NTNU – Trondheim
Norwegian University of
Science and Technology

Modeling of Safety Barriers in Risk Analyses

Kjetil Holter Næss

Master of Science in Product Design and Manufacturing
Submission date: June 2012
Supervisor: Stein Haugen, IPK
Co-supervisor: Astrid Folkvord Janbu, Det Norske Veritas

Norwegian University of Science and Technology
Department of Production and Quality Engineering

NTNU

Fakultet for ingeniørvitenskap og teknologi
Institutt for produksjons- og kvalitetsteknikk

Vår dato
2012-01-11

Vår referanse
SHA/LMS

MASTEROPPGAVE

Våren 2012

for

stud. techn. Kjetil Holter Næss

MODELLERING AV SIKKKERHETSBARRIERER I RISIKOANALYSER (Modeling of safety barriers in risk analyses)

Det er krav fra Petroleumstilsynet og selskapene selv innenfor olje & gass industrien om at tilstand på tekniske og menneskelige/organisatoriske sikkerhetsbarrierer på en installasjon skal reflekteres i risikoanalysene av installasjonen. Det har imidlertid vist seg å være en utfordring å implementere dette i dagens metoder og modeller på en slik måte at man sikrer hensiktsmessige analyse- og beslutningsstøtteprosesser. Formålet med oppgaven er å se på hvordan barrierene kan reflekteres metodisk/modellteknisk og på hvilket detaljeringsnivå dette kan gjøres.

1. Litteraturstudium – hva omfattes av sikkerhetsbarrierebegrepet? Identifisere relevant litteratur og oppsummere kort.
2. Hvilke barrierer er relevante for en offshoreinstallasjon? Et konkret case (en type storulykke) velges ut og brukes som eksempel. Barrierene klassifiseres på ulike måter som grunnlag for kvantifisering.
3. Hvilke beslutninger som berører barrierene skal risikoanalysene gi innspill til? Beslutningene klassifiseres i kategorier/grupper.
4. Hva er viktige egenskaper ved barrierene som påvirker risiko/risikoanalysen?
5. Hvilke kan kvantifiseres, hvordan kan de kvantifiseres, og hvordan kan det modelleres inn i risikoanalysene? Både muligheter for å gjøre dette innenfor rammen av eksisterende analyser og gjennom andre metoder skal vurderes.

Oppgaveløsningen skal basere seg på eventuelle standarder og praktiske retningslinjer som foreligger og anbefales. Dette skal skje i nært samarbeid med veiledere og fagansvarlig. For øvrig skal det være et aktivt samspill med veiledere.

Innen tre uker etter at oppgaveteksten er utlevert, skal det leveres en forstudierapport som skal inneholde følgende:

- En analyse av oppgavens problemstillinger.
- En beskrivelse av de arbeidsoppgaver som skal gjennomføres for løsning av oppgaven. Denne beskrivelsen skal munne ut i en klar definisjon av arbeidsoppgavenes innhold og omfang.
- En tidsplan for fremdriften av prosjektet. Planen skal utformes som et Gantt-skjema med angivelse av de enkelte arbeidsoppgavenes terminer, samt med angivelse av milepæler i arbeidet.

Forstudierapporten er en del av oppgavebesvarelsen og skal innarbeides i denne. Det samme skal senere fremdrifts- og avviksrapporter. Ved bedømmelsen av arbeidet legges det vekt på at gjennomføringen er godt dokumentert.

Besvarelsen redigeres mest mulig som en forskningsrapport med et sammendrag både på norsk og engelsk, konklusjon, litteraturliste, innholdsfortegnelse etc. Ved utarbeidelsen av teksten skal kandidaten legge vekt på å gjøre teksten oversiktlig og velskrevet. Med henblikk på lesning av besvarelsen er det viktig at de nødvendige henvisninger for korresponderende steder i tekst, tabeller og figurer anføres på begge steder. Ved bedømmelsen legges det stor vekt på at resultatene er grundig bearbeidet, at de oppstilles tabellarisk og/eller grafisk på en oversiktlig måte og diskuteres utførlig.

Materiell som er utviklet i forbindelse med oppgaven, så som programvare eller fysisk utstyr er en del av besvarelsen. Dokumentasjon for korrekt bruk av dette skal så langt som mulig også vedlegges besvarelsen.

