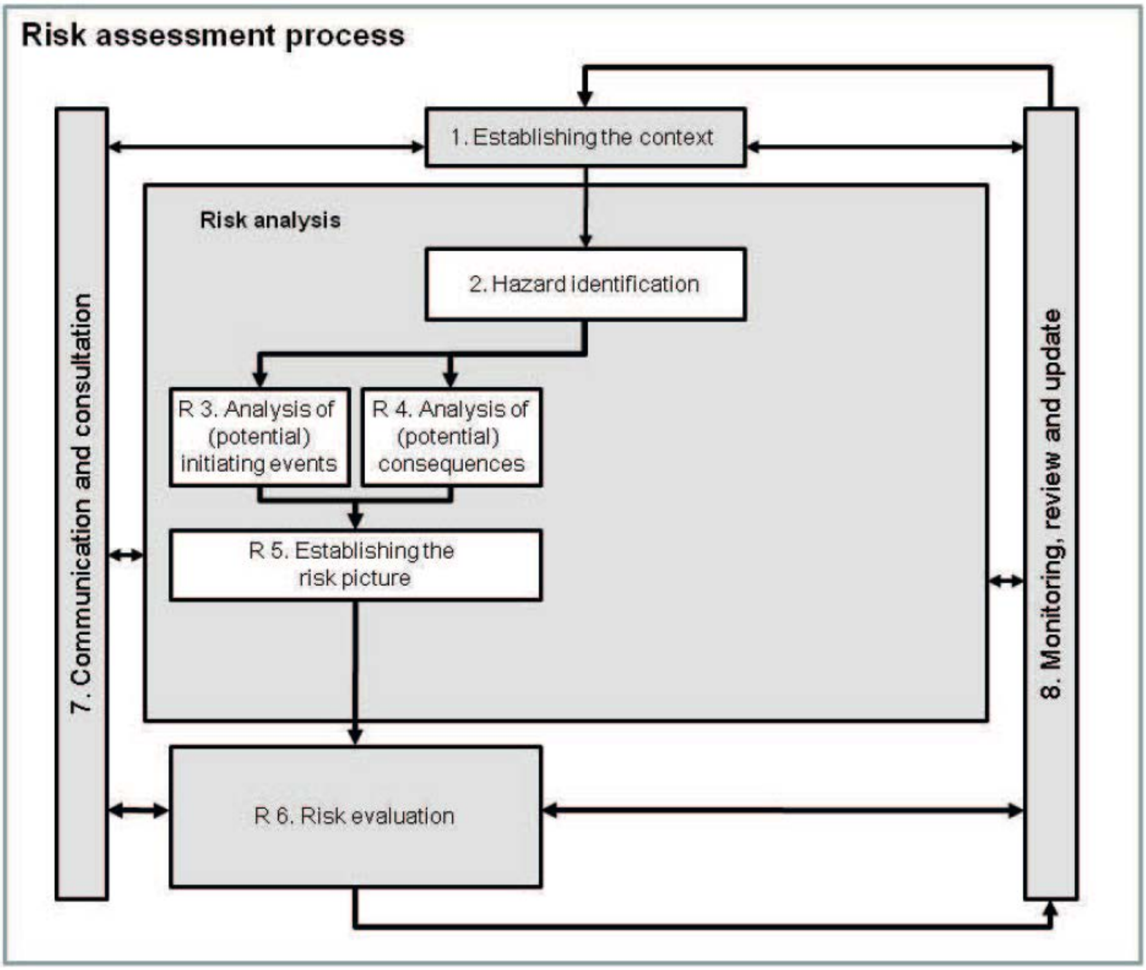


Figure 2.2: Risk assessment process (NORSOK, 2010 p19)

Risk assessment is categorised in the literature in different ways. For example, risk assessment classification can be based on the type of and/or the method used in the analysis. However, with reference to type classification, risk assessment can be qualitative or quantitative. In qualitative risk assessment, consequences and probabilities of the hazardous events are determined qualitatively. On the other hand, the QRA introduces probabilities and consequences as numerical estimates. The QRAs, in that case, is more suitable for modelling of major hazards, which has low probability of occurrence and sever consequences.

Furthermore, risk analysis could be identified based on the method of the analysis. For this purpose, there are three methods of risk analysis have been introduced by Aven (2008). The first method is the simplified the risk analysis, which is primarily qualitative analysis that is used to introduce a coarse risk picture based on discussions and brainstorming sessions. Alternatively, the standard risk analysis is performed by means of more formal analysis tool, and risk matrices usually used to present risk. In that case, analysis can be qualitative or quantitative. The last method is the model-based risk analysis. In this group, the analysis is quantitative and uses more complicated tools to calculate risk.

Another method has been proposed by Skogdalen and Vinnem (2011) for categorising the risk assessment based on the incorporation level of the human and organisational factors (HOFs). The method is restricted only to QRAs. The method has been developed based on the assessment of 15 different QRAs against the level of incorporation of the HOFs. The results of these assessments revealed that QRAs level can be classified as shown in (Table: 2.1)

QRA Level	QRA Requirements
Level 4	HOFs are explained, models adjusted and included in the overall risk management.
Level 3	HOFs are explained and the models are adjusted
Level 2	HOFs are explained but not adjusted
Level 1	HOFs are none existing

Table 2.1: Levels of Integration HOFs in QRA (Skogdalen and Vinnem, 2011 p476)

In the light of the above table, the level 1 QRA is mainly based on the representation of the technical knowledge about the hazardous events. Where, the operational knowledge has not been considered or addressed during the study.

On the other hand, in the level 2 QRA, the HOFs are explained and their importance are addressed during the study. However, in this category, the impact of HOFs does not reflected on the model.

Alternatively, the level 3 QRA is considering the HOFs as an integrated part of the analysis. That is achieved by adjusting the model of the QRA in order to incorporate the impact of HOFs on the final risk picture. For this purpose, some models have been developed in order to present the systematic procedures of incorporating the HOFs to the QRA. However, some of the well-known models are described and discussed later in chapter 4.

In addition, the level 4 QRA is reflecting the impact of HOFs during the entire risk management process. In particular, HOFs in that context are accounted as a part of the daily operations and acting as indicators of the status of safety barriers.

2.2 Safety Barriers

Oil and gas industry is considered as one of the most hazardous industries in the globe. This fact is due to the hazardous nature of the hydrocarbon substances, if not managed and controlled adequately. Therefore, it is mandatory to establish a set of measures that is ensuring a proper prevention and protection from any harmful events. The measures which are used for these purposes are called safety barriers.

In this section, a brief description of the concept and definition of safety barriers is introduced based on some literature survey. Furthermore, some methods of classification of safety barriers are introduced such as; classification with nature, function, and system. In addition, a presentation of some criteria that used for measuring the performance of safety barriers is introduced on the last subsection. However, further detailed discussions, in this context, are presented in (Sklet, 2006), (Johansen and Rausand, 2015) and (DNV GL, 2014).

2.2.1. Barrier Concepts and Definitions

The concept of safety barriers has introduced initially by Gibson (1961) under the name of the *energy-flow* model. Accidents from this model perspective are occurring due to the exposure of the vulnerable object(s) to a harmful energy. That can occur due to the absence of the proper barrier between the impacted target(s) and the source of the harmful energy as illustrated in (Figure 2.1).

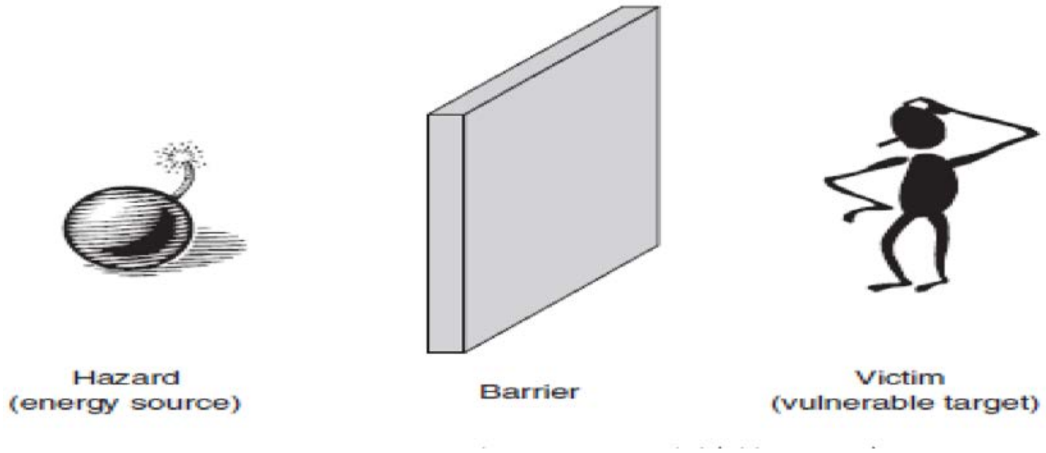


Figure 2.3: The Energy Model (Sklet, 2006 p495)

Later, the *Swiss cheese* model has introduced by Reason (1997). The model represents the weakness points of all barriers as Swiss cheese holes. Accordingly, accidents are occurring when these holes line up allowing the harmful energy to reach the vulnerable object, as illustrated in (Figure 2.4). The more the safety barrier degrades, the more the holes' sizes increase leading to higher risk level. Therefore, it is mandatory to establish a consistent SBM in the operations phase in order to keep the holes as small as possible.

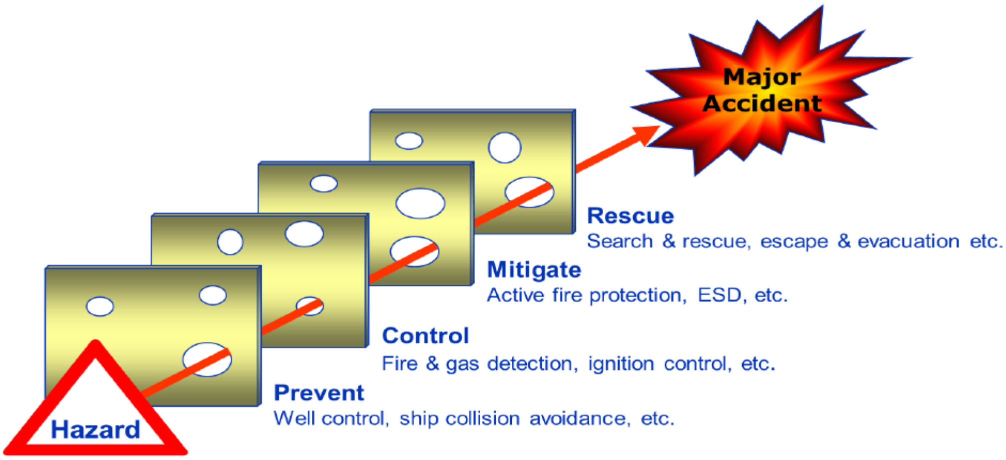


Figure 2.4: The Swiss cheese Model (DNV.GL, 2014 p13)

The term barrier has no common definition in the literature. However, according to PSA (2013) a barrier is defined as a measure or a set of measures that implemented in order to prevent the occurrence and/or reduce the impact of hazardous events. Alternatively, Sklet (2006) defined a barrier as *"a physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents"*. However, the definitions here are considered ambiguous and do not provide the reader with a clear understanding about what a barrier is. Accordingly, it is recommended to split the term barrier to three different terms, which are barrier function, barrier system, and barrier element (Johansen and Rausand, 2015). According to NORSOK Z-013 (2010) the three terminologies can be defined as:

- ***Barrier function****: Function planned to prevent, control, or mitigate undesired or accidental events.*
- ***Barrier system***: *system designed and implemented to perform one or more barrier functions.*
- ***Barrier element****: Technical, operational or organisational component in a barrier system.*

On the other hand, there are other literatures using different definitions of safety barriers. For example, in DNV GL (2014), the term barrier is split into barrier function and barrier elements. The two terms are defined as:

- ***Barrier function****: The purpose or the role of the barrier.*
- ***Barrier element***: *Technical, operational or organisational measures which alone or together realizes one or more barrier functions.*

A mentioned before, there are different definitions and understanding of the term barrier in the oil and gas industry. Therefore, the identification of the different terms and their definitions before conducting a barrier analysis is essential to avoid confusion.

Based on the definition of barrier elements, it is also required to provide a separate definition for each of technical, operational, and organisational barrier elements. According to DNV GL (2014), barrier elements are defined as:

- ***Technical barrier element****: Engineered systems, structures, or other design features which realize on or several barrier functions.*
- ***Operational barrier element****: A task performed by an operator, or team of operators, which realizes one or several barrier functions.*
- ***Organizational Barrier element****: Personnel responsible for, and directly involved in realising one or several barrier functions.*

Moreover, a further characteristic of safety barriers needs to be addressed and clarified, as it may cause confusion to many. However, consider we have a task to be performed in order to fulfil a barrier function. For example, perform a maintenance activity for one of the process equipment in order to maintain the containment integrity. The task itself is considered as an operational barrier element, whereas the personnel performing the task are organisational barrier elements. The probabilities of success or failure of both barrier elements are affected by number of RIFs. Some other literatures are referring to the RIFs as performance influencing factors (PIFs). The RIFs in our case could be competence, work environment, supervision, etc. It is obvious that the RIFs are not considered as a part of the barrier element itself, but can they have a considerable influence on its performance. However, According to PSA (2013) RIFs are defined as "*conditions which are significant for the ability of barrier functions and elements to function as intended*"

2.2.2. Categorisation of safety barriers.

Similar to barrier definitions, safety barriers can be categorised and classified by several ways and methods. Safety barriers can be classified based on their function, system, or even nature. If we consider classification based on barrier functions, safety barriers can be categorised as proactive (prevention) or reactive (mitigation) barrier functions. Such classification is illustrated in (Figure, 2.5). The proactive barriers are established to prevent and/or reduce the probability of occurrence of the hazardous events. Whereas, the mitigation barriers are acting to reduces the associated consequences of these accidents if occurred. Further, another classification method of barrier functions can be made according to the accident sequence. The ISO 13702 (1999) classifies barrier functions as prevention, control, and mitigation barriers.

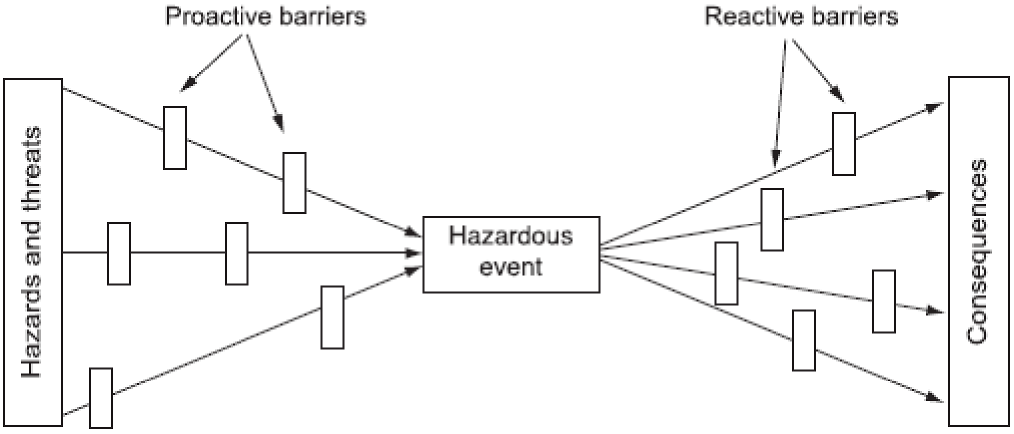


Figure 2.5: Proactive and reactive barrier functions in bow-tie (Johansen and Rausand, 2015 p50)

On the other hand, barrier systems can be classified as, physical or non-physical barriers. There is a broad agreement in the literature that physical barriers refer to technical systems, while non-physical barriers denote non-technical barriers. Non-physical barriers, in that case, involve both human and organisational factors and operational barrier elements, as defined earlier in this section. However, this classification does not differentiate clearly between operational barrier elements and their associated RIFs. For example, non-physical barriers may include human actions, procedures, organisational factors, and so on. Consequently, that could lead to confusion when it comes to barrier analyses. Therefore, it is more precise if safety systems are classified as active and passive systems. Rausand (2011) defined both systems as:

- ***Active system:*** *A system that is dependent on the actions of an operator, a control system, and/or some energy sources to perform its functions e.g. active fire system.*
- ***Passive system:*** *A system that is integrated into the design of the workplace and does not require any human actions, energy source, or information sources to perform its function e.g. passive fire system.*

The above categorisation is compatible to a large extent with the definitions of barrier function and element, as well as safety systems. In other words, such categorisation can allow better identification of safety barriers in different levels of hierarchy; see (Figure, 2.6). Unlike the previous classification method that does not provide a clear distinction between operational barrier elements and RIFs.

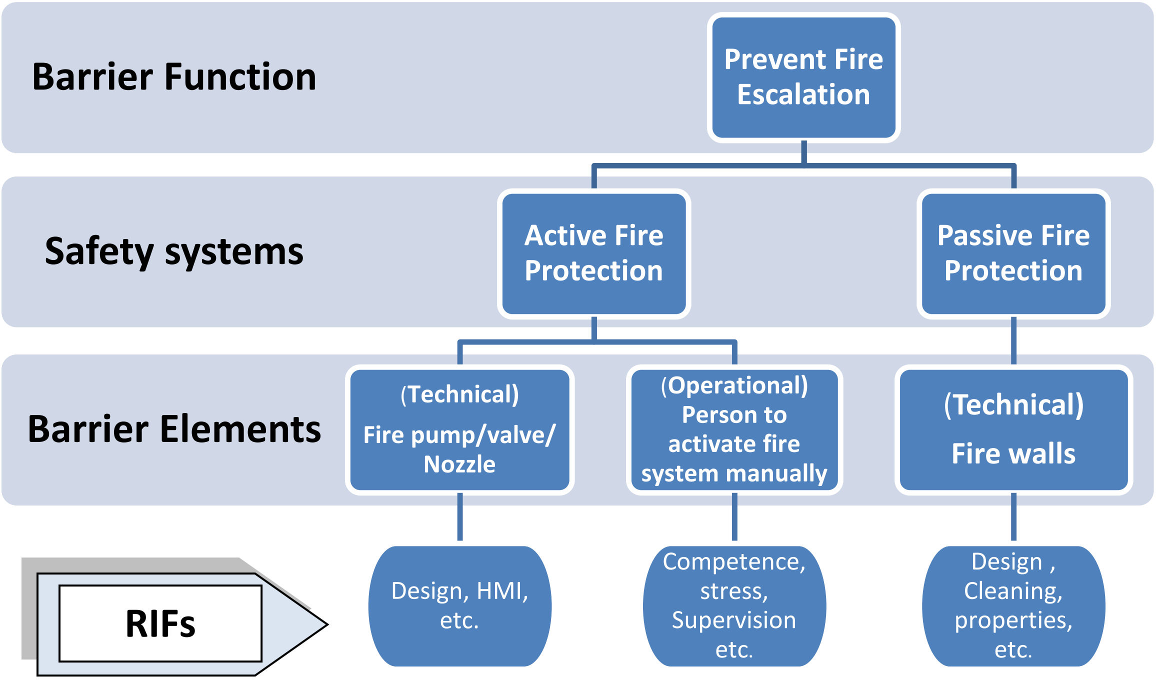


Figure 2.6: Hierarchy of barrier levels including RIFs (adapted from Sklet, 2006)

Regarding barrier classification by nature, Hollnagel (2004) divided barriers to four groups with respect to their nature. Barriers in this classification are material barriers, functional barriers, symbolic barriers, and incorporeal barriers. However, since barrier classification by nature is not considered in this project, the four groups of barrier nature are not defined or discussed any further.

2.2.3. Performance of safety barriers.

Safety barriers that used on board the oil and gas production facilities are a main focus for all concerned parties. Further, it has to be well designed and maintained in order to perform its intended functions when needed. Therefore, there should be a set of predefined requirements for verifying and evaluating the performance of safety barriers while design and operations. Such requirements are called performance criteria.

Performance criteria of safety barriers have been identified and discussed in many literatures. However, Sklet (2006) has proposed five characteristics that are representing the performance criteria of safety barriers. Such characteristics are *functionality, reliability, response time, robustness, and triggering event or condition.* These aspects are determined based on several literature reviews and experience from several projects (Sklet, 2006). However, such criteria are defined as mentioned below according to the above reference:

- ***Functionality / effectiveness****: is the ability of a safety barrier to perform a specified under given technical, environmental, and operational conditions.*
- ***Reliability / availability***: *is the ability of a safety barrier to perform a function with an actual functionality and response time while needed, or on demand.*
- ***Response time :****is a time of a safety barrier is the time from a deviation occurs that should have activated a safety barrier, to the fulfilment of the specified barrier function*
- ***Barrier robustness:*** *is the ability of a safety barrier to resist given accident loads and function as specified during accident sequences.*
- ***Triggering event or condition:*** *is the event or condition that triggers the activation of a barrier.*

3. Safety Barriers on the Norwegian Continental Shelf

Prevention and mitigation of major accidents on board the offshore production facilities is a top concern for all of the involved parties in the petroleum industry. Accordingly, the topic of safety barriers is a higher priority in the international and the local regulations and standards. In addition, further efforts are being conducted by oil and gas companies, as well as the other consulting firms and classification societies. Therefore, there are several regulations, standards, and reports covering and describing the various aspects of safety barriers during on offshore facilities.

This chapter introduces a brief revision of the current regulatory requirements that being used on the NCS for managing safety barriers on board the offshore production units. These requirements include regulations and guidelines that presented by the Petroleum Safety Authority (PSA), in addition to, the NORSOK standards. Also, a revision of the current approach for managing safety barriers at DNV GL is presented.

3.1 Safety Barriers in PSA.

The PSA is an independent governmental regulator that responsible of regulating safety, emergency preparedness and working environment in the Norwegian petroleum industry. The PSA has issued a number of regulations stating the key obligatory requirements that have to be followed by the operators working in the NCS. In addition, it has also released different supplementary publications in order to provide a better understanding to the relevant topics of safety and risk management.

The current sections introduces a brief revision of the topics that relevant safety barriers management as mentioned in the PSA regulations. However, the report that has been published by PSA (2013) under the name of the principles of for barrier management is not reviewed, as it is not considered as a part of the regulatory requirements.

3.1.1 Barriers in PSA Regulations.

The PSA has five sets of regulations as listed below:

- The framework HSE regulations
- The management regulations
- The facilities regulations
- The Activities regulations and,

- The technical and operational regulations.

The framework HSE regulations (PSA, 2010c) introduce the basic principles, which have to be considered and implemented by the operators on NCS in order to ensure that all activities are being conducted with high standards of health, safety and environment. Also, it is enforcing the concerned parties to implement the required measures in accordance with the predefined requirements, as well as ensuring a systematic development and improvement of health, safety and environmental level. However, safety barriers are not mentioned explicitly in this set of regulations.

Unlike the management regulations (PSA, 2010d), which states in section five the necessary requirements of safety barriers on board the offshore and onshore facilities. Specifically, it has been mentioned that the establishment of safety barriers is mandatory for the sake of reducing the possibility of occurrence and development of undesired events. The undesired events can be failures, hazard and/or incidents. The proposed barriers and barrier strategies are implemented and performed after the identification of the conditions that lead to the above mentioned adverse events. Moreover, in case of existence of such events, barriers have to control and limit the consequent harms to human, environment and assets.

On the other hand, independence between barriers is essential in case of presence of more than one barrier for the same purpose. Also, the operators have to provide sufficient information about principles and strategies that act as the basis for design, operation and maintenance of safety barriers. The purpose of presenting such information is to guarantee that the intended barrier functions are adequately existing and preserved with the required performance through the life cycle of the asset.

Additionally, personnel must be aware of the available barrier functions on board the facility, as well as the relevant performance of these barriers. The measures, in that case, are defined as technical, operation and organizational barriers. In the case of presence of impairment or malfunction of barriers or barrier elements, the issue has to be known by all personnel. That is mandatory in order to ensure that workers on board the unit are aware of the degraded barriers. Furthermore, degradation of safety barriers has to be addressed with the necessary remedial actions.

Regarding the facilities regulations (PSA, 2010b), this set of regulations is providing the operators with the regulatory requirements for the design and equipment of facilities. With respect to safety barriers, sections seven and eight are introducing the requirements of main safety functions and safety functions respectively. The earliest section describes the characteristics of main safety functions in terms of, preventing escalation, sustaining accidental loads, protecting safe areas on the facility, and maintaining at least one escape route for each area where personnel are found, so they can abandon the facility safely. Whereas, the latter section states the intended roles of safety functions on board facilities. In particular, it is mentioning that facilities shall be equipped with necessary safety functions in order to detect abnormal conditions and prevent them from developing into harmful situations. In addition, safety functions have to limit the consequence of the resulting accidents and to maintain losses as low as possible. Moreover, performance requirements of safety functions shall be described clearly. In addition, the status of active safety functions shall be available in the central control room.

In Chapter five of the same regulations, the descriptive requirements of physical barriers are introduced. Physical barriers in this chapter are presented as technical safety systems, for example, fire detection, fire systems and emergency shutdown system (ESD). Further, with regards to drilling operations, in section forty-eight, the requirement of well barriers in different situations are provided.

As an important part of the activities regulations (PSA, 2010a), section twenty-six states that safety systems that perform all safety functions must have predefined measures and restrictions to compensate impairment. Implementation of these measures shall be done immediately when any impairment occurs. Furthermore, the status of all safety systems shall be known by and available for relevant personnel at all times. In addition, section forty-five indicates that all safety systems shall be maintained in a good condition, so they can meet the required performance in case of demand.

3.2 Safety Barriers in NORSOK Standards.

The NORSOK standards have been developed by the Norwegian petroleum industry in order to ensure safe and sufficient design and operations of the oil and gas facilities. The NORSOK standards cover a broad range of topics that relevant to oil and gas industry. In particular, the topic of safety barriers has been mentioned in several standards, as it is a main focus on the NSC. However, on the other hand, a limited number of these standards have been described safety barriers explicitly. Such standards are:

- NORSOK S-001(2008): Technical safety

- NORSOK Z-013 (2010): Risk and emergency preparedness assessment
- NORSOK D-010 (2013): Well integrity in drilling and well operations.

In this section, a brief review of the above standards is presented. However, the NORSOK D-010 (2013) is not covered in this section, as the drilling activities are not in the focus of the thesis.

3.2.1 Safety Barriers in NORSOK S-001

The NORSOK S-001 (2008) introduces a set of the technical safety systems and functions that being used on board the offshore installations. The purpose of this standard is to describe the principles and requirements for the development of the installations' safety design. The standard is mainly targeting the production installations. However, offshore drilling units can also use it where applicable.

In particular, this standard covers a specified number of elements for each of the presented safety systems and/or functions. However, the aspects that covered in this standard for each safety barriers are as mentioned below:

- **The role of the system / function.**

In this part, a brief description of the intended task that needs to be performed by this function/system is given. For example, "*the firefighting system has to provide quick and reliable means for fighting fires and mitigate explosion effects*".

- **Interface with other safety systems and barriers**.

This aspect provides the reader with the safety barriers and elements that interfaces with the descried safety function/system. Consider the firefighting system again. The standard states that the firefighting system is interfering with all of:

  - Open drain;
  - ESD;
  - Gas detection;
  - Fire detection;
  - Ignition source control (ISC);
  - Emergency power.

- **Required utilities.**

The required utilities involve all the required utilities for the system in order to fulfil its role. For instance, the performance of the firefighting system depends on instrument air system, emergency power system, etc.

- **Functional requirements.**

Functional requirements provide the answer of what is the required performance for this safety barrier for fulfilling its system. Such requirements could, for example, be the discharge capacity of the fire pump, the number of fire nozzles on each compartment, and so on. In other words, functional requirements are representing the performance criteria that introduced in the previous chapter except the robustness criterion.

- **Survivability requirements.**

Such requirements determine the needs for the safety system/function to withstand the dimensioning accidental loads (DALs). This part covers the robustness performance criterion or the safety system. As an example, "*all firefighting equipment shall maintain its integrity during DALs. This includes cables for fresh water (FW) and centralised foam pumps*".

However, the NOSOK S-001 (2008) introduces generic safety systems/functions, as well as common performance requirements. Therefore, more specific requirements and systems could be identified by other specific standards and /or companies' internal guidelines.

3.2.2 Safety Barriers in NORSOK Z-013

The NORSOK Z-013 (2013) is a standard that describes the general requirements of risk assessment on offshore oil and gas platforms during the different phases of the life cycle. The standard has identified how to include the performance of safety barriers in the risk assessment framework. In addition, it has proposed a set of hazardous events that should be accounted in the analysis as a minimum requirement. In addition, a collection of different safety barriers those are used to confront these accidents are introduced. These barriers have to be assessed against accidents with respect to their performance criteria. However, if the process leaks hazard is considered, some of associated safety barriers will be:

- Detection systems,
- ESD System,
- Active fire system,
- Passive fire system,

- Escape routes.

The above barriers are examples of what is provided in this standard. However, these barriers are not restricted only for the process leaks hazard. In other words, some of these barriers are used to deal with different hazardous events as well. For instance, the active fire system is used also in riser leaks, blowout, and utility fire hazards.

The standards has also mentioned some tools and techniques for modelling operational and technical barriers in risk analysis such as event trees (ET) and fault trees (FT). However, more details about modelling safety barriers in risk analysis are introduced in the next Chapters.

3.3 Safety Barriers in DNV GL.

Similar to the NORSOK standards, the DNV GL has published several reports and guidelines that involve the topic of safety barriers. The current section presents a brief review of the contents of a report that describes the SBM process in operations phase. The report has been released by DNV GL in 2014 under the title of "*Barrier Management in Operation for the Rig Industry*" (DNV GL, 2014).

This report is focusing on the management of safety barriers in the operations phase. In detail, this report starts with introducing a background and the rationale behind safety barriers, as well as presenting a number of the relevant definitions to safety barriers. However, some of these definitions are used earlier in Chapter 2. Moreover, a detailed explanation of the process that following the establishment of performance standards has been introduced. The process involves different activities such as; the role of maintenance in prevention of barrier degradation. Furthermore, the topic of managing the operational barriers are introduced. This part highlights the necessity of performing drills and training in order to maintain the good performance of all personnel that involving at any safety critical task.

In addition, the assurance and verification activities are fairly described. The assurance and verification activities are primarily concerned about guarantee that all safety barriers are consistent and matching the performance requirements. In other words, they are ensuring that the Swiss cheese holes in all safety barriers are kept as small as possible.

Another topic has been covered in this report, which is monitoring the performance of safety barriers. The performance of safety barriers is a key parameter of the final risk picture of any offshore facility. For example, if the performance of one or more safety barriers has been reduced during the operational phase, a latent change will occur to the final risk level.

Consequently, the offshore unit might fall within the unacceptable region of risk without notifications to the operators. Therefore, the monitoring activity is mandatory in order to keep track of the status of safety barriers in time. That can be achieved, for example, by identifying and monitoring the most critical parameters of a safety barrier and monitoring them continuously by personnel located in the Central Control Room (CCR). However, the most critical parameters are usually chosen bases on their sensitivity in the risk assessment.

In addition, a framework for managing the safety barriers from day-to-day activities, as well as the continuous improvement has been proposed at the end of this report. This part discusses the importance of reviewing the different work permits (WP) and assessing their influence on the safety systems. Also, it is mandatory to identify the influence of each permit on the other activities and works that being conducted at the same duration of the task. Moreover, this part also has mentioned the importance of reporting and investigation of incidents and the reflection of them of the safety barriers' performance.

4. Safety Barrier Analyses in QRA

The preceding Chapters presented a general overview of the concepts of risk assessment and safety barriers, as well as their relevant regulatory requirements on the NCS. In addition, the PSA management regulations (PSA, 2012d) have also mentioned the important role of safety barriers on board the production facilities. The importance of safety barriers is originated from their significant effect on preventing and reducing the possibility of occurrence of MAH. Furthermore, the NORSOK Z-013 states that the effect of safety barriers in risk reduction is calculated through QRAs. However, all these facts raise the below three important questions:

1. What are the MAH that need to be considered when performing the QRA, as well as their associated safety barriers?
2. How could these safety barriers be included in the QRA model?
3. How can the performance of safety barriers being quantified sufficiently in QRA to present a better prediction of risk level?

The answers of the above questions are introduced in this Chapter. Each of these answers is introduced in a separate section in the same order of the questions. Moreover, an additional section is introduced at the end of the Chapter for highlighting the major findings from the entire Chapter.

4.1 Major Accident Hazards and Safety Barriers on Offshore Platforms.

4.1.1 Major Accident Hazards

As mentioned earlier in Chapter 2 the QRAs are used for managing the major accident hazards which has a low probability of occurrence and severe consequences. However, the offshore platforms are complex structures and consist of several modules that contain a large diversity of equipment. Therefore, it is mandatory to identify exactly what are the major hazards in order to establish the necessary prevention and mitigation barriers. Accordingly, the NORSOK Z-013 has introduced the following nine groups of hazards as a minimum to include when analysing risk in quantitatively.

1. Process leaks;
2. Risers/landfall and pipeline accidents;
3. Storage accidents (Liquid and gas);
4. Loading/offloading accidents;

5. Blowouts and well releases;
6. Accidents in utility systems;
7. Accidents caused by external impact and environmental loads;
8. Structural failure;
9. Loss of stability and/or buoyancy.

All of the above hazards can lead to severe losses to human, environment, and assets if not controlled with the proper barriers.

Among all of the above hazards, the process leaks, riser accidents and blowouts are the most hazardous events that can result in catastrophic consequences. That is due to the potential leak of huge quantities of Hydrocarbons (HC), especially when it is under pressure. Therefore, it is mandatory in risk analysis to identify the causes and scenarios that can result in such events. However, the following part of this section describes the process leaks hazard. The other hazards are not described further as they are out of the main focus of the report.

4.1.2 Process Leaks Hazards

According to Spouge (1999), process leaks is defined as HC releases from a production platform other than those occurring from well releases, riser leaks and other systems that separate from production flow. The production flow may include separators, compressors, pipes, flanges, valves, etc.

The process leaks can be in the form of liquid leaks, gas clouds or mixture of both of them. The consequences of a hydrocarbon releases can vary from an un-ignited minor leak/cloud up to a catastrophic fire(s) and explosion(s). Therefore, it is mandatory to address the different scenarios that could lead to such releases in the hazard identification step of the risk analysis. Afterwards, the frequency of each release scenario and the probabilities of the consequent escalation scenarios have to be calculated in order to identify the final risk level. The safety barriers are playing an important role at this stage for reducing the release frequencies and consequence probabilities.

The identification of safety barriers being used for preventing the occurrence of major accidents that resulting from the HC releases on production platforms is a challenging task. For example, which barriers should be implemented, as well as how these barriers can be categorised under separate functions. For this purpose, Sklet et al (2005) has introduced the following barrier functions:

- Prevent loss of containment,
- Prevent ignition,
- Reduce cloud/emissions,
- Prevent escalation, and
- Prevent fatalities.

Some of the safety systems that being used in connection to the above five barrier functions are illustrated in (Figure, 4.1).

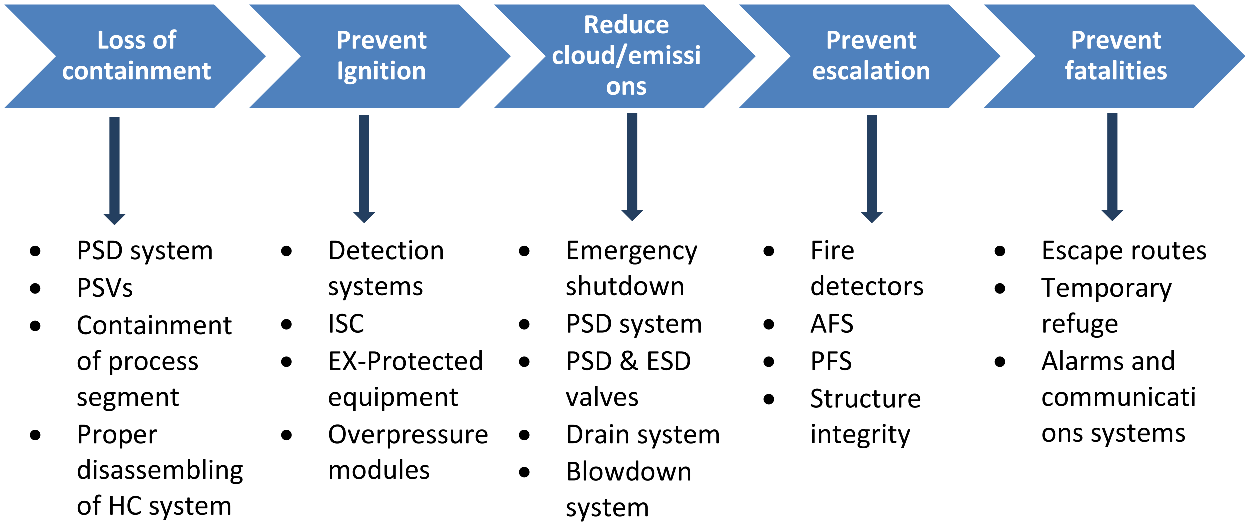


Figure 4.1: Process leaks' barrier functions and systems adapted from

The above five barrier functions are the most relevant when the HC leaks are considered. As introduced earlier in Chapter 2, each barrier function is consisting of a number of barrier elements and safety systems. Some of these systems can be a part of more than one barrier function. For examples, gas detection system is interfering with ESD and firefighting system (NORSOK, 2008). On the other hand, independence between the different safety systems is also necessary in order to ensure sufficient redundancy.