Kandidaten skal rette seg etter arbeidsreglementet ved bedriften samt etter eventuelle andre pålegg fra bedriftsledelsen. Det tillates ikke at kandidaten griper inn i betjeningen av produksjonsmaskineriet, idet alle ordrer skal formidles på vanlig måte gjennom fabrikkens bedriftsledelse.

Eventuelle reiseutgifter, kopierings- og telefonutgifter må bære av studenten selv med mindre andre avtaler foreligger.

Hvis kandidaten under arbeidet med oppgaven støter på vanskeligheter, som ikke var forutsett ved oppgavens utforming og som eventuelt vil kunne kreve endringer i eller utelatelse av enkelte spørsmål fra oppgaven, skal dette straks tas opp med instituttet.

Oppgaveteksten skal vedlegges besvarelsen og plasseres umiddelbart etter tittelsiden.

Besvarelsen skal innleveres i 1 elektronisk eksemplar (pdf-format) og 2 eksemplar (innbundet).

Innleveringsfrist: 11. juni 2012

Ansvarlig faglærer/veileder ved NTNU:
Professor Stein Haugen
Telefon: 73 59 01 11
Mobiltelefon: 934 83 907
E-post: stein.haugen@ntnu.no

Veileder ved DNV:
Astrid Folkvord Janbu
Mobiltelefon: 478 45 860
E-post: astrid.janbu@dnv.com

**INSTITUTT FOR PRODUKSJONS-
OG KVALITETSTEKNIKK**

Per Schjølberg

Per Schjølberg
førsteamanuensis/instituttleder

Stein Haugen
faglærer

Preface

The following report is the dissertation written in partial fulfillment of the MSc program in mechanical engineering, focusing on Reliability, Availability, Maintainability and Safety (RAMS) at the Department of Production and Quality Engineering (IPK) at the Norwegian University of Science and Technology (NTNU), in cooperation with Det Norske Veritas (DNV). The thesis was written during the spring semester of 2012. The topic of barrier modeling in risk analyses was proposed by DNV and developed further by professor Stein Haugen at IPK.

Trondheim, June 8, 2012

Kjetil H. Næss

Kjetil Holter Næss

Acknowledgment

Throughout the process of preparing and writing this report, several people have provided important input and guidance. I would like to express my appreciation and gratitude to the following people for their invaluable contributions: First and foremost, I would like to thank my supervisor at the Norwegian University of Science and Technology, Professor Stein Haugen, for his help and guidance throughout the process of writing this report. A special thank you also goes to Astrid Folkvord Janbu, my supervisor at Det Norske Veritas (DNV), for her assistance and practical guidance. I would like to thank everybody at DNV who provided additional input, particularly Andreas Falck, Henning Olin, Inger Elise Bjørkedal, Kirstine Kenich and Sondre Øie, as well as Tom Arne Bakken for making this thesis a possibility. Last but not least, I would like to thank DNV for the hospitality during my visits to the Høvik office, as well as practical help with housing during these visits.

K.H.N.

Summary and Conclusions

In recent years, the concept of safety barriers has become increasingly popular in regulations and standards for the offshore oil and gas industry, both in Norway and internationally. There are requirements from the Petroleum Safety Authority Norway and operators in the oil and gas industry that the condition of both technical and human/organizational safety barriers on installations should be reflected in risk analyses. However, implementing this in a manner which supports appropriate analysis- and decision making processes has proved to be difficult. The peformance of barriers is often not explicitly modeled in analyses, and human/organizational aspects are often not addressed in detail.

This master thesis examines how safety barriers can be modeled in risk analyses, and to which level of detail this can be achieved. A comprehensive literature review is performed in order to examine how the concept of safety barriers is defined, and which barrier properties are used to categorize and measure the performance of barriers. In addition, relevant standards and guidelines for the offshore oil and gas industry are reviewed in order to identify which barriers are important for offshore operations. A brief case study of blowouts is performed to illustrate how safety barriers are implemented on oil and gas installations.

Methods and techniques for modeling safety barriers in risk analyses are reviewed and presented. The different objectives of risk analysis, and the relevant barrier properties for risk analyses, are discussed. The tools developed in *Barrier and Operational Risk Analysis*, *Hybrid Causal Logic in Offshore Risk Analysis* and *Risk Modelling - Integration of Organizational, Human and Technical Factors* are included in the discussion. The current approach for quantitative risk analysis in DNV is presented briefly.