4.2 Modelling of Safety Barriers in QRA

4.2.1 Introduction

The safety barriers are considered as the pivot point of risk analysis. That because they are the measures that used to prevent and mitigate the occurrence of undesired events. However, with reference to the different steps of risk assessment that have been introduced in Chapter 2. The safety barriers are included in the risk assessment after the hazard identification stage. At this point, the proactive barriers are modelled in the cause analysis in order to calculate the frequency of the initiating/hazardous events. Whereas, reactive barriers are used for calculating the probabilities of the different accident scenarios in order to reduce the outcomes. In other words, the identification of hazardous events in risk analysis should be followed by the specification of the triggering events. For example, Vinnem (2014) has proposed the below categories of triggering events that used when a process leak is considered as an initiator.

- Technical degradation of system,
- Human intervention (introducing latent error or causing immediate release),
- Process disturbance,
- Inherent design errors and
- External events.

In this case, the proactive barriers are implemented to prevent the release from the process segment. Whereas, when the initiating events occur, the reactive barriers are present in order to stop or reduce the escalation of the accident scenario.

The bow-tie diagram is one of the well-known tools for combining the cause analysis and the modelling of the accident sequences in risk assessment. As illustrated in (Figure 4.2), the left side of the diagram depicts the paths of the different causes of a specific hazardous event including the proactive barriers. In this case, the barriers are modelled by means of FTs. While, on the right side the reactive barriers are modelled in the accident sequences with ETs.

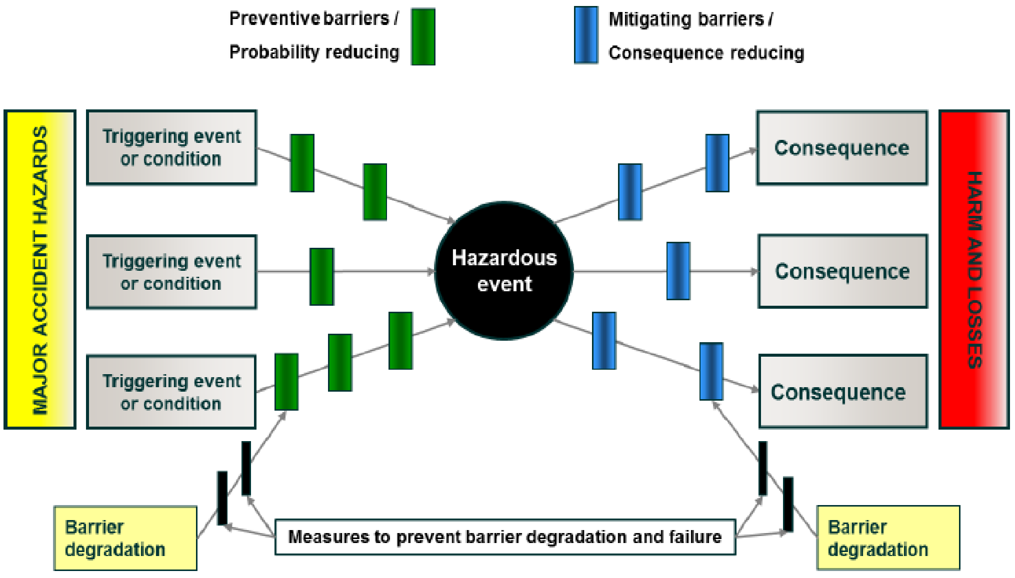


Figure 4.2: Bow-tie diagram (DNV GL, 2014)

The reactive barriers are usually represented in the ETs with probability of failures. Such probabilities are reflecting the background knowledge about the failure of these barriers. However, the safety barriers are not included in the ET separately. Rather, they are categories under a number of roles and in a predefined order. Such categorisation and sequence are identified previously in the accident development scenarios. The accident scenarios are determined normally based on several factors, for instance, the release source and its location, as well as the nature of the HC. However, the following section introduces more details about modelling safety barriers in ETs.

4.2.2 Modelling of safety barriers in ETs.

According to Vinnem (2014), an event tree is a tool that is used to illustrate the chain of development of a hazardous event against the performance of the mitigation safety barriers (e.g. the right side of the bow-tie model). An ET starts with the frequency or probability of occurrence of a hazardous event. Afterwards, it followed by a sequence of questions with two possible answers which are 'yes' or 'No'. The answers of these questions denote the success or failure of the assigned mitigation barriers. Each of these questions is considered as a node in the event tree where the two possible answers of each node are leading to two more branches. However, this might be the most used approach, but a node in the ET can also have more than 2 branches as long as the probabilities of that node sum up 1.

These processes are repeated until the ET ends up with the different probabilities or frequencies of the different outcomes. The ending events are also called termination events; see (Figure, 4.3). However, The NORSOK Z-013 standard states that when using event trees, the nodes shall reflect the most important barriers that being used with the particular hazard.

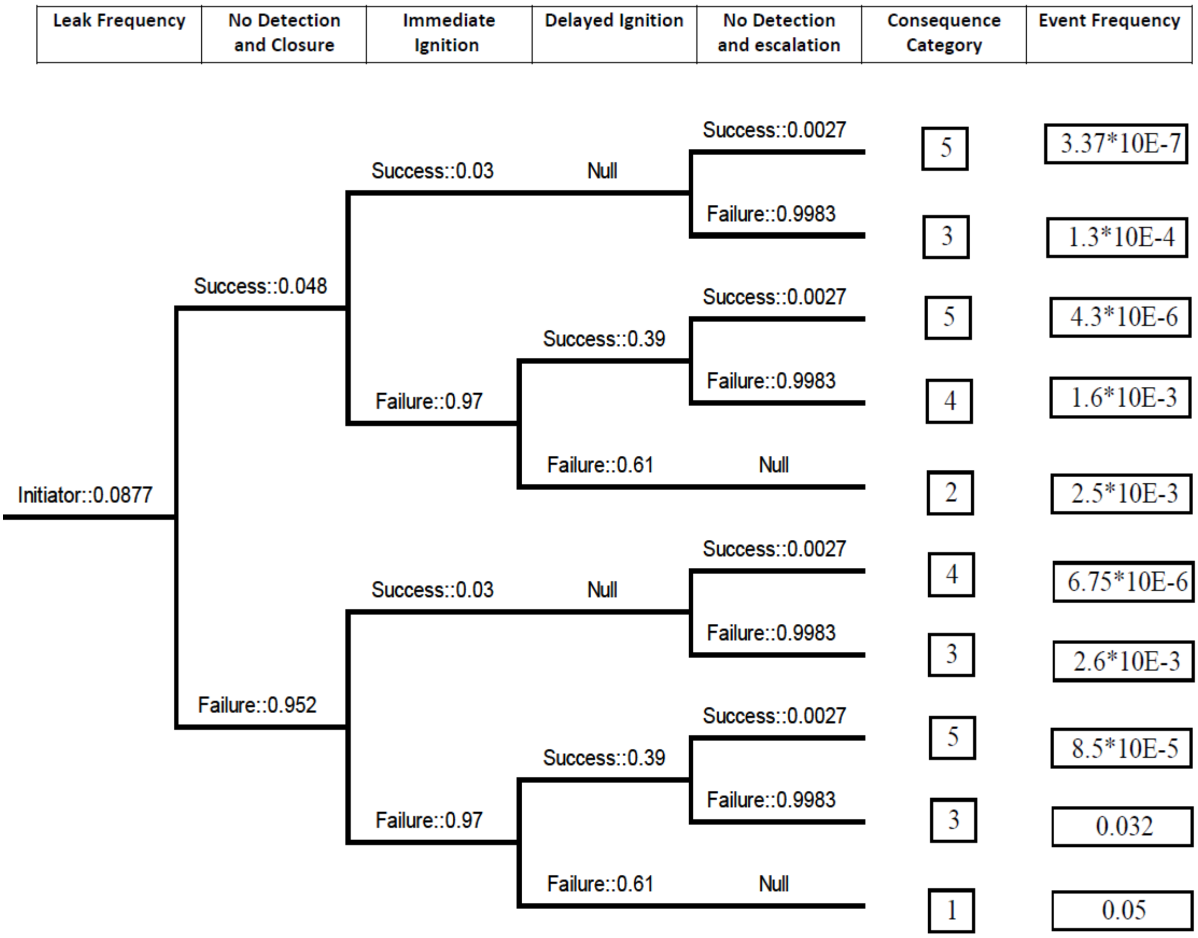


Figure 4.3: Illustration of event tree analysis

Example:

Let us consider that we have a gas leak from a process separator. The question here is how could this release modelled in an ET. A released gas cloud is normally having three possible outcomes which are:

- No ignition,
- Immediate ignition and
- Delayed ignition.

The occurrence of each of the above results is influenced by the performance of the relevant safety barriers. Furthermore, the development of the ignited cloud is affected by the feed of the released HC substance and the performance of the escalation prevention barrier functions. At this point of the ETA, we will get the probabilities of all the accident outcomes. Each of these outcomes is considered an initiator of the emergency preparedness assessment

(EPA). However, since we are focusing on the mitigation barriers of the HC leaks in this report, therefore, such assessment is not considered.

In the light of the above example, the nodes of the event tree can be identified in many different ways and orders. As an example, please see (Figure, 4.3):

As mentioned before in this chapter, each node is displayed in the ET as a probability of failure. But it is important to identify the underlying parameters of this probability. Such probability is assigned based on a combination of different PFDs of the contributing barrier elements in this node. Therefore, the probability of each node is usually connected with a separate FT, which involves all the elements that participating to realize the node. However, a simplified illustration of the FT that realize the 'Detection failure and escalation' node is introduced in (Figure, 4.4).

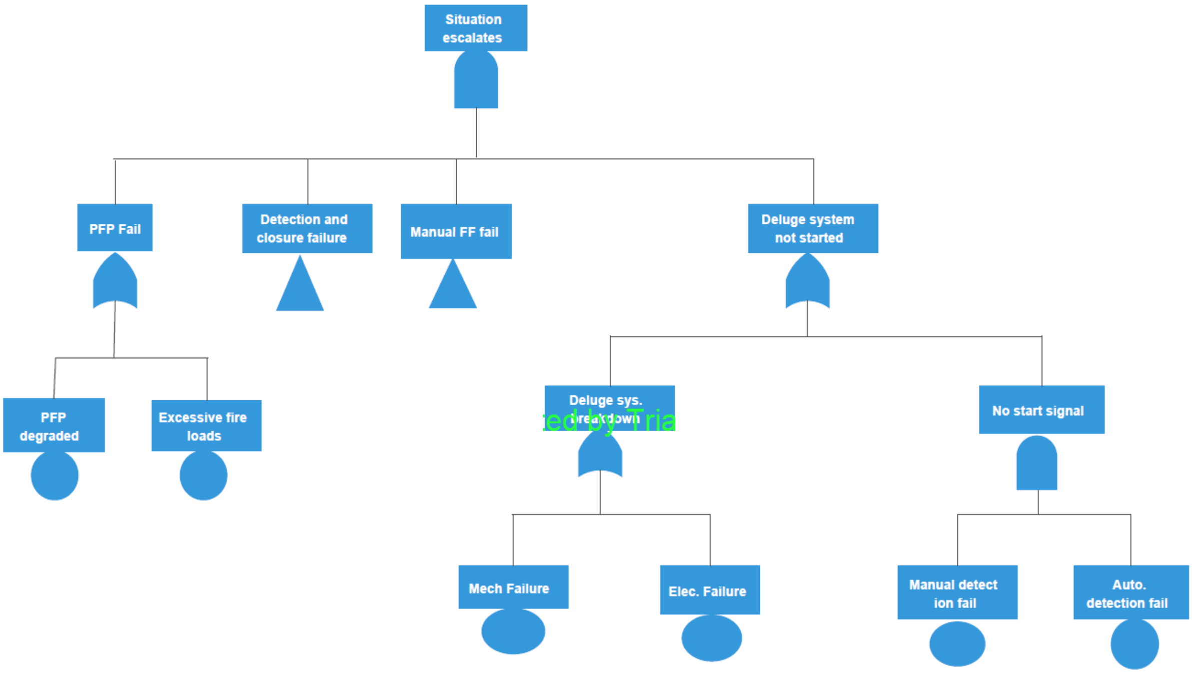


Figure 4.4: Integrated FT with detection failure and escalation node.

The above figure shows that a single node can involve several technical and operational barriers when modelled with FT. However, in order to obtain the node's probability we need to quantify the underlying barrier elements. The quantification of technical barrier elements is done by means of reliability analysis. While, the human reliability analysis (HRA) is used for quantification of operational barriers. The next section show how could the performance of safety barriers be quantified in QRAs. However, the quantification of the operational barriers is not addressed any further as it is out of the scope of the thesis.

4.3 Quantification of Safety Barriers in QRA.

According to NORSOK-Z013, the required details for modelling the performance of safety barriers are depending on the phase that the QRA is performed in. In the concept selection phase, the assigned probabilities of safety barriers do not involve too many details. That because the main purpose of the QRA, in this phase, is to introduce guidance for the decision makers in order to select between the different alternatives. Unlike the design phase, where the QRA is performed primarily for ensuring that all the hazardous activities in operations will be carried out as safe as reasonable. Therefore, the probability assignment of safety barriers has to be based on a detailed analysis. In particular, actual experience data have to be obtained for the determination of the probability of failures of safety barriers. Moreover, for the Safety Instrumented Systems (SIS), the probabilities of failure shall be in accordance with the Safety Integrity Level (SIL) requirements. However, for more details about SIS and SIL requirements see Appendix (A).

In accordance to the above requirements, the safety systems are usually well designed and tested before operations. That is captured from the high reliability of the components that included in these systems. However, it is also necessary to look beyond the technical matters when considering the performance of safety barriers in operations (Vinnem, 2014). Therefore, the NORSOK Z-013 is also requires that as far as possible, the effect of HOFs has to be considered when computing the reliability of safety barriers in QRA. For example, competence of the person who is performing the maintenance for a safety system can affect the system performance. In other words, the more the person is experienced, knowledgeable and well trained the more the system is maintained properly. On the other hand, the lack of competence in this situation can lead to poor maintenance and consequently result in latent degradation in the system performance.

Accordingly, different models have been developed in order to reflect the impact of HOFs as well as technical factors on the performance of safety barriers. Some of these models are:

- BORA-Release project (Sklet et al, 2006)
- Risk_OMT (Vinnem et al, 2012)

The first model is mainly determines the impact of MTO factors on the performance of safety barriers used to prevent loss of containment. The soft relationship between the MTO factors and safety barriers is addressed through a set of RIFs. Furthermore, the RISK_OMT is a model that built on the results of the BORA project (Vinnem, 2014). This model is giving more importance for HOFs than the BORA model. However, a detailed presentation of both models is introduced in the following parts of this section.

4.3.1 Barrier and Operational Risk Analysis (BORA Project)

The BORA project is a result of a research that has been conducted in the period from 2003 till 2006 in Norway. The motivations for this project were the findings that gained from one of the scientific papers that introduced by Vinnem et al (2003). The paper showed that there is a significant need for improving the barrier analysis. In particular, it is required to consider the effect of the MTO factors on the performance of safety barriers in operations phase. The BORA method is developed primarily for modelling the associated barriers with loss of containment barrier function. However, the methodology can be adjusted and used also with the other barrier functions. The methodology is described in this part is based on Haugen et al (2007) unless otherwise mentioned.

The methodology consists of ten sequential steps as presented below:

Step 1: Identification of initiating events

The starting point of the BORA project is the identification of the triggering events that if developed can lead to the initiating events. When taking into consideration the HC leaks as a hazardous events. The different initiating events can be grouped under the below categories:

A) Technical degradation of system.
B) Human intervention introducing latent error
C) Human intervention causing immediate release
D) Process disturbance
E) Inherent design errors
F) External events.

Step 2: Assignment of generic initiating event frequencies.

The assignment of the frequencies of the initiating events can be done in two different methods.

1. To assign the probabilities based on the generic leak frequency of each equipment as calculated in the QRA and then multiplying them in the probability of distribution of the initiating events. This method is providing the leak frequency that each IE

contributes in. Assume that the gas leaks that occur from the incorrect isolation/blinding error is 10% and the total leak frequency of the small leak category is 10^{-4}. Then the frequency of small leaks for the entire segment due to this error is 10^{-5}. See the below equation.

$$f_{GL,IE_1} = f_{GL,Total} * P_{IE_1}$$

2. Alternatively, the assignment of the frequency of the initiating event can be obtained based on the human error probabilities (HEP) of the underlying activities of the initiating events. In this approach, the leak frequency is computed by multiplying the HEP in the frequency of performing a particular activity. Accordingly, the project has introduced a number of the recommended HEP that can be used for this purpose. See (Table, 4.1).