Based on these discussions, two main suggestions for improvement are identified:

1. *Include relevant barrier functions for each scenario as events in event tree models.*
2. *When appropriate and practicable, the technical and human/organizational condition of barriers should be taken into account using fault tree and/or Risk Influence Diagram/ Bayesian Belief Network models.*

Safety barriers should be included more consistently in event trees in order to better illustrate the effect of barriers on major accident risk, and to allow for explicit modeling of

the barrier systems implemented to perform each barrier function. Fault tree and bayesian belief network analysis can be applied to model both the technical and human/organizational condition of barrier systems.

It is suggested that simplified methods for adjusting industry average probabilities are applied for the modeling of risk influencing factors. Because of the massive workload and amount of data required for detailed statistical modeling of each risk influencing factor, these simplified methods are considered to be a more feasible alternative.

While it may seem inappropriate to tamper with probabilities which are based on historical data, it is important to consider whether the historical data accurately reflects the object under analysis. If conditions deviate from the industry average, industry average numbers will not reflect the reality of the specific installation. Using adjusted probabilities will be particularly useful when barriers are found to be in worse condition than than the industry average, because this means the average frequencies will be artificially optimistic. In this case, an adjusted probability will be a conservative estimate.

It should be noted that the energy-barrier perspective has received criticism from some researchers because it is based on linear causal chains, and does not account for complex interactions in larger socio-technical systems. While the approach does have its shortcomings, methods based on the barrier approach have proved to be useful and suitable for a number of applications. The approach is also continuously improved, as manifested by the introduction of bayesian belief networks in traditional risk analysis.

Sammendrag

Konseptet om sikkerhetsbarrierer har i senere tid blitt gjenstand for økende popularitet i offshore olje- og gassindustrien både her hjemme og internasjonalt. Det er krav fra Petroleumstilsynet og operatørene i industrien om at tilstand på tekniske og menneskelige/organisatoriske sikkerhetsbarrierer skal reflekteres i risikoanalyser. Imidlertid har det vist seg å være vanskelig å implementere dette på en måte som sikrer hensiktsmessige analyse- og beslutningsstøtteprosesser. Påliteligheten til barrierer modelleres ofte ikke i detalj i analyser, og menneskelige og /eller organisatoriske aspekter tas ofte ikke hensyn til i det hele tatt.

Formålet med denne masteroppgaven er å se på hvordan barrierene kan reflekteres i risikoanalyser, og på hvilket detaljeringsnivå dette kan gjøres. Et grundig litteraturstudium er gjennomført for å undersøke hvordan barrierebegrepet er definert, samt hvilke egenskaper som brukes til å kategorisere og måle effekten av sikkerhetsbarrierer. I tillegg er relevante standarder og retningslinjer for offshoreindustrien gjennomgått for å undersøke hvilke barrierer som beskrives som viktige for offshoreinstallasjoner. Et kort casestudie er gjennomført for utblåsningsulykker, for å illustrere rollene forskjellige barrierer har i praksis.

Metoder og teknikker for modellering av barrierer i risikoanalyser gjennomgås og presenteres. Ulike målsetninger for risikoanalyser diskuteres utifra hvilke beslutningsprosesser analysene skal støtte. Barriereegenskaper som er viktige for risikoanalysen diskuteres kort. Verktøyene som er utviklet i prosjektene *Barrier and Operational Risk Analysis*, *Hybrid Causal Logic in Offshore Risk Analysis* og *Risk Modelling - Integration of Organizational, Human and Technical Factors* behandles i rapporten. Den nåværende fremgangsmåten for risikoanalyse i DNV presenteres, og på grunnlag av dette er to forslag for forbedring presentert:

1. *Relevante barrierefunksjoner bør inkluderes som egne hendelser i hendelstrær.*
2. *I så stor grad som mulig bør den tekniske og menneskelige/organisatoriske tilstanden til barrierer tas hensyn til, ved hjelp av metoder som feiltrær og/eller risikopåvirkningsdiagram/bayesianske nettverk.*

Barrierefuksjoner bør inkluderes mer konsekvent i analysene. Dette vil tydeligjøre sikkerhetsbarrierenes rolle i forhold til risiko, og vil tilrettelegge for systematisk modellering av

barrierefunksjoner og -systemer. Feiltrær og bayesianske nettverk kan benyttes for å modellere både tekniske og menneskelige/organisatoriske faktorer i barrieresystemene.