Initiating Event Group	**Specific Initiating Event**	**Recommended HEP Assignment**		
		Lower Assignment	**Upper Assignment**	**Average**
B. Human intervention introducing latent error	B.1 Incorrect blinding/isolation	$1 . 10^{-2}$	$1 . 10^{-1}$	$5 . 10^{-2}$
	B.2 Incorrect fitting of flanges or bolts	$1 . 10^{-3}$	$1 . 10^{-2}$	$5 . 10^{-3}$
	B.3 Valve(s) in incorrect position after maintenance	$1 . 10^{-2}$	$1 . 10^{-1}$	$5 . 10^{-2}$
	B.4 Erroneous choice/installation of sealing device	$5 . 10^{-3}$	$5 . 10^{-2}$	$3 . 10^{-2}$
	B.5 Maloperation of valve(s) during manual operation.	$1 . 10^{-2}$	$1 . 10^{-1}$	$5 . 10^{-2}$
	B.6 Maloperation of temporary hoses.	$1 . 10^{-2}$	$1 . 10^{-1}$	$5 . 10^{-2}$
C. Human intervention causing immediate release.	C.2 Maloperation of valve(s) during manual operation.	$1 . 10^{-2}$	$1 . 10^{-1}$	$5 . 10^{-2}$

Table 4.1: Recommended HEP assignments to be used for IEs (Haugen et al, 2007, p8)

Step 3 – 6: Development of barrier block diagram (BBD), development of FT, assignment of the generic input data, and calculating the leak frequency based on the generic input data.

The steps located in this interval are quite similar to the approach that has been introduced in section 3 of this Chapter. Specifically, after the identification of the HC leak frequencies, different BBDs are developed. The BBDs are modelling the mitigation barriers that are used to stop the development of the specific leak scenario, see (Figure, 4.5). Further, each block in the BBD is connected with an underlying FT. Such FT shows the logical relationship between the different errors that contribute in the safety barrier's failure.

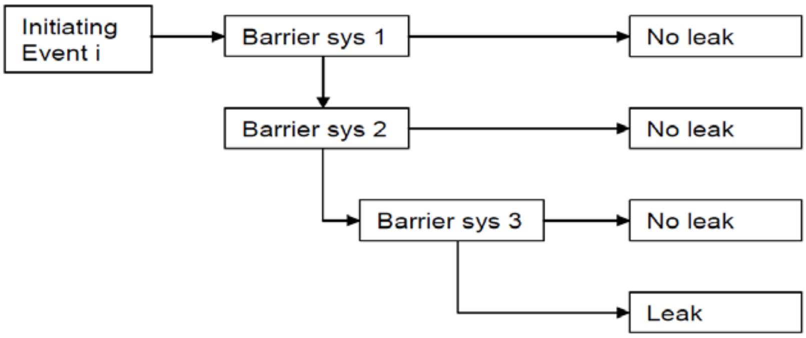


Figure 4.5: Leak development scenario in BBD

Afterwards, the assignment of the probability of failure of each basic event in the FT should take place. The basic events, in this case, can be a reliability of a technical component (e.g. reliability of a pressure transducer) or a HEP for a specific activity (e.g. fail to tighten bolts correctly). The probabilities of failure are normally assigned based on the historical data sources. However, other probabilities are included in the FT are from the platform specific data.

Thereafter, the generic leak frequency that resulting from a particular IE is calculated based on the below formula:

$$f_{GL,IE_1} = f_{IE_1} * P_{f,BS1} * P_{f,BS2} * P_{f,BS3}$$

Where

$$P_{f,BSi} = probability\ of\ failure\ of\ barrier\ system\ i$$

The FT is used for calculating the probability of failure of each barrier system that modelled in the BBD.

Step 7: Identification of RIFs for IEs and basic events.

As mentioned earlier in the thesis, the RIFs are factors that influencing the performance of the safety barriers. However, the BORA project has introduced five groups of RIFs that are affecting the frequency of IEs as well as the basic events in FT. The RIFs categories are:

- Personnel characteristics
- Task characteristics

- Characteristics if the technical systems
- Administrative control
- Organisational factors / operational philosophy

See Appendix (B) for the full list of RIFs with a short description for each as presented in the BORA project.

However, Each IE and basic event in the fault tree has a number of RIFs that influence its performance. However, for simplification, the most important 3 – 5 RIFs are selected and modelled with the event by means of a risk influence diagram (RID) see (Figure, 4.6)

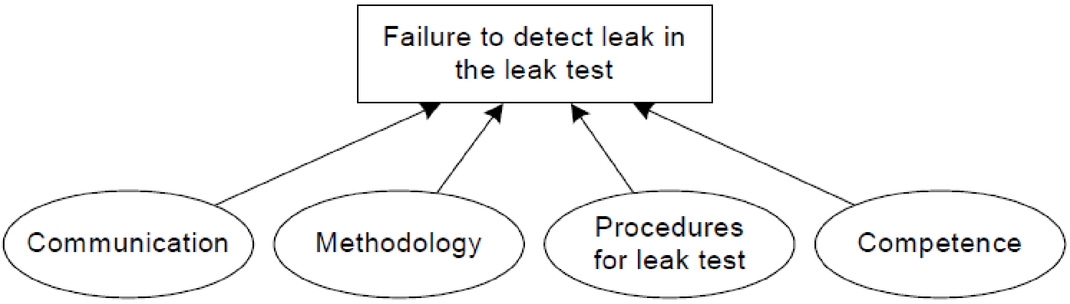


Figure 4.6: Risk influence diagram example (Aven et al, 2006)

Step 8: Assignment of weights and scores of RIFs

After the identification of the relevant RIFs to each IE and basic event, each of these RIFs is assessed against the below two criteria:

1. Their effect (importance) on the occurrence of the IEs or basic events.
2. Their status with respect to the industry standards.

The first criterion is fulfilled by assigning importance weights for all of the selected RIFs to the particular event. The weighting process is based on a five point scale, which is 10-8-6-4-2. In such scale 10 denotes the highest importance where the lowest is denoted 2. Afterwards, the weights are normalized where the sum of the weights or RIFs for a particular event equal to 1.

In order to fulfil the second criterion, the status of the RIFs are scored according to the industry standard based on the below scheme.

Score	Explanation
A	Status corresponds to the best standard in industry
B	Status corresponds to a level better than industry average
C	Status corresponds to the industry average
D	Status corresponds to a level slightly worse than the industry average
E	Status corresponds to a level considerable worse than industry average
F	Status corresponds to the worst practise in industry

Table 4.2: Generic scoring scheme for RIFs (Haugen, et al, 2007, p14)

Step 9: Collection of data for RIFs

This step is answering two important questions, which are on what basis the RIFs are selected, as well as how their scores and weights are assigned. The best practice for performing this process is to rely on the work meetings of the different experts. Also, the data from precursor MTO investigations, audits, and operational experience can be used as an important source for this process. However, the selection, scoring and weighting of the RIFs cannot be treated as a general rule for all platforms. Rather, each platform has a different nature and circumstances that affecting the performance of the safety barriers. Even if a similar safety barrier is being used on board two different platforms. In addition, if there are two identical platforms are operating in two different countries. There is still a need for performing the process of selecting and weighting RIFs specifically for each platform.

Step 10: Calculation of platform specific leak frequency.

Calculation of the platform specific leak frequency is the last step in the BORA project. The purpose of this step is to present the procedures of including the effect of the different RIFs on the IEs and basic events. In other words, it is introducing a method of adjusting the industry average data into a platform specific data. Hence, the platform specific leak frequency is calculated based on the following procedure:

$$P_{rev}(A) = P_{avr}(A).\, k_i$$

$P_{rev}(A)$ Denotes the revised probability of occurrence of event A.

Where

$$k_i = \sum_{i=1}^{n} w_i \,.\, Q_i$$

w_i denotes the weight of RIF no. i for event A. Whereas, Q_i is quantitative value for measuring the status of the RIF i, and n is the number of RIFs.

The sum of all weights of RIFs for a particular event is equal to 1. On the other hand, the values of the different Q_i's are calculated by the following method:

First we need to assign a lower limit and a higher limit for the revised probability based on the expert judgement. Further, let us denote the RIFs status s, and then we assign different numbers for each score. i.e. $S_A = 1, S_B = 2, \dots \dots and\ S_F = 6$. Accordingly, the different values of the measure $Q_i(s)$ can be calculated as follows:

$$Q_i(s) = \begin{cases} \frac{P_{low}}{P_{avr}} if\ s = A \\ 1 \quad if\ s = C \\ \frac{P_{high}}{P_{avr}} if\ s = F \end{cases}$$

Furthermore, to assign values for $Q_i(B), Q_i(D)\ and\ Q_i(F)$, we assume a linear relationships between $Q_i(B)\ and\ Q_i(C)$, as well as between $Q_i(C)\ and\ Q_i(F)$ separately. Hence, we can get the values of the other $Q_i s$ as shown below.

$$Q_i(B) = \frac{P_{low}}{P_{avr}} + \frac{(s_B - s_A) \,.\, (\frac{P_{low}}{P_{avr}})}{s_C - s_A}$$

$$Q_i(D) = 1 + \frac{(s_D - s_C) \,.\, (\frac{P_{high}}{P_{avr}} - 1)}{s_F - s_C}$$

Whereas, $Q_i(E)$ is calculated same as $Q_i(D)$ but by using s_E instead of s_D.

The BORA project is adding a significant value to the safety barriers modelling in QRA. Such value gained through the reflection of the operational factors impact on the assigned failure probabilities. It can also be used for identifying the possible improvements in the risk level based on improving the operational activity standards. Moreover, the model has combined the historical data and expert judgement when identifying the weighing the RIFs. The integration of both sources of information introduces a better understanding of safety barriers, in addition to, more robust results. However, the BORA model has received some criticism about the lack of justification of the weighing process of RIFs importance and the factor Q_i . Nevertheless, such improper justification does not reduce the value and applicability of the model (Rausand, 2011).

4.3.2 Risk_OMT Project

The Risk_OMT model is an extensive development of the work performed in the BORA and OTS projects (Vinnem et al, 2012). In the BORA model, all RIFs are given the same importance in structure as shown earlier in (Figure: 4.6). However, in the Risk_OMT model, the RIFs are categorised into two different levels of importance in the modelling structure. The first (upper) level of RIFs has a direct effect on the IEs and basic events. Whereas, the RIFs in the second (lower) level involves the managerial aspects that influencing the RIFs in the upper level. The project introduced two different generic RIFs models. The first model represents the planning activities, while the other belongs to the execution activities. The interrelationships between the RIFs in both levels are determined through a Bayesian Belief Network (BBN) see (Figure, 4.7). However, for more details about BBN see (Aven, 2008).

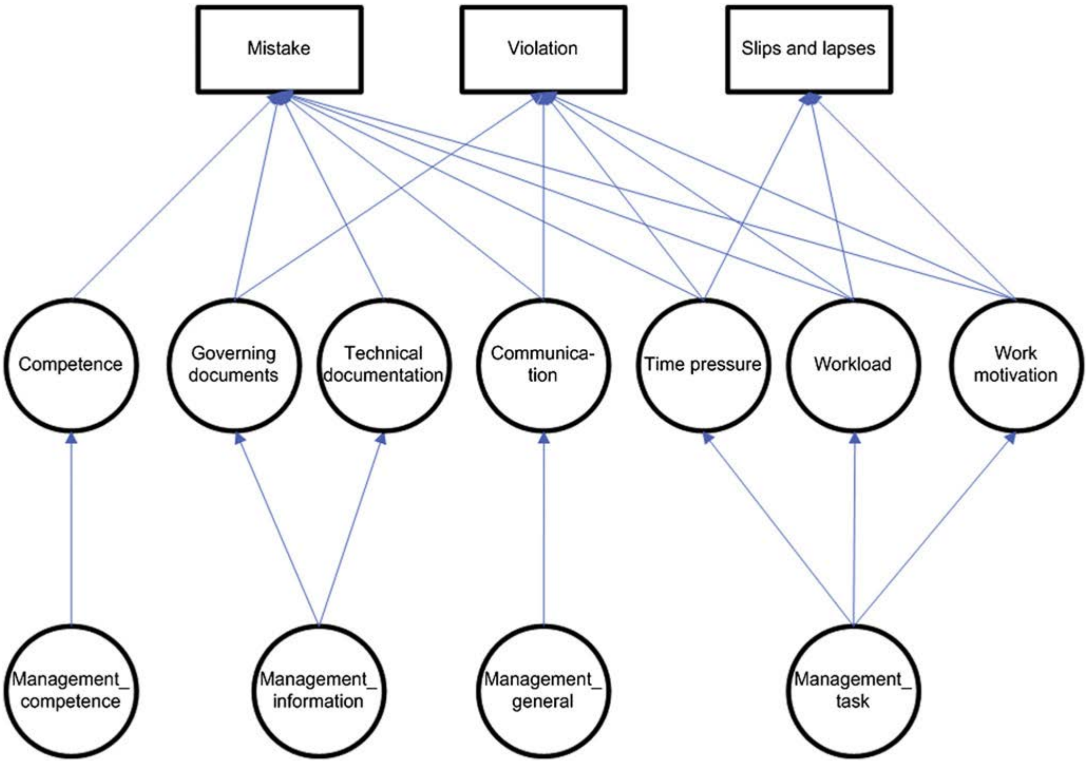


Figure 4.7: Generic RIF model for planning activities (Vinnem et al, 2012)

The Risk_OMT project uses a classification of the initiating events similar to the one has presented in the BORA project. However, the main focus in the Risk_OMT model is the process leaks resulting from human errors during maintenance activities. In particular, the model has been built primarily on the below scenarios:

- B: Human intervention introducing latent error
- C: Human intervention causing immediate release.

The above scenarios are modelled by means of BBD, ET, FT and risk influence diagram as shown in (Figure, 4.8). The risk influence diagram is introduced as a simplified BBN as shown in (Figure, 4.7).

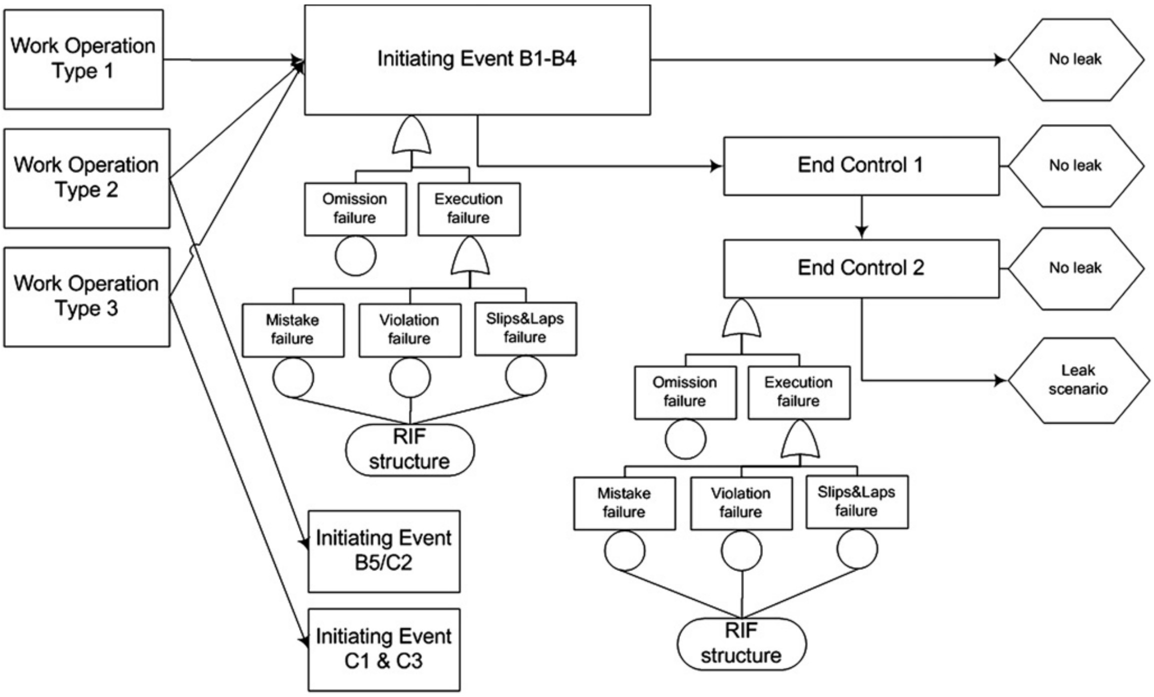


Figure 4.8: Modelling principle for the leak scenario (Vinnem, et al, 2012 p278)

From the above figure, the model shows that the initiating events and their subsequent leak prevention barriers can fail due to omission or execution failures. According to Vinnem et al (2012), the two groups of failure that introduced in this model are defined as:

- **Omission failure**: this group covers failures caused due to inadequate of insufficient performance of the work task or the barrier system. For example, a barrier system in not specified or not in use.
- **Execution failure**: this group is mainly covering the human failures of performing a specific task. Human failures in this context can occur due to violation or human error. Where human errors categorised into mistakes or 'slips and laps' of planning or performing the activity (Reason, 1990).

It is clear that the Risk_OMT model has more focus on failures caused by human errors than the BORA model. The model has also introduced better analysis to the tasks and activities that carried out by human. Moreover, a significant value has been added by modelling the RIFs in two hierarchal levels. Another aspect that strengthen the model is classifying the human errors into mistake, violation and 'slips and lapse'. The use of this taxonomy of human errors can help to identify which group is more sensitive and has the most contribution in risk. On the other hand, the model is more complicated than the BORA model when it comes to calculations and work load.

5. Monitoring the Performance of Safety Barriers in daily operations.

The previous Chapter has introduced a description on how the performance of safety barriers can be modelled in QRAs. In addition, the importance of reflecting the RIFs effect on safety barriers to improve the prediction of the final risk picture was also mentioned. However, in spite of these improvements, there are still some uncertainties associated with the final risk picture. Uncertainties in the risk picture occur due to the lack of the background knowledge about the parameters that included in QRA. The background knowledge, in this case, involves historical data, system performance characteristics and knowledge about phenomena in question (Abrahamsen et al, 2011). Moreover, the situation may become more complicated if the uncertain parameters are highly sensitive to the final risk picture. Therefore, it is necessary to rely on strong knowledge while performing QRAs. However, in some cases, such uncertainties cannot be reduced due to the limitation of the available information, especially the operational knowledge during the design phase.

The RIFs are one of the main inputs that reflect the operational knowledge on the performance of safety barriers when modelled in QRA. In addition, they are also acting as a measure of safety barriers' status during the operations phase. Accordingly, uncertainties in RIFs can introduce a poor prediction of the barriers' performance and may introduce latent risks. The existence of such uncertainties in the performance of safety barriers can result in surprising events if not managed properly. Therefore, it is important to identify the RIFs that are causing uncertainties in the QRA results and include them in the SBM process during operations. In addition, they should be monitored continuously and included in the decision process of the daily activities that performed on board the production platforms.