Forenklede metoder for justering av gjennomsnittlige sannsynligheter basert på historiske data er anbefalt for modellering av risikopåvirkende faktorer, på bekostning av detaljert beregning av hver enkelt faktor. Denne typen justering anbefales fordi både mengden av data og arbeid som kreves for detaljert modellering er så stor at dette vil være vanskelig å gjennomføre i praksis.

I utgangspunktet kan det virke unaturlig å tukle med sannsynligheter som er basert på historiske data, men det er viktig å tenke på om datagrunnlaget reflekterer situasjonen som skal beskrives i analysen. Hvis tilstanden på en installajon avviker fra gjennomsnittet, vil ikke gjennomsnittsdata reflektere virkeligheten på installasjonen. Bruk av justerte sannsynligheter vil være spesielt nyttig dersom barrierer viser seg å være i dårligere stand enn gjennomsnittet, ettersom gjennomsnittstall i en slik situasjon vil være kunstig optimistiske. En justert sannsynlighet vil da være et konservativt estimat.

Det bør bemerkes at energi- og barriereperspektivet har mottatt kritikk fra enkelte forskere fordi det baserer seg på lineære årsaksforhold, og ikke tar hensyn til de komplekse årsaksforhold som finnes i større sosiotekniske systemer. Selv om perspektivet kanskje kommer til kort på enkelte områder, har metoder basert på barrieretenking vist seg å være passende og nyttige for en rekke applikasjonsområder. I tillegg er prinsippene i stadig forbedring, for eksempel illustrert ved introduksjonen av bayesianske nettverk i de tradisjonelle metodene.

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Chapter 1

Introduction

1.1 Background

Since the origin of human beings, safety barriers have been used to protect humans and property from enemies and natural hazards (Sklet, 2006). The notion of safety barriers in industry is based on the accident theory known as the energy model, pioneered by Gibson (1961) and Haddon (1980). Since the idea was developed, the safety barrier concept has evolved from simple physical barriers protecting against harmful energies to include successive risk reducing measures either of a technical, human or organizational nature. The concept of safety barriers has become increasingly popular in regulations and standards for the offshore oil and gas industry, both in Norway and internationally.

There are requirements from the Petroleum Safety Authority Norway (PSA) and operators in the oil and gas industry that the condition of both technical and human/organizational safety barriers on installations should be reflected in risk analyses. However, implementing this in a manner which supports appropriate analysis- and decision making processes has proved to be difficult. The peformance of barriers is often not explicitly modeled in analyses, and human/organizational aspects are often not addressed in detail.

1.2 Problem Formulation

The purpose of this master thesis is to examine how safety barriers can be modeled in risk analyses, and to which level of detail this can be achieved. The report will examine how the concept of safety barriers is defined and which types of barriers are most important for offshore oil and gas installations. The decision-making processes that different risk analyses should support will be identified in order to evaluate what information the analyses should contain. Different types of barriers and barrier classification will be discussed and important properties of barrier performance will be identified. Relevant methods for barrier analysis and quantification of barrier properties will be presented, and the current QRA approach will be discussed. Based on this, the report will discuss how the performance of safety barriers may be quantified and implemented in Quantitative Risk Analyses (QRAs), including both technical and human/organizational aspects. Possibilities of doing this both within the scope of existing analyses and other methods will be examined.

1.3 Objectives

The main objectives of the master thesis are as follows:

1. Literature study - What does the safety barrier concept entail? Identify relevant literature and summarize briefly.
2. Which barriers are relevant for offshore installations? A specific case (a major accident scenario) is chosen and used as an example. The barriers are classified in different ways to allow for quantification.
3. Which decision processes affecting barriers should the risk analyses provide input to? Decisions are classified into groups/categories.
4. What are important properties of barriers which affect the risk/risk analysis?
5. Which of these can be quantified, how can they be quantified, and how can they be modeled in risk analyses? Possibilities of doing this both within the scope of existing analyses and other methods shall be considered.