The purpose of this Chapter is to introduce a methodology for monitoring the performance of safety barriers in the daily operations through RIFs indicators. The selection of the RIFs to be monitored continuously is done based on a result of criticality assessment of the different RIFs. The criticality level of the different RIFs is identified based on a combination of both uncertainty and sensitivity analyses for the different RIFs. However, the different steps of the selection and building indicators of the highly critical RIFs are introduced in four sections, in addition to, the current background.

In section one, a description of the different approaches that used for treatment of uncertainty in barrier analysis is introduced. Moreover, a brief description of sensitivity analysis is highlighted. In addition, other points are highlighted in this section, such as the difference between uncertainty and strength of knowledge, as well as, uncertainty and sensitivity. Furthermore, section two introduces the ranking criteria for criticality of RIFs based on the uncertainty and sensitivity analyses. Afterwards, section three describes the methodology used for building indicators for the most critical RIFs, and using them for monitoring the barriers' status in daily operations. At the end of this Chapter, a summary of the methodology is introduced in a separate section.

5.1 Uncertainty treatment in barrier analysis in QRA.

5.1.1 Introduction

The performance of safety barriers are represented in the QRA model with probabilities. Such probabilities are used to express the expected future values of failure of these barriers to function when needed. In this case, the description of risk is introduced based on the (A, C, P) risk perspective, where probabilities are used to represent the background knowledge K. The utilisation of probabilities is providing the decision makers with a good estimation of the barriers' performance. However, the assigned probabilities do not reflect uncertainties precisely, as uncertainties are hidden in the background knowledge. For example, consider that the BORA model is used for assigning a probability of failure for a deluge system. In addition, the specific probability of failure is calculated based on the influence of different RIFs. However, one of these RIFs, e.g. technical condition, has been given a B score. The assigned score is done based on scarce and/or unreliable information, so the real score might be C or even E. In this case, such uncertainty in the background knowledge is camouflaged in the assigned PFD of the deluge system.

Therefore, it is crucial to perform an independent uncertainty assessment for these values in order to highlight the uncertain factors and to produce more precise prediction of the performance of safety barriers. In this context, the risk perspective used is the (C, U), where risk is described with (C', Q, K) as introduced earlier in Chapter 2. However, the treatment of the uncertain factors in barrier analysis can be probabilistic or semi-quantitative as shown in the following subsections.

5.1.2 Probabilistic treatment of uncertainties

The methodology

The failure probabilities of the different safety barriers are usually calculated based on the industrial average data. In some cases, such as BORA model, these data are subjected to an adjustment process to represent a specific platform. However, despite the adjustment process, the final probability is associated with uncertainties. In this case, the probabilistic treatment of uncertainty can be used in order to present a prediction interval for the probability of failure. Such interval provides the decision makers with a range of probabilities with a best estimate of the failure probability.

For example, let us consider a deluge pump, where it can fail due to mechanical or electrical components' failure. The failures of both components are denoted $p_1\ and\ p_2$ respectively, where both components are the basic events in a FT. Moreover, the assessor has been using the BORA model to calculate both components' reliabilities. However, the assessor was not able to produce the exact reliabilities of both components due to uncertainties in the adjustment process. Accordingly, it has been decided to assign subjective probabilities for the different possible values of both components as given in (Table 5.1).

Components	p_1			p_2		
Value	0.95	0.96	0.97	0.93	0.95	0.96
Subj. P	0.25	0.5	0.25	0.25	0.5	0.25

Table 5.1: Subjective probabilities of different values of components' reliabilities

The above values are assigned based on the assessor's degree of belief about the occurrence the values' of each component. Hence, under the assumption of independence between component 1 and 2, the different values of reliability (h) with the associated subjective probabilities are given in (Table, 5.2).

h values	0.9965	0.9975	0.998	0.9972	0.998	0.9984	0.9979	0.9985	0.9988
Subj. P	0.0625	0.125	0.0625	0.125	0.25	0.125	0.0625	0.125	0.0625

Table 5.2: Deluge pump reliability distribution based on (table 5.1)

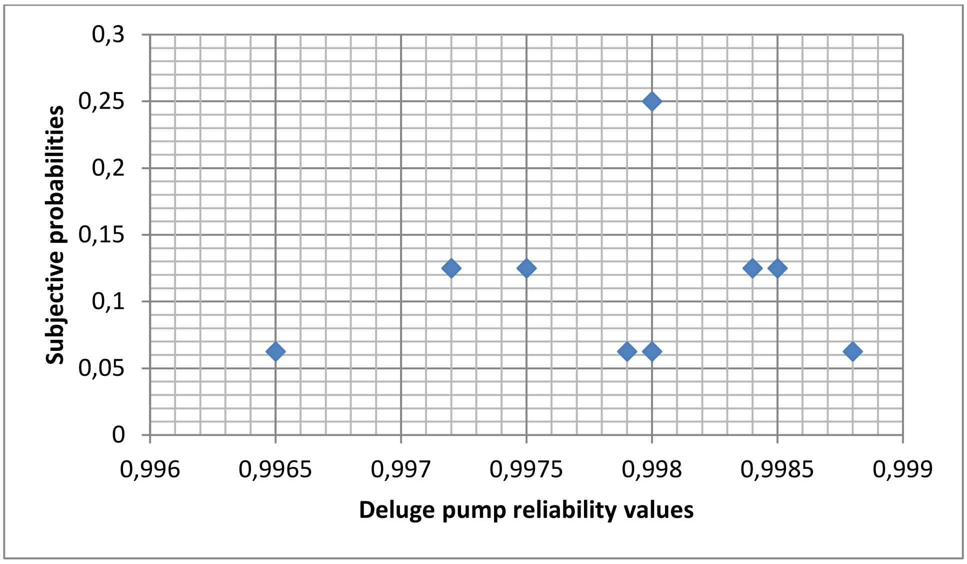


Figure 5.1: Probability distribution of the different values of deluge pump reliability.

From the above figure we can see that the reliability of the deluge pump is located in the interval [0.9965, 0.9988]. From this prediction interval, we can obtain the value that to be used in the barrier analysis in QRA by calculating the expectation. In this case, the mean equals to 0.998. However, the value of the system reliability is relying on the probability distribution of the underlying components i.e. the value of (h) can deviate from the expected value (Aven, 2010).

The uncertainty analysis introduced in this section is compatible with the approach that presented in (Aven, 2010) as illustrated in (Figure, 5.2).

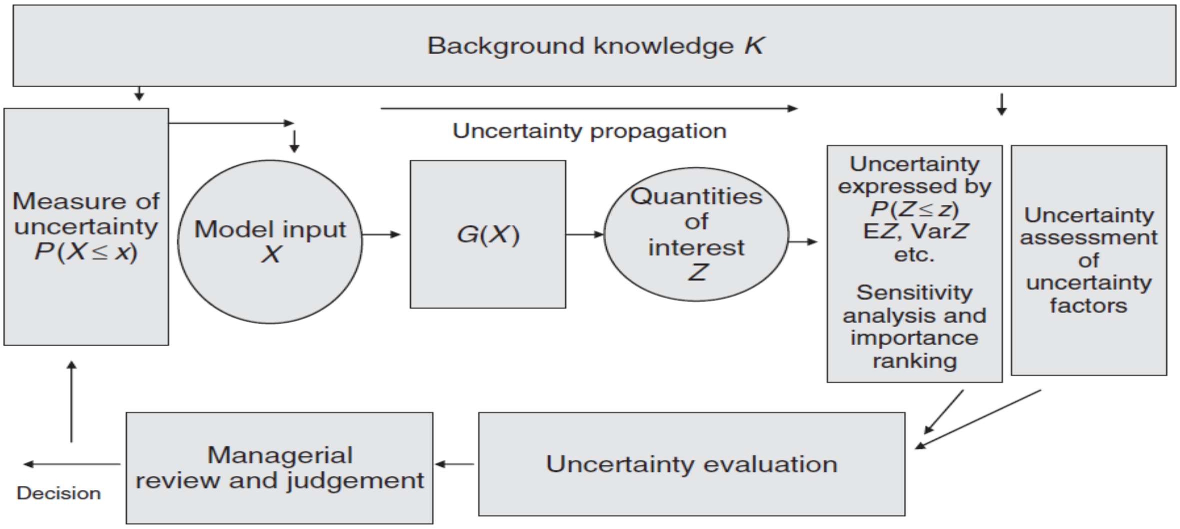


Figure 5.2: A framework of the probabilistic treatment of uncertainty assessment (Aven, 2010)

In the light of the above figure, the uncertainty analysis is performed to assess the results obtained from the QRA. Such analysis starts with the assignment of knowledge-based probabilities for the uncertain parameters based of the assessor's degree of belief. The assigned probabilities are referred as the model input X. Moreover, the model used in this analysis could be an analytical approach or Monte Carlo simulation (Aven, 2010). Afterwards, the quantities Z that obtained from the model G(X) are subjected to further sensitivity analysis in order to determine the effect of the uncertain parameters on the calculated probabilities. In addition, it can also be used for the sake of ranking the different uncertain quantities based on their importance. However, a further explanation of the sensitivity analysis is introduced in section 5.2.

Discussion

The probabilistic treatment of uncertainty, in reliability context, has introduced a considerable improvement in expressing uncertainties about the occurrence of future events based on the background knowledge. The method is based on the concept of probability of chance, where each possible frequentist probability is assigned a subjective probability. In this case, the uncertainty measure Q is described as $P(P_f)$. This is done to express the assessor's degree of belief about the occurrence of the different values of chances (see, Lindley, 2006). The use of this method is beneficial to provide the concerned parties with a broad overview of the system performance beyond the expected probabilities. However, such quantitative method does not reflect the uncertainties associated with the background knowledge K, where these numbers are based.

With respect to barrier analysis in QRA, this method can be sufficient for producing a prediction interval of probabilities of failure. This range of probabilities is representing the different opinions of assessors and experts about the failures of the underlying components of safety barriers. However, the assigned numbers are not reflecting the strength of the supporting information/knowledge behind these values.

Let us consider the deluge pump example again. In this example, we assumed that the probabilities of the underlying basic events are calculated by using the BORA model. Afterwards, the basic events are assigned a number of subjective probabilities to a range of the possible chances. The assignment of the subjective probabilities is reflecting the experts' judgment about the generic data, in addition to, the scores and weights of the contributing RIFs. However, the assigned probabilities do not refer to the strength of the supporting knowledge of these numbers. For example, if two separate components are assigned the same probabilities e.g. 0.9. Moreover, the first probability is assigned based on a strong knowledge, whereas the second was relying on poor knowledge. In this case, the strength of knowledge does not expressed sufficiently by using subjective probabilities. In addition, it does not provide the decision makers with precise information about the RIFs that need to be monitored during operations phase. In other words, such numbers can simply tell the different parties that there are uncertainties with this component. However, they do not elaborate exactly what are the sources and causes of uncertainties. Moreover, such probabilities are determined based on further assumptions and suppositions that can be an additional source of uncertainties. Therefore, it is required to look for different alternatives for expressing the uncertainties beyond probabilities (Aven, 2014). For this purpose, a semi-quantitative approach can be used as an alternative to the probabilistic uncertainty treatment. However, the semi-quantitative approach is explained and discussed in the following part of this section.

5.1.3 Semi-quantitative treatment of uncertainty

The semi-quantitative assessment of uncertainty is a hybrid method that combines the probabilistic uncertainty with an independent qualitative assessment for the supporting knowledge. This approach has been developed to assess the uncertainty beyond the assigned number, as probabilities are not considered a perfect tool for this purpose. In particular, the semi-quantitative uncertainty assessment is developed to identify the hidden uncertain factors in the background knowledge K, where the probabilities are based. This assessment is useful to provide the decision makers with an additional informative dimension of the quantities of interest. However, it is important to understand the meaning of poor or strong knowledge, as well as what is the difference between the lack and strength of knowledge.

The concept of strength of knowledge is meant to indicate the level of trust in the underlying information and knowledge of the risk assessment. For example, we assume that there are two separate analysts are assigned to calculate the average leak frequency for an offshore platform. The two analysts end up with almost similar intervals of leak frequency. Moreover, the first analyst has been relying in his analysis on sufficient data and precise models, whereas, the other analyst was not. In this case, the semi-quantitative assessment is beneficial to highlight this fact in order to allow the different parties to take the right decision to overcome the effects of the poor knowledge.

At first glance, the strength of knowledge can be seen similar to the epistemic uncertainty (Aven, 2014). In other words, the poor knowledge means high degree of uncertainty and vice versa. Therefore, it is worthy to indicate the difference between both concepts.

The epistemic uncertainty is defined as the lack of knowledge about the parameter of interest, and it can be reduced by gaining more information. Furthermore, the epistemic uncertainty can occur due to uncertainty in quantity, uncertainty in future prediction and uncertainty about the phenomena (Aven, 2014). Let us consider the first type, which is uncertainty about the quantity. This group of uncertainty involves different factors such as, data and model uncertainty. The uncertainty caused by the lack of data about a certain parameter, e.g. component reliability, can be reduced by acquiring more data. However, the strength of these data is not highlighted in this case. For example, the new data could be non-relevant to the same component or industry. Therefore, strength of knowledge is beneficial to bring the attention of the decision makers about the factors that assigned based on poor knowledge. However, there are two methods have been developed in order to perform the semi-quantitative uncertainty assessment. The two methodologies are described below.

1. Crude strength of knowledge assessment

The crude assessment of strength of knowledge is introduced by Flage & Aven (2009). This approach has been developed based on the belief that the assigned probabilities are not a perfect tool to express uncertainties. In addition, the analysts and experts need to see beyond these numbers to identify the hidden uncertain factors in the background knowledge. The assessment is performed for the different parameters involved in the risk assessment based on the criteria introduced in (Table, 5.3).

Strength of Knowledge Scale		
Strong	Poor	Medium
All of the following conditions are met: a) The assumptions made in calculating P are seen as very reasonable b) Many reliable data are available. c) There is broad agreement among experts. d) The phenomena involved are well understood: the models used are known to give predictions with the required accuracy.	One or more of the following conditions are met. a) The assumptions made in calculations of P represent strong simplification b) Data are not available, or are unreliable c) There is lack of agreement/consensus among experts. d) The phenomena involved are poorly understood: models are non-existent or known/believed to give poor prediction.	Conditions are between those characterizing high and low uncertainty.

Table 5.3: Strength of knowledge criteria (Bjegra &Aven, 2015)

2. Assumption deviation risk

Risk assessments are usually performed based on a number of assumptions and presuppositions (Aven, 2008). The assumptions are made for several purposes, for example, to compensate any lack of knowledge in the underlying parameters or phenomena. Accordingly, the final results of the risk assessment are influenced by those assumptions. However, assume that the risk level on a production facility is judged to be acceptable based on several assumptions. For example, one of these assumptions is that a gas leakage will be detected within 30 seconds (Berner & Flage, 2015). This assumption is made based on the available information and the analyst judgment. Furthermore, the assumption is considered strong if the background knowledge is poor. Whereas, it is weak if identified based on strong knowledge (Berner & Flage, 2015). However, such assumption identifies the starting point of the fire and explosion accident scenario. In other words, the gas leak detection has a key role to initiate the subsequent mitigation measures in order to prevent and eliminate the consequences. Therefore, the assumption deviation uncertainty treatment is beneficial to assess the consequence of deviation of each assumption. Based on Aven (2014), the methodology consists of the below three steps:

- Determine the magnitude of deviation,
- Probability that each magnitude will occur and,
- The effect of this change on the consequence C as introduced in risk assessment.

Let us take the gas leak detection example again to clarify this methodology. In this case, we will consider a gas leak is detected within 30 seconds. This assumption is used when calculating the consequence of the base case, which is described (C', Q, K). Afterwards, the analyst has identified the potential magnitudes of deviation from this assumption to be 0 and 90 seconds. Moreover, the consequences are described as $(\Delta C', Q, K_D)$, where $\Delta C'$ denotes the change in the consequence C as given in the base case, and K_D is the background knowledge where these deviations are based.

The assumption deviation assessment is a strong tool that provides the concerned parties with a broad overview about uncertainties in the different assumptions. However, it is also recommended to combine this approach with strength of knowledge assessment to give a comprehensive picture about uncertainties in assumptions. The strength of knowledge assessment can be performed base on the criteria provided in the previous method. However, by taking the different factors into consideration, the findings from this assessment can be used to determine the criticality of the different assumptions as given in (Table, 5.4).

Belief of deviation from assumption	Effect of deviation on the risk index	Strength of knowledge	
		Strong	Medium/High
Low	Low	Setting I	Setting II
	Medium/High	Setting III	Setting IV
Medium/High	Low	Setting III	Setting IV
	Medium/High	Setting V	Setting VI

Table 5.4: Criticality classification of assumptions (Adapted from, Berner & Flage, 2015)

The assumption deviation assessment is primarily developed to assess the uncertainty in the assumptions, where the risk assessment based. Alternatively, it can also be used as a tool for linking the QRA with SBM process in operation phase. Let us consider the BORA model again as a tool for modeling safety barriers in QRA. Moreover, we will replace the assumptions with the status of the different RIFs. In this case, we can use the RIFs deviation assessment to identify the critical RIFs to the safety barriers. The identification process is connected with different monitoring schemes of safety barriers. However, more discussion about RIFs criticality is introduced later in this Chapter. On the other hand, a simplified method of the assumption deviation assessment is proposed by Aven (2014). The simplified version is integrating the crude strength of knowledge assessment with sensitivity analysis. The sensitivity analysis is used to express the effect of change of each assumption on the risk indices. However, the next section introduces further explanation of the sensitivity analysis.

5.1.4 Sensitivity Analysis

Sensitivity analysis is used in the context of risk assessment to calculate the effect of the different factors on the final risk picture if the values of these factors are changed. In other words, sensitivity analysis measures the change of the output of the risk assessment with respect to changes in the input parameters. In addition, sensitivity analysis can be used also to rank the importance of the different components with respect to their system. That is beneficial to identify the components which have the largest improvement potential than others. In this case, sensitivity analysis is considered as an importance measure.

In some situations, sensitivity analysis can be seen as a type of uncertainty analysis. However, this classification is not precise, as sensitivity analysis does not inform anything about the uncertain factors. Rather, it gives an overview about the effect of their changes. For example, the performance of sensitivity analysis on the gas leak frequency can provide the analyst with the magnitude of change in risk indices when changing the value of the leak frequency. On the other hand, the uncertainties in quantities and/or phenomena are not captured in such analysis. However, sensitivity analysis assists the analyst to identify the important parameters and factors in risk assessment which in return could be a significant source of uncertainty. Therefore, sensitivity analysis can play an important role as a foundation for the uncertainty analysis (Aven, 2010).

5.2 Criticality Assessment of RIFs

Criticality assessment is performed, in this thesis, to classify the RIFs under different groups, where each of these groups is linked with a particular monitoring scheme. However, in this section, the focus is on how to identify the highly uncertain and sensitive RIFs in order to include them in the daily monitoring process.

5.2.1 Uncertainty assessment of RIFs

Risk influencing factors are playing a key role in reflecting the operational knowledge on the safety barriers' performance. The reflection of the RIFs effect on the performance of safety barriers can improve the prediction of the future probabilities of failure of these barriers. However, there could be uncertainties associated with the operational knowledge when carrying out the QRA in the design phase. Based on this fact, there is a high necessity to assess the uncertainty of these factors in order to consider them in the risk management process in operations phase.

With reference to the BORA model, the reflection of the operational knowledge is done through the assignment, scoring and weighing of RIFs of a particular event. This process is relying, to a large extent, on the experience of the different experts, as well as the availability of the relevant data. Accordingly, the proposed method for assessing the uncertain factors has to cover the different components of the background knowledge. However, based on the uncertainty treatment methods that introduced earlier in section one of this Chapter, the semi-quantitative method are seen more applicable for assessing uncertainty in RIFs.

The selected approach for uncertainty assessment is seen in line with the methodology that has been introduced in Abrahamsen et al (2011). In this method, the authors claimed that probabilities give good insight to the analysts about the system of interest. However, they are also mentioned that it is necessary to look beyond these probabilities by reflecting the uncertainties. Uncertainties, in this case, can occur due to several reasons. For example, lack of knowledge is one of the main contributors in uncertainties. However, they may also occur due to a conflict among the analysts and experts who assigned such probabilities. The variation in the different analysts' perspectives, values and backgrounds can result in quite far values for the same system.

The methodology has recommended that uncertainty assessment is applied on a number of the MTO factors. Where, these factors are not clear to the analyst when calculating probabilities in the design phase. However, with respect to safety barriers, this situation is similar to the assignment and weighing of RIFs in the BORA model. In other words, such assessment can be applied on the generic RIFs that introduced in the BORA project. However, the criteria used for classifying the different levels of strength of knowledge are similar to the criteria introduced earlier in (Table, 5.3).

The identification of criticality of the different RIFs should not be restricted only to the above criteria. However, the criticality assessment has to take into consideration the impact of each of those RIFs on the change of the PFD value. For example, if a particular RIF is classified as highly critical and it has a minor change in the final probability. In this case, this RIF might be downgraded to the medium or even low criticality group. Therefore, it is beneficial to integrate the above uncertainty assessment with a sensitivity analysis to give more informative picture about the RIFs. Further, that is also beneficial to identify the most critical RIFs to the system that have to be monitored continuously and considered as a part of the planning process of the daily activities. However, the next part of this section describes how the BORA model can be used to identify the sensitivity of the different RIFs.

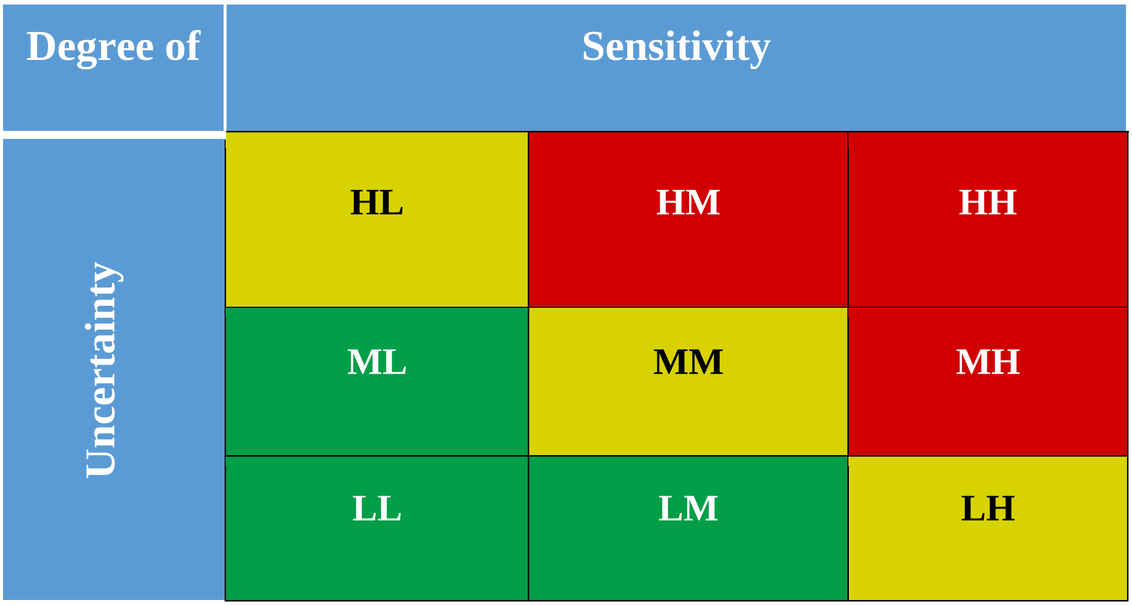
5.2.2 Sensitivity analysis of RIFs

The sensitivity analyses, in this part, are used to identify the most important RIFs that affect the PFD of the safety barrier. The sensitivity of the different RIFs are measured through the reduction/increment percentage in PFD when changing the score of each RIF, whether up or down. Afterwards, the degree of sensitivity is assigned based on the value of the percentage. Similar to the qualitative uncertainty assessment, the degree of sensitivity is categorised into three groups, low, medium, and high. However, the percentage interval of each sensitivity group is determined separately for each safety barrier.

The same method of classifying the uncertainty and sensitivity of RIFs has been used in different applications. For example, (Selvik et al, 2011) have implemented the methodology with the risk based inspection (RBI) application. In this reference, the importance ranking of the different factors has been used and combined with uncertainty and sensitivity assessments. However, when it comes to RIFs in the BORA project, the importance of the different RIFs has been reflected already in the weighing process. Therefore, if a particular RIF has been assigned high importance score, its impact on the final probability will be high in return. So, there is no need to perform a separate importance ranking to the different RIFs out of the BORA model.

5.2.3 Criticality ranking of RIFs

The performance of the previous uncertainty and sensitivity analyses on the different RIFs gives a broad overview on the underlying parameters of the safety barriers. In addition, they will provide the concerned parties with the information regarding the RIFs which have the higher impact on the barriers' performance. Therefore, it is necessary to give those RIFs more attention than others in order to avoid any potential surprises during operations. However, based on the results of the uncertainty and sensitivity analyses the RIFs criticality can be ranked as shown in (Table, 5.5).



Degree of	Sensitivity		
Uncertainty	HL	HM	HH
	ML	MM	MH
	LL	LM	LH

Table5.5: Criticality ranking of RIFs

The results from the above criticality ranking are used for the identification of the RIFs to be monitored continuously and considered as a part of the planning of the daily activities. The real time monitoring process of all RIFs would be beneficial to track all aspects that may deteriorate the performance of the safety barriers during operations. However, it will be also difficult to cover all these aspects when planning to the daily activities. Therefore, such special treatment of the different RIFs is restricted on the RIFs located in the red region in the criticality ranking. Afterwards, the monitoring process will be carried out through building indicators of the critical RIFs. However, the proposed methodology for monitoring the performance of safety barriers through indicators is described in the following section.

5.3 Real time monitoring process of safety barriers

5.3.1 Introduction

According to the management regulations (PSA, 2010d), the responsible party for operating the offshore or onshore facility has to establish indicators to monitor the change in the major accident risk. Moreover, the monitoring process of safety barriers will allow the decision makers to capture any early warning about the deterioration of safety barriers' performance (DNV GL, 2014). Consequently, they will be able to adapt the ongoing activities, as well as establishing the necessary measures to maintain risk within the acceptable level. For this purpose, RIFs indicators can be used for monitoring the performance of safety barriers in operations phase.

This section introduces how to connect the previous criticality ranking of RIFs with the real time monitoring process through indicators. This process consists of the following steps:

- Identify the relevant indicators for each RIF,
- Establish the criteria for scoring and rating the different indicators,
- weighing the indicators with respect to their effect on the particular RIF,
- Presentation of the RIF's status.

The above process is built on a method that introduced by Okstad et al (2014). This method is presented for developing indicators for on-line monitoring of risk level on the offshore production facilities. However, a description of the above steps is introduced in the following section.

5.3.2 Risk influencing factors indicators.

Step 1: Identification of the relevant indicators for each RIF.

The identification of indicators is done according to their ability to introduce early warnings about the critical RIFs. In addition, the identification process has not to be based on a generic list of predefined indicators. Rather, there are several variables have to be considered when identifying the relevant indicators for each RIF.

However, let us think about the identification of the relevant indicators for the competence RIF in two different situations. For example, the RIF will be assessed in relation to maintenance activity and a manual firefighting task. In the maintenance case, the experience of the personnel performing the activity can give a better indication for the RIF of interest. While in the other situation, the training and findings from drills' records can give a better indication on the status of the competence RIF.

The identification of the different indicators has to be done based on the different experts' background knowledge. The different experts can be risk analysts, different managers and operation personnel. Furthermore, there should not be a restricted number to the identified indicators for a particular RIF. However, the number of the indicators has to be as much as necessary and as low as possible to introduce reliable early warnings.

Step 2 - 3: Establish the criteria for scoring the rating of the indicator, and weighing the indicators with respect to their effect on the particular RIF.

The indicators are given scores based on a common scale from 0 to 10. Further, the scale is divided into three different intervals as shown below in (Table, 5.6).

Interval	0 – 3	>3 - 7	>7 - 10
Colour code	🟩	🟨	🟥
Definition	Low	Medium	High

Table 5.6: Rating intervals of RIFs indicators

The intervals used in rating the RIFs' status are reflecting the degree of severity of the different values of a particular indicator. However, setting the intervals for each risk level can be changed according to the experts' agreement. Moreover, the experts who identified the different indicators for each RIF have to adjust the different values of indicators to the above scale.

For example, let us consider the competence RIF's again, where the average years of experience of the personnel performing a task is considered as an indicator. In this case, the experts have to assign a value of the average years of experience for each number in the above scale. For example, if the average years of experience is 3, then the associated score will be 8. Accordingly, the RIF's status will fall in the high risk interval.

The adjustment process depends on several aspects such as; the nature of the task, the involved equipment and the task location. It means that the adjustment of the indicator values to the risk scale has to be dynamic and specific for each situation.

On the other hand, in case of presence of more than one indicator for a single RIF, then each indicator has to be assigned a weight based on its influence on the RIF. The weighing scale of the different indicators is starting from 0 to 1, where the sum of all indicators weights is equal to 1. However, the weight of an indicator of a particular RIF is reflecting the degree of belief of the experts about the impact of this indicator on the RIF's status. Afterwards, the information obtained from the first three steps for each safety barrier has to be documented as shown in (Table, 5.7).

Monitoring criteria of the critical RIFs for X safety barrier.						
RIF (i)		Competence			Technical condition	
Indicator (j)		Drills findings	Avg. Exp (years)	Expired Trainings	Number of open barrier breaches	Number of finding from inspection
Weight (w)		0,2	0,4	0,4	0,6	0,4
Relative scoring scale	**0**					
	1					
	2					
	3					
	4					
	5					
	6					
	7					
	8					
	9					
	10					
Indicator ID		$X_{1,1}$	$X_{1,2}$	$X_{1,3}$	$X_{2,1}$	$X_{2,2}$

Table 5.7: Illustration for monitoring criteria of critical RIFs for a particular safety function

Step 4: Presentation of the RIF's status.

The presentation of the RIF's status at a particular time is depending on the average value of the underlying indicators at the same time. For this purpose, let us denote the status of the i RIF $S_{X,i}$, where X denote the safety barrier of interest. Also, the values and weights of the j indicators are denoted $X_{i,j}\ and\ w_{i,j}$ respectively. Then we can calculate the RIF's status by the following formula.

$$S_{X,i} = \sum_{i,j} X_{i,j} \ . w_{i,j}\ (t)$$

The above method of identifying the RIF's status can be linked with a computerised system in order to receive a real time data about the different RIFs' conditions. The different values of the RIFs status can be presented by a risk barometer as proposed by Okstad et al (2014), see (Figure, 5.3).

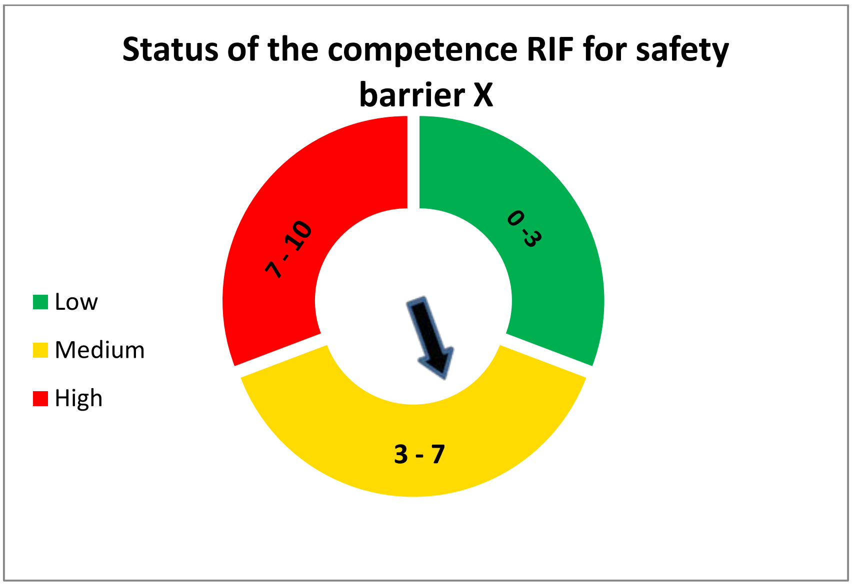


Figure 5.3: Risk level indicator of the competence RIF (Adapted from Okstad et al, 2014)

The presentation of the risk level of the critical RIFs is providing an overview about the current status of the safety barrier. However, it is also beneficial if the scores of the different RIFs have been combined in one risk barometer to represent the total score of risk of the safety barrier. In this case, the similar approach that used to represent the score of the RIFs will be used with the safety barrier. Therefore, it is also required to assign a weight form 0 to 1 for each RIF, where the sum of all weights is equal to 1. The below equation is used to calculate the total score of risk to the safety barrier X.

$$TS_X = \sum_{X,i} S_{X,i} \ . w_{X,i}$$

Where, $w_{X,i}$ denotes the weight of the RIF i with respect to safety barrier X.

The results obtained from this analysis can be also linked to a common risk barometer to present the status of all safety barriers. Moreover, such results have to be linked with a set of predefined actions in order to maintain the risk level within the acceptable region. For clarification, assume that the on-line monitoring process is performed to monitor the gas detection system. The operator has to identify and document some of the corrective actions to deal with the different situations. For example, if the pointer of the risk barometer refers to the yellow region, all hot works in a particular area have to be suspended until the pointer goes back to the green region. Whereas, if the pointer refers to the red region, all hot works on board the platform must be suspended.

5.4 Summary

The reflection of the operational knowledge on the performance of safety barriers is essential for more precise prediction of failure probabilities. The risk influencing factors can be used as a good tool for representing the effect of the operational knowledge on the calculated probabilities. Furthermore, RIFs are representing the soft relationship between the different MTO factors and safety barriers (Vinnem, 2014). However, some of these RIFs can introduce uncertainties in barrier analyses if assigned based on poor background knowledge. Moreover, the uncertain RIFs can be very critical if they are highly sensitive to the final probabilities. Therefore, it is necessary to identify the critical RIFs in order to avoid and confront any surprises that they could result in during operations.

Accordingly, the continuous monitoring of the critical RIFs can be a good solution to track their effect on the performance of safety barriers and consequently the final risk picture. Moreover, the real time monitoring process of safety barriers through RIFs indicators can introduce early warnings about the degradation of barrier performance during operations. By capturing such warning signals, the operator would be able to take the remedial actions to avoid the undesired events that may occur due to the latent degradation in safety barriers. However, the monitoring process of safety barriers through RIFs indicators is illustrated in (Figure, 5.4).