1.4 Limitations & Scope

The following master thesis is developed in cooperation with Det Norske Veritas (DNV) Safety Risk Assessment, with the objective of examining how barriers can be modeled in risk analyses. Possibilities of doing this will be examined both within the scope of existing analyses and other methods. Development of a complete approach for barrier modeling in risk analyses is, however, not within the scope of this report. While large parts of the report will provide a general discussion on the topic of safety barriers and risk analysis, the results of this report will be based on, and reflect, the specific needs of DNV Safety Risk Assessment QRAs.

The report is based on standards and regulations applicable to the offshore oil and gas industry on the Norwegian Continental Shelf (NCS), and will be specific to this industry. In addition, the scope of the report is limited to focus on major accident risk.

1.5 Approach

The report is the result of the following work process:

- A literature study of literature on safety barriers, risk analysis, and relevant standards and regulations for oil and gas activities on the NCS
- A case study of barriers relating to blowouts
- A review and discussion of relevant approaches for QRA
- Informal meetings and interviews with DNV personnel and review of a typical DNV QRA

1.6 Structure of the Report

The rest of the report is structured in the following manner: Chapter 2 contains an introduction to the concept of safety barriers, based on a comprehensive literature review on the subject. Chapter 3 presents a number of important barriers for offshore oil and gas installations, along with a brief case study of barriers related to blowouts. Chapter 4 examines how barriers can be modeled in risk analyses. Chapter 5 contains a brief summary and the conclusions of the report, as well as suggestions for further work on the subject.

Chapter 2

An Introduction to Safety Barriers

2.1 Introduction

The concept of safety barriers is relatively well known in the oil and gas industry, and the industry has seen a considerable focus on safety barriers in recent years. However, the concept is often loosely defined, and a number of similar concepts exist and are often used interchangeably when referring to safety barriers. The Management Regulation (PSA, 2001) contains several references to safety barriers, but the concept itself is not defined in the regulation. An increased focus on barriers from the PSA, has made the need for a common definition of safety barriers more obvious. This chapter will present a brief literature survey on the topic of safety barriers. A selection of literature on the subject will be presented and discussed. Different ways of categorizing barriers will be presented, as will common properties related to barrier performance.

2.2 The Safety Barrier Concept

In colloquial speech, the word *barrier* is often used to dscribe an obstacle, physical or otherwise, which prevents something from happening. A fence is a typical example of a barrier, restricting access to either side. Language differences is often referred to as a non-physical barrier, preventing communication between people of different nationalities. The Merriam-Webster online dictionary defines the word barrier in the following two relevant ways (Merriam-Webster, 2012):

1. a: something material that blocks or is intended to block passage

   b: a natural formation or structure that prevents or hinders movement or action
2. something immaterial that impedes or separates

A *safety barrier* in industry can be explained as a barrier which prevents an accident from happening, or reduces the consequences. The introduction of the term safety barriers is often accredited to the work of Gibson (1961) and Haddon (1970, 1980), who developed the accident perspective known as the energy-barrier model. The model describes accidents as the potential consequence of a vulnerable target or asset being affected by the release of a harmful energy. Barriers were introduced to separate targets from harmful energies, thereby preventing the harmful energies from affecting the target. This idea is illustrated in figure 2.1. Haddon introduced his famous ten strategies for accident prevention. The ten strategies focus on eliminating or modifying the hazard, limiting the exposure of the assets or victims to the hazard (e.g. by physical barriers), and on protecting and rehabilitating the assets or victims (Haddon, 1970).

Similar approaches, using a number of similar terms have been developed in different industries. In addition to safety barriers or simply barriers, terms such as countermeasures, safety functions/systems, safety critical functions/systems, defenses, lines of defense, defense in depth, levels/layers of protection and safeguards are used in literature (Rausand, 2011; Sklet, 2006). While all these terms are used to describe the same concept, there are often slight differences in their definitions. The interchangeable use of many of these different terms can be a source of confusion. As an illustration, Sklet (2006) notes that the International Atomic Energy Agency (IAEA, 1999) describes defense in depth as a concept ”. . . centred on several levels of protection, including successive barriers preventing the release of radioactive material to the environment. . . ”. This definition mixes together three of the terms presented above: Barriers are presented as a subset of levels of protection, which itself is used to describe the defense in depth principle.

Today, the term *safety barrier* is often used in a broader sense, including virtually any thinkable measure implemented to reduce the risk related to an activity. Reason (1997)

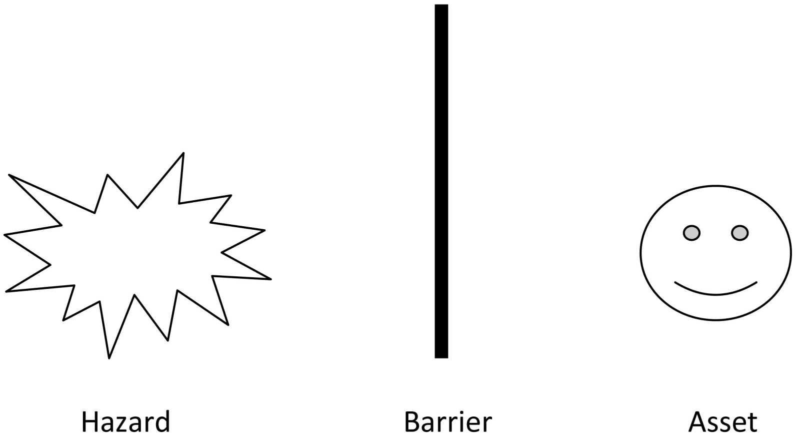


Figure 2.1: Simplified illustration of barriers in the energy model. Based on Haddon (1980).

defines barriers (although using the term *defences*) as ”various means by which ensuring the safety of people and assets can be achieved”. Hollnagel (2004) even includes what he calls symbolic and immaterial barriers in his classification of barriers. A symbolic barrier is one that requires interpretation, such as traffic lights or warning signs. An immaterial barrier is one that is not physically present, such as supervision or guidelines. The issue of barrier classification will be discussed further in section 2.3.

The NORSOK Z-013 (2010) standard defines safety barriers in the following way:

- *Safety barrier:* Physical or non-physical means planned to prevent, control, or mitigate undesired events or accidents.

Because the term safety barrier may be used in reference to both systems and their intended functions, it is common to distinguish between *barrier function* and *barrier system* (Sklet, 2006). NORSOK Z-013 (2010) provides the following definitions:

- *Barrier function:* Function planned to prevent, control, or mitigate undesired or accidental events. (The standard also uses the term *safety function* which has similar meaning.)

- *Barrier system:* System designed and implemented to perform one or more barrier function (sic).
- *Barrier element:* Physical, technichal or operational component in a barrier system.

These definitions are almost identical to those proposed by Sklet (2006). PSA (2011) proposes the terms *barrier*, *barrier function* and *barrier element*. Here, the term barrier is used to describe a barrier system, while the definitions of barrier functions and barrier elements are similar to those mentioned above.

2.3 Barrier Classification

In order to distinguish between barriers of different types, and to facilitate barrier managment, barriers are often categorized based on different properties. Several ways of categorizing barriers, based on a variety of properties, have been introduced in literature. As shown by Sklet (2006), some methods categorize barriers based on properties one would normally attribute to barrier functions, while others categorize barriers based on properties one would normally attribute to barrier systems. This section will present a selection of ways in which barrier functions and barrier systems may be categorized.

2.3.1 Categorization by Function

When safety barriers are categorized by function, it is often related to the effect the barrier function has on the accident scenario. The definition of safety barriers introduced in section 2.2 states that barriers are physical or non-physical means which either prevent, control or mitigate undesired events or accidents. Using the verbs prevent, control and mitigate to classify barrier functions is common when the functions are related to an accident or event sequence (Sklet, 2006). Barriers are often related to the accident model known as the bow-tie diagram. A bow-tie diagram shows the relationships between a hazardous event (sometimes called the Initiating Event (IE)), and barriers limiting either its causes or its consequences. The diagram has its name from its characteristic shape, illustrated in figure 2.2. The bow-tie diagram shows barriers which reduce the frequency of the event on the left side, and barriers which reduce the consequences of the event on the right. It is therefore often purposeful to classify barriers as proactive and reactive (Rausand, 2011). Hollnagel (2004) uses the terms prevention and protection. The classification of prevent, control and mitigate is based on the same logic, but reactive barriers have been divided into control and mitigation. Barriers intended to prevent escalation are classified as control, while barriers intended to reduce the effects of a hazardous event are classified as mitigation. Sklet (2006) argues