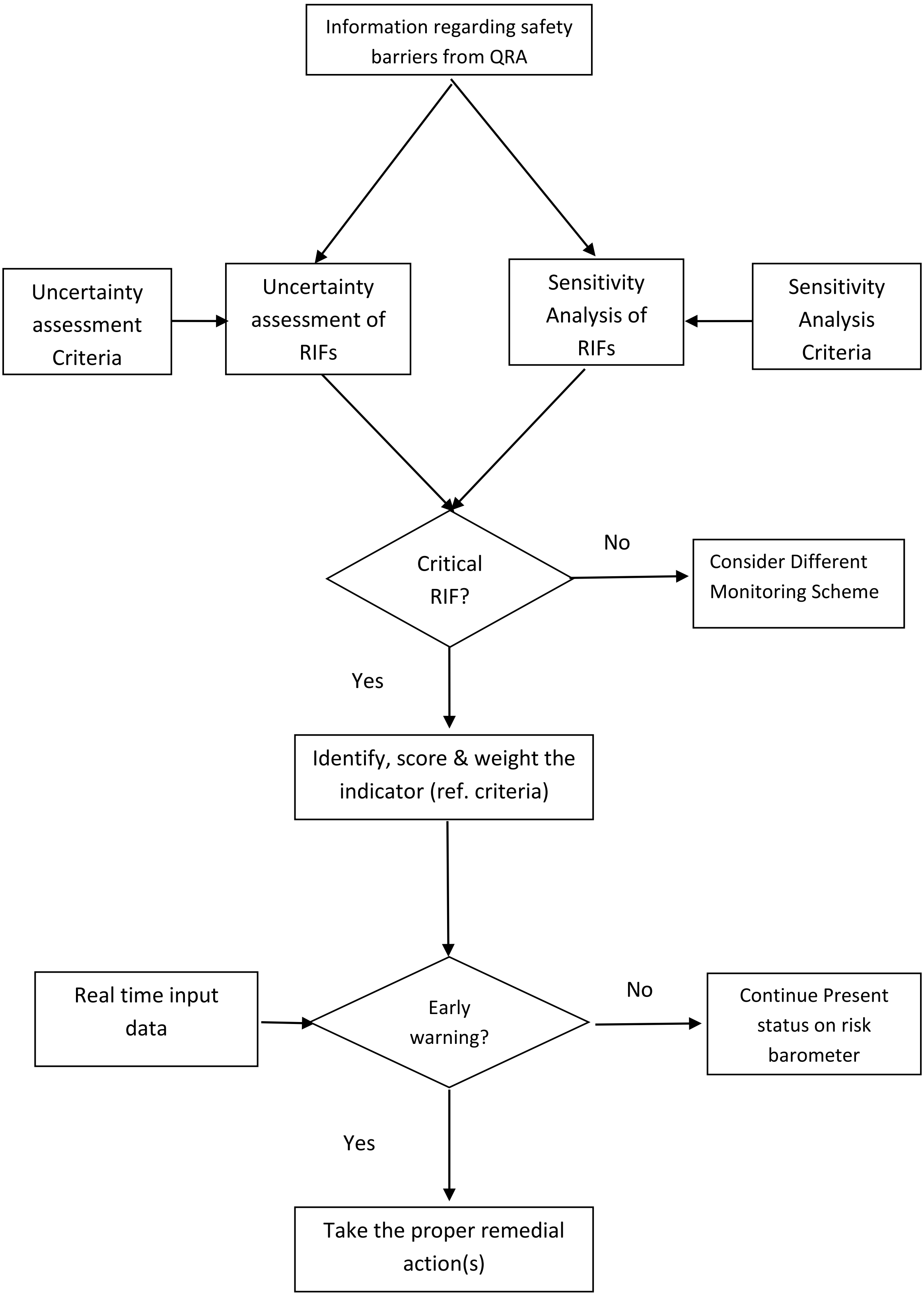


Figure 5.4: Daily monitoring process of safety barriers through RIFs indicators

6. Case Study

6.1 Background

This Chapter introduces an application of the methodology that has been proposed in the previous Chapter. The methodology is implemented on a deluge system, which is used, in this case, to cover a process module on board an offshore production platform. Furthermore, the platform is assumed as a gas production platform which is operating in the NCS.

Moreover, this Chapter consists of four sections. The first two sections introduce a background on and description of the case study. Afterwards, section three is introducing the implementation of the proposed methodology on the deluge system. Finally, in section four, a combined discussion of the proposed method and the purpose of its implementation is introduced.

6.2 Case description

According to the NOSOK S-001, the deluge system on board a gas platform, is used for minimising the explosion loads and to prevent escalation of fire and explosion hazards. In other words, the deluge system shall operate once a gas leak detected, and it has to remain operating until the hazardous situation became clear. Unlike the oil platforms, where deluge systems start to flood the covered area when a fire is confirmed. For example, on a gas platform, the deluge system starts to flood the area upon a gas detection. Where on oil platforms, the gas detection is initiating the deluge system, but the deluge system starts to flood the area when a fire is confirmed.

Based on the classification of safety barriers that has been introduced in Chapter 2, in addition to, the five barrier functions that proposed by Sklet (2005). The deluge system is considered a part of the prevent escalation barrier function. Moreover, the deluge system consists different technical barrier elements such as; deluge pump, diesel engine and deluge valve. That in addition to the other pipelines and isolation valves which are connecting those barrier elements together. Moreover, the initiation of the deluge system relies on the starting signal from the gas and fire detection systems. The initiating signal can be manual or automatic. However, (Figure, 6.1) introduces a simple block diagram to show the components of the deluge system.

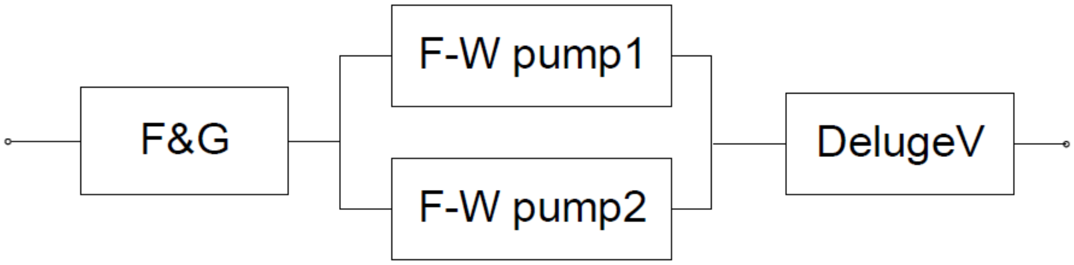


Figure 6.1: Deluge system reliability block diagram (OLF, 2004).

In the light of the above diagram, the deluge system can fail due to two main causes. The first is the failure of the starting system, and the second is the failure of one of the deluge system's components. However, the following section indicates how to calculate the probability of failure of the deluge system by using the BORA model.

6.3 Case Calculations

Based on the information provided in (Figure, 6.1), the deluge system consists of three technical barrier elements, which are the F&G logic, deluge pump system, and deluge valves. Both deluge pump system and valve are relying on the gas and fire detection for initiating them. Therefore, it is required to identify the probability of failure of all these components in order to calculate the probability of failure of the entire system. Such probabilities can be obtained from a source of the historical failure data such as OREDA Handbook (OREDA, 2009). However, for simplicity, the data used in our case is obtained from the (OLF, 2004) standard. However, the contributing components in the deluge system's FT and their failure probabilities are given in (Table, 6.1). On the other hand, the lower and upper limits of failure probabilities are assigned subjectively for the sake of calculating the RIFs effect.

Component	**Failure probability**		
	Lower	**Average**	**Upper**
Deluge pump system	$1.5 * 10^{-3}$	$2.8 * 10^{-3}$	$6 * 10^{-3}$
Deluge valve	$5 * 10^{-3}$	$1 * 10^{-2}$	$2 * 10^{-2}$
F&G detection	$6 * 10^{-4}$	$1.2 * 10^{-3}$	$2.4 * 10^{-3}$
F&G logic	$2.2 * 10^{-3}$	$4.4 * 10^{-3}$	$8.8 * 10^{-3}$

Table 6.1: Deluge system components failure data (OLF, 2004)

As mentioned earlier, in this Chapter, the probability of failure of the deluge system is calculated by using the BORA model. According, the first step is to calculate the generic probability of failure base on the above data. These data are representing the probabilities of basic events as shown in the below FT.

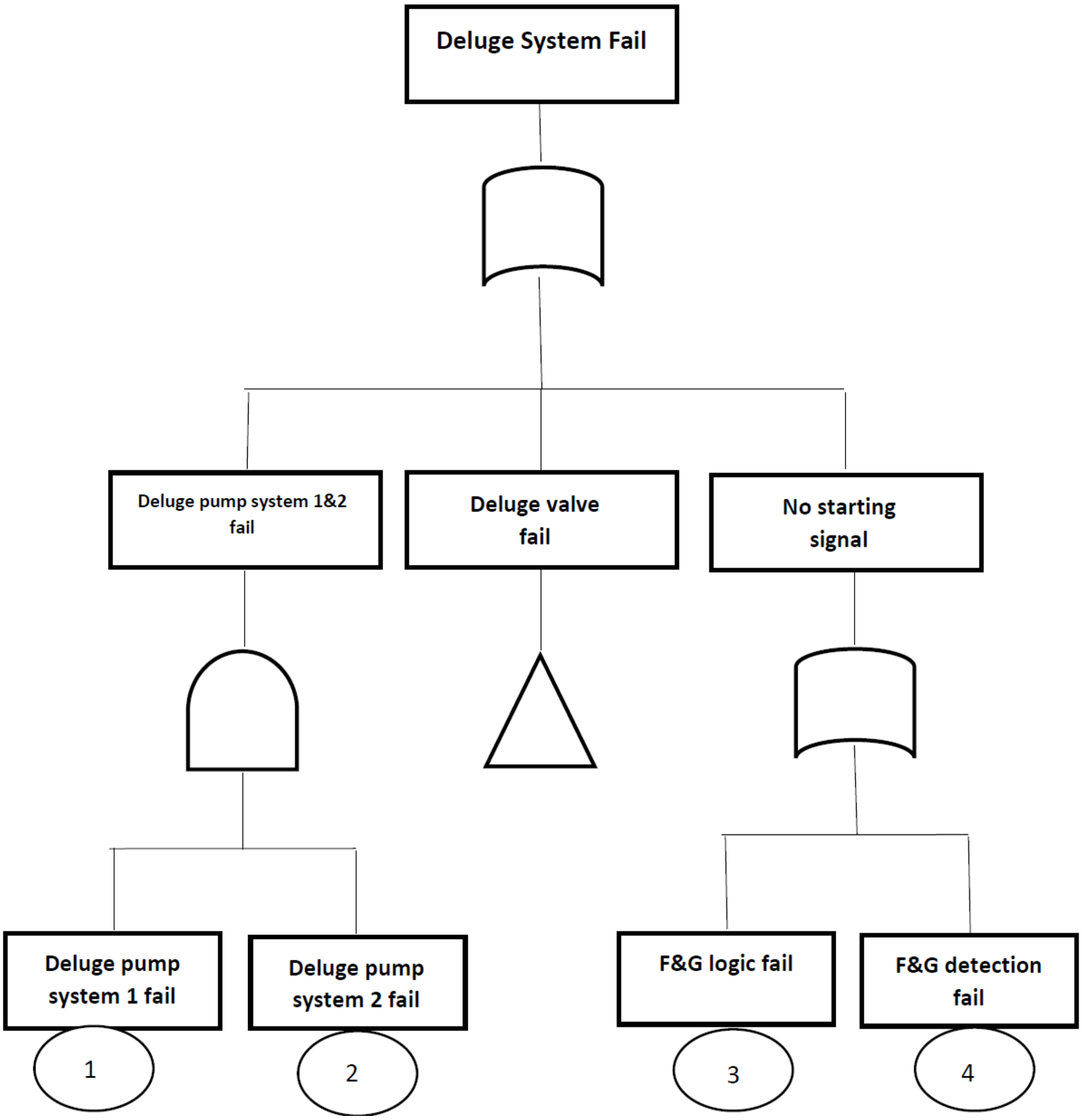


Figure 6.2: Simplified FT for deluge system failure

Based on the above fault tree, the calculated probability of failure of the deluge system is 0.015. However, this value is based on the generic failure data of the different components as given earlier in (Table, 6.1). Therefore, in order to calculate the specific probability of failure it is required to identify and weighing the different RIFs for each based event.

Intuitively, the selection of the RIFs varies from component to another. That because each component has its own nature and circumstances, even if all the basic events are technical components as given in the above FT. But there could be, also, a large similarity between the associated RIFs of the different technical barriers (e.g. technical condition, equipment design, and programs). However, an illustration of the different RIFs of the FT's basic events and their weights are given below in (Table, 6.2).

Failure of deluge system			
RIF	**Status**	**Importance**	**Normalized weight**
Basic events 1 & 2, failure of deluge pump system. & transfer event deluge valve failure			
Equipment design	C	4	0.15
Material properties	D	4	0.15
Technical condition	C	10	0.39
Programs	E	8	0.31
Basic event 3, failure of F&G logic.			
Technical condition	C	10	0.625
Programs	E	4	0.25
Equipment design	C	2	0.125
Basic event 4, failure of F&G detection.			
Technical condition	C	10	0.42
Equipment design	C	2	0.08
System feedback	E	4	0.17
programs	E	8	0.33

Table 6.2: Weighing of RIFs for deluge system failure

From the above table we can see that the technical condition RIF has the top score among the other RIFs of the different basic events. The importance of this RIF is originated from the criticality of this factor to the technical barrier elements. As it is considered the most factor can be subjected to change during the operations phase. For example, the air starting system of the diesel engine could be affected dramatically if the starting air has a high percentage of humidity. Also, we can think about the degradation of the mechanical seals of pumps or engines due to the low demand of operation, which can subject them to dryness and cracks. That is in contrast with the equipment design RIF, which is deemed to remain constant, unless the system is subjected to design changes.

On the other hand, the programs quality RIF, which is representing the quality and extent of the different programs of preventive maintenance, inspection, control of work, checklists and so on. If we look into the preventive maintenance program as an example, such program establishes the schedules of the required maintenance activities to maintain the technical systems in a good condition. However, the quality of these programs might be an area of debate between the relevant stakeholders, as these programs are built by humans. But the existence of the different standards and recommended practices in the oil and gas industry can resolve such debates between the concerned parties.

In line with the previous paragraph, it is clear that both of the technical condition and program quality RIFs have a significant impact on the performance of the system of interest. Moreover, they situation would be more critical if those RIFs are assigned based on poor knowledge. Therefore it is recommended to perform a strength of knowledge assessment in order to identify the degree of uncertainty in of each of them. Such assessment is done qualitatively based on the criteria that introduced in Chapter 5.

At first glance, both factors are seem to be assigned based on poor knowledge, where each factor has a different reason. As for the technical condition RIF, the weakness of knowledge may occur due to the lack of knowledge about the degradation of the different parts while operations. In addition, there also could be large simplification from the concerned parties in estimating the wear out mechanism of the mechanical parts. On the other hand, the poor knowledge in the program quality RIF could be resulting from the consensus among the experts who are establishing such programs. However, as mentioned before, the available standards that provided by the local regulations and consultancies may clear such debate between experts. And consequently, reduces uncertainty potential of this factor to be medium or low. However, according to the previous facts, the technical condition risk influence factor can be easily accounted as highly uncertain to the deluge system. Therefore, this uncertain factor needs special treatment in operations phase, as it can result in a latent degradation of the deluge system's performance.

As the real time monitoring process is the main focus of these assessment, it is also necessary to perform a sensitivity analysis in order to identify the critical RIFs to the system. However, the sensitivity analysis, as introduced in Appendix C, is carried out by comparing the revised probability of failure of the base case with the revised probability when each of both RIFs status is changed one point downwards. In other words, the base case revised probability is compared with the revised probabilities in the below cases:

- The technical condition RIF score is changed to be D instead of C (**Case 1**).
- The programs quality RIF's score is changed to be F instead of E (**Case 2**).

The calculations performed in Appendix C have resulted in the values that mentioned in (Table, 6.3). However, these results have to be accompanied with sensitivity criteria in order to identify the degree of sensitivity of each RIF.

Case	P_{rev}	Change %
Base Case	0.0203	0%
Case 1	0.0222	9.4%
Case 2	0.0215	6%

Table 6.3: Presentation of RIFs sensitivity analyses.

As given earlier in Chapter 5, the degree of sensitivity is classified based on the percentage of change in the probability of failure of the safety barrier. Further, it has been mentioned that the value of each degree of sensitivity is different from a safety barrier to another. For example, for SIL 3 or 4 safety barriers, the degree of sensitivity should be assigned based on tight values of deviation from the base case. On the other hand, for SIL 1 and 2, the deviation values for each sensitivity class can be larger than SIL 3 and 4.

According to OLF (2004), the deluge system is classified as a SIL 2, low demand system. Therefore, the sensitivity value for each class can be assigned based on the intervals introduced in (Table, 6.4).

	Degree of Sensitivity for deluge system		
	Low	Medium	High
Percentage (X)	$X < 5\%$	$5\% \leq X \leq 10\%$	$X > 10\%$

Tale 6.4: Sensitivity Criteria for deluge system

Based on table 6.3 and 6.4, both RIFs have a medium degree of sensitivity to the deluge system. The technical condition RIF can contribute in almost 10% increment in the probability of failure of the deluge system if its status has decreased. This fact indicates that the technical condition RIF is falling in the red region of the criticality ranking of RIFs as introduced in the previous Chapter in (Table 5.5), as it is also considered highly uncertain. On the other hand, the sensitivity results showed that the program quality RIF contributes in 6% increment in the calculated probability when degraded. However, when combining this result with the result of the uncertainty assessment, we can see that this factor falls in the yellow region of the criticality ranking of RIFs. Accordingly, among the different RIFs that affect the performance of the deluge system, the technical condition is considered as highly critical and should be included in the real time monitoring process of the safety barriers.

The online monitoring process of the performance of safety barriers is performed through RIFs indicators. The indicators are selected by the different experts from management and operation personnel in order to represent the status of these RIFs. Moreover, there is no generic set of indicators for RIFs, rather the indicators has to be selected separately for each RIF that affect a particular barrier. For example, the indicators used to represent the technical condition factors for the gas detector are different than those used with the deluge pump. However, there is also a large similarity between indicators of the different technical safety barriers. Such indicators can, for example, be the number of open barrier breaches on SAP, and the findings from the inspections and maintenance tasks (Okstad et al, 2014). Furthermore, the relevant unsafe conditions of safety barriers and their areas can act as a good indicator as well.

On the other hand, the assignment of weights and scaling the intervals for each indicator has to be specific for each safety barrier. For instance, if the competence and training are used as indicators for two different operational barrier elements, such as, manual firefighting and maintenance activity. Where, the average year of experience and the number of expired training certificates are taken as a measure for these indicators. In the manual firefighting case the training will take the higher weight, while the competence will prevail in the maintenance case. Accordingly, the relevant parties have to take several factors in consideration when planning for monitoring the various critical RIFs.

In our case, the establishment and scaling process of the indicators are requiring the access to a real platform data in order to produce a consistent indicators to represent the technical condition factor’s status. Unfortunately, such data were not available at the time of writing this thesis. Therefore, the case study was covering the implementation of the criticality assessment of the RIFs of the deluge system. In addition, the case study is introducing the concepts that should be followed when selecting the indicators of the uncertain RIF.

6.4 Discussion

The monitoring of safety barriers’ performance in operations phase of production platforms is adding a significant value to the operational risk management process. Specifically, the monitoring process is allowing the operation personnel and management group to capture early warning signals about the degradation of safety barriers’ performance.by capturing early warning signals about the degradation of safety barriers. The early warnings is deemed a considerable input for taking the remedial actions that will maintain the performance of the affected barriers as it was designed for.

The early warning signals, in the context of monitoring the performance of safety barriers, are usually representing the occurrence of a minor defect of the safety barrier. Where such defect can reduce the performance if developed (e.g. a minor leak in the deluge pump casing or a high vibration level from the attached diesel engine). Such warnings are raising the attention of the responsible parties about the potential degradation of the barrier's performance. However, this type of warnings can be seen as a reactive signal, as the trouble has started to occur. Even though, the performance of this barrier does not actually reduced. Additionally, in other literature, the isolation of a gas or fire detector is considered as a proactive indicator of the degradation of the gas or fire detection systems (Okstad et al, 2014). That, in fact, is not fully representing the proactive warnings idea, because such event has already increased the probability of failure of the detection system. Therefore, it is more beneficial to rely on more proactive indicators, which are providing the interested personnel with earlier warning signals than other indicators do.

The use of the risk influencing factors' indicators, as proposed in this thesis, can be a good solution for this challenge. In particular, the reliance on such indicators is informative about the possibility of occurrence of these minor defects. Consequently, the implementation of the corrective action would be easier, as well as more economic than the other reactive remedial actions. If we thinks about the engine's vibration example, there are several aspects can produce warning signals before the vibration occurs. For instance, the condition of the engine rubber foundations and/or loose bolts. Then, the remedial actions can be as simple as tightening the loose bolts or replacing the damaged foundations.

However, despite the benefits of implementing this methodology for all safety barriers, **but** it can also deemed unnecessary and excessive work in some occasions. Accordingly, the approach has to be restricted to the most critical RIFs to the safety barriers. The nomination of the critical RIFs is done based on the results of a combination of uncertainty and sensitivity analyses of the different RIFs.

On the other side, the early warnings obtained from this methodology can be used also to support the decision for planning of the daily operations on board the platform. The decisions, in the light of the available information, are taken to avoid the occurrence of the unforeseeable risks that resulting from the large uncertainty in the RIF of interest. For example, the decision makers could suspended the hot works outside the accommodation, if the risk barometer of the gas detection system refers to the red region. However, the concept that followed, in this case, is compatible with the precautionary principle of risk management. According to Aven (2008), the precautionary principle says “*in the case of lack of the scientific certainty on the possible consequences of an activity, we should not carry out the activity*”.

In addition to the above benefits of implementing of this approach, the methodology has introduced a solution for bridging the gap between QRAs and SBM in operations phase. As the information used for identifying the critical factors to the different safety barriers have been obtained from the QRA results. Subsequently, this factors became the input of the online monitoring process, which is, according to DNV GL (2014), considered a part of the operational SBM process.

7. Conclusion and Recommendations

7.1 Conclusion

The purpose of this master thesis was to introduce a methodology for integrating QRA with SBM in operations phase. The objective was achieved by introducing a methodology for monitoring the performance of safety barriers in operations phase, based on the information provided in the QRA. Moreover, the thesis has involved four integrated stages of work in order to produce the final methodology.

The first stage was to introduce the scientific background about the concepts of risk, risk assessment and safety barriers. In this context, the relevant definitions and methods of classification of risk assessment and safety barriers are introduced familiarise the readers with the different aspects of these concepts. Moreover, it was clarifying the meanings of the definitions used in the rest of thesis, in order to avoid any potential confusion. Subsequently, the second stage was discussing the requirements of the regulations and standards used in the NCS for managing safety barriers.

The information provided in the previous stages was formulating the foundations of the remaining work in the thesis. That is clear in stage three, where the main motivation was to investigate the possible approaches for integrating safety barriers in QRA model effectively within the regulatory requirements' framework. In this part, it was mentioned that the inclusion of the MTO factors effect, in the form of RIFs, is improving the modelling of the barriers' performance in QRA model. However, it was also stated that there is a significant need to identify the critical factors in order to monitor them continuously is operations phase.

The last stage of work in the thesis was performed to produce a methodology for assessing the criticality of the different RIFs that influencing the performance of the safety barriers. The criticality ranking of RIFs is determined based on a combination of a qualitative uncertainty assessment and a quantitative sensitivity analysis. However, the real-time monitoring of the critical factors is performed through indicators. The indicators then is linked to with risk monitor in order to provide the operators and management with early warnings about the barrier degradation. These warning signals is linked with number of precautionary measures that should be implemented in order to avoid the occurrence of the surprising events. The methodology, afterwards, was implemented on a case study in order to show how it could be implemented in the real situations.

7.2 Recommendations for further work

The integration of QRA with the SBM in operations phase shall not be restricted to the monitoring of the performance of the safety barriers. Rather, there should be other frameworks of integration between both concepts in order to ensure better management of risk on board the offshore production platforms. The other frameworks could be, maintenance management, testing and inspections.

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Appendices

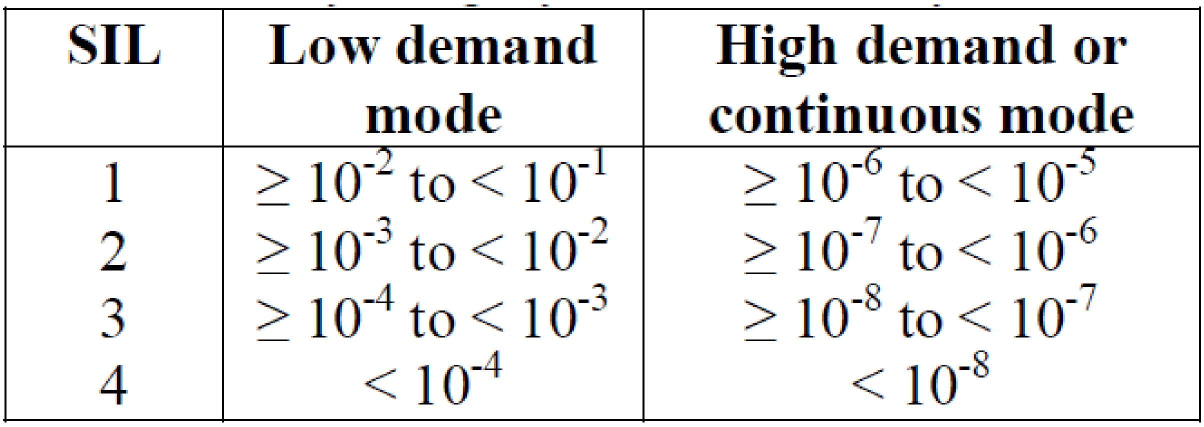
Appendix A

Definition of SIS and SIL.

According to Rausand (2011), a safety instrumented system (SIS) consists of three integrated parts or components. These components are an input element(s), logic solver and actuating element. In practice, a SIS appears on the offshore platforms in different applications such an active fire system, emergency shutdown valve or pressure relief valve. However, if we consider the active fire system, the input element is the fire detector, which is located to sense the existence fires. The signal obtained from the fire detectors are interpreted in logic solver in order to give the start signal to the actuating system to take its intended action. The logic solver of the fire system is the fire panel, whereas the actuating elements could be a deluge pump and deluge valve. Moreover, each SIS has one or more Safety Instrumented Function (SIF)

The SIF are divided into two different categories, which are the low demand and high demand mode SIF. The low demand SIF are the systems that operate when an emergency situation exists. For example, the active fire system is operating when a gas leak or a fire are detected. On the other hand, the high demand mode SIF, are representing the systems which are working continuously, such as fire and gas detection.

The high and low demand mode SIF are also classified based on their Safety Integrity Levels (SILs). A SIL indicates the values of the PFDs of the different SIF. In addition, the SILs are divided into four levels for each mode of operation. Where, SIL 1 is representing the SIS which have slightly hire PFDs if compared with the PFDs of SIL 4 SIF. However, the different values of PFDs for the low and high demand SIS are introduced in the below table.

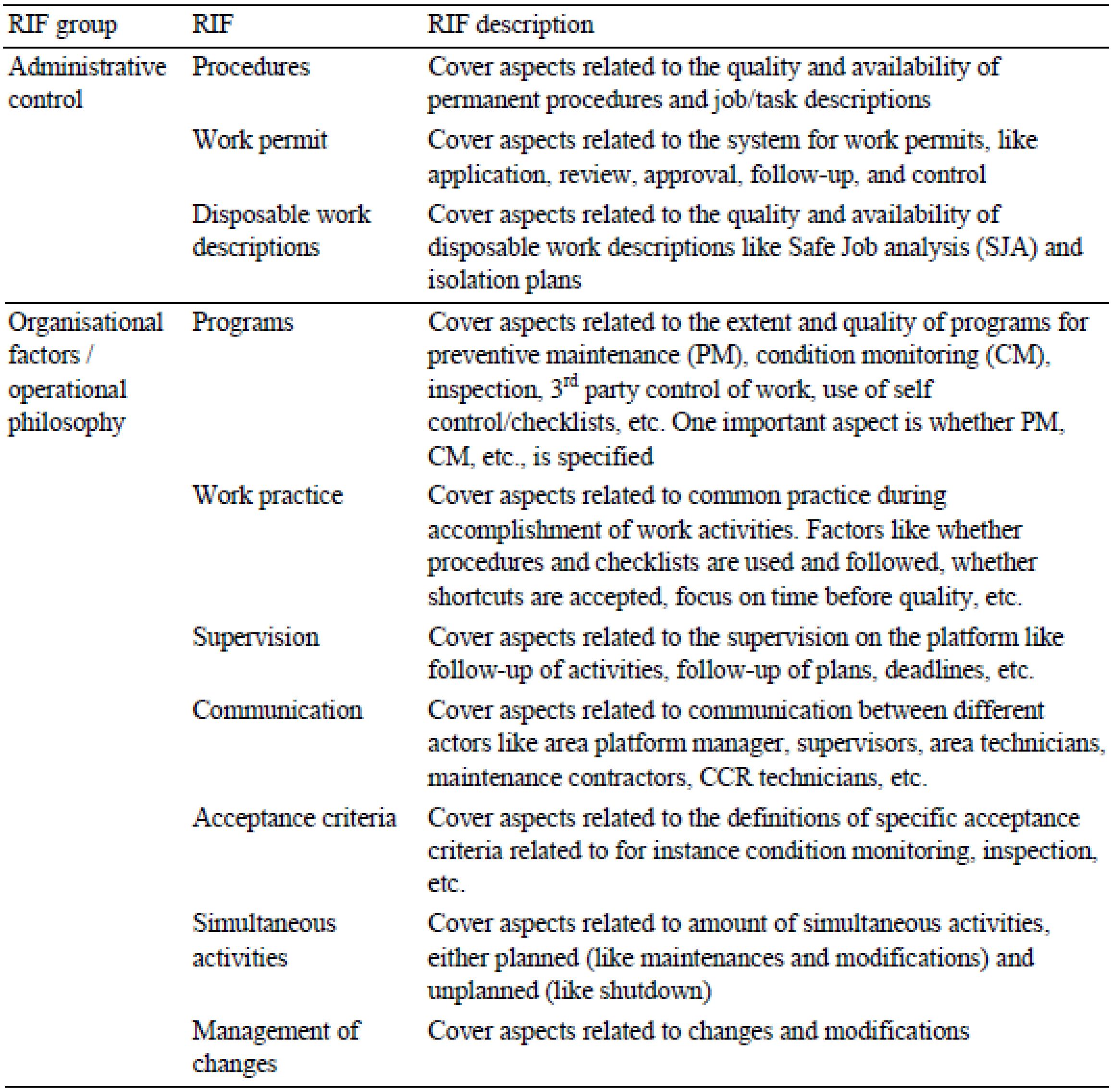


SIL	Low demand mode	High demand or continuous mode
1	$\geq 10^{-2}$ to $< 10^{-1}$	$\geq 10^{-6}$ to $< 10^{-5}$
2	$\geq 10^{-3}$ to $< 10^{-2}$	$\geq 10^{-7}$ to $< 10^{-6}$
3	$\geq 10^{-4}$ to $< 10^{-3}$	$\geq 10^{-8}$ to $< 10^{-7}$
4	$< 10^{-4}$	$< 10^{-8}$

Table A.1: SIFs' PFDs values of the different SILs (Abrahamsen and Røed, 2011 p20)

Appendix B
List and description of the generic risk influencing factors.

RIF group	RIF	RIF description
Personal characteristics	Competence	Cover aspects related to the competence, experience, system knowledge and training of personnel
	Working load / stress	Cover aspects related to the general working load on persons (the sum of all tasks and activities)
	Fatigue	Cover aspects related to fatigue of the person, e.g., due to night shift and extensive use of overtime
	Work environment	Cover aspects related to the physical working environment like noise, light, vibration, use of chemical substances, etc.
Task characteristics	Methodology	Cover aspects related to the methodology used to carry out a specific task.
	Task supervision	Cover aspects related to supervision of specific tasks by a supervisor (e.g., by operations manager or mechanical supervisor)
	Task complexity	Cover aspects related to the complexity of a specific task.
	Time pressure	Cover aspects related to the time pressure in the planning, execution and finishing of a specific task
	Tools	Cover aspects related to the availability and operability of necessary tools in order to perform a task.
	Spares	Cover aspects related to the availability of the spares needed to perform the task.
Characteristics of the technical system	Equipment design	Cover aspects related to the design of equipment and systems such as flange type (ANSI or compact), valve type, etc.
	Material properties	Cover aspects related to properties of the selected material with respect to corrosion, erosion. fatigue, gasket material properties, etc.
	Process complexity	Cover aspects related to the general complexity of the process plant as a whole
	HMI (Human Machine Interface)	Cover aspects related to the human-machine interface such as ergonomic factors, labelling of equipment, position feedback from valves, alarms, etc.
	Maintainability/ accessibility	Cover aspects related to the maintainability of equipment and systems like accessibility to valves and flanges, space to use necessary tools, etc.
	System feedback	Cover aspects related to how errors and failures are instantaneously detected, due to alarm, failure to start, etc.
	Technical condition	Cover aspects related to the condition of the technical system



RIF group	RIF	RIF description
Administrative control	Procedures	Cover aspects related to the quality and availability of permanent procedures and job/task descriptions
	Work permit	Cover aspects related to the system for work permits, like application, review, approval, follow-up, and control
	Disposable work descriptions	Cover aspects related to the quality and availability of disposable work descriptions like Safe Job analysis (SJA) and isolation plans
Organisational factors / operational philosophy	Programs	Cover aspects related to the extent and quality of programs for preventive maintenance (PM), condition monitoring (CM), inspection, 3rd party control of work, use of self control/checklists, etc. One important aspect is whether PM, CM, etc., is specified
	Work practice	Cover aspects related to common practice during accomplishment of work activities. Factors like whether procedures and checklists are used and followed, whether shortcuts are accepted, focus on time before quality, etc.
	Supervision	Cover aspects related to the supervision on the platform like follow-up of activities, follow-up of plans, deadlines, etc.
	Communication	Cover aspects related to communication between different actors like area platform manager, supervisors, area technicians, maintenance contractors, CCR technicians, etc.
	Acceptance criteria	Cover aspects related to the definitions of specific acceptance criteria related to for instance condition monitoring, inspection, etc.
	Simultaneous activities	Cover aspects related to amount of simultaneous activities, either planned (like maintenances and modifications) and unplanned (like shutdown)
	Management of changes	Cover aspects related to changes and modifications

Figure B.1: Description of the RIFs (Sklet el al, 2006)

Appendix C
Sensitivity Analysis of RIFs

Component	RIF	W	Q	K	P_{avr}	P_{rev}
Deluge pump system	Technical condition	0.39	1	1.3	$2.8 * 10^{-3}$	$3.6 * 10^{-3}$
	Equipment Design	0.15	1			
	Material properties	0.15	1.38			
	Programs	0.31	1.76			
Deluge Valve	Technical condition	0.39	1	1.262	$1 * 10^{-2}$	$1.3 * 10^{-2}$
	Equipment Design	0.15	1			
	Material properties	0.15	1.3			
	Programs	0.31	1.7			
F&G logic	Technical condition	0.625	1	1.28	$1.2 * 10^{-3}$	$1.54 * 10^{-3}$
	Programs	0.25	1.7			
	Equipment Design	0.125	1			
F&G detection	Technical condition	0.42	1	1.35	$4.4 * 10^{-3}$	$5.9 * 10^{-3}$
	Programs	0.33	1.7			
	System feedback	0.17	1.7			
	Equipment Design	0.08	1			

Table C.1: Base case revised probabilities presentation of the deluge system's components.

Component	**RIF**	**W**	**Q**	**K**	P_{avr}	P_{rev}
Deluge pump system	Technical condition	0.39	1.38	1.45	$2.8 * 10^{-3}$	$4 * 10^{-3}$
	Equipment Design	0.15	1			
	Material properties	0.15	1.38			
	Programs	0.31	1.76			
Deluge Valve	Technical condition	0.39	1.3	1.38	$1 * 10^{-2}$	$1.4 * 10^{-2}$
	Equipment Design	0.15	1			
	Material properties	0.15	1.3			
	Programs	0.31	1.7			
F&G logic	Technical condition	0.625	1.3	1.48	$1.2 * 10^{-3}$	$1.776 * 10^{-3}$
	Programs	0.25	1.7			
	Equipment Design	0.125	1			
F&G detection	Technical condition	0.42	1.3	1.48	$4.4 * 10^{-3}$	$6.5 * 10^{-3}$
	Programs	0.33	1.7			
	System feedback	0.17	1.7			
	Equipment Design	0.08	1			

Table C.2: Case 1 revised probabilities presentation of the deluge system's components (*decrement the status of the technical condition RIF).*

Component	**RIF**	**W**	**Q**	**K**	P_{avr}	P_{rev}
Deluge pump system	Technical condition	0.39	1	1.41	$2.8 * 10^{-3}$	$3.95 * 10^{-3}$
	Equipment Design	0.15	1			
	Material properties	0.15	1.38			
	Programs	0.31	2.14			
Deluge Valve	Technical condition	0.39	1	1.35	$1 * 10^{-2}$	$1.36 * 10^{-2}$
	Equipment Design	0.15	1			
	Material properties	0.15	1.3			
	Programs	0.31	2			
F&G logic	Technical condition	0.625	1	1.25	$1.2 * 10^{-3}$	$1.5 * 10^{-3}$
	Programs	0.25	2			
	Equipment Design	0.125	1			
F&G detection	Technical condition	0.42	1	1.45	$4.4 * 10^{-3}$	$6.4 * 10^{-3}$
	Programs	0.33	2			
	System feedback	0.17	1.7			
	Equipment Design	0.08	1			

Table C.2: Case 2 revised probabilities presentation of the deluge system's components (*decrement the status of the programs quality RIF).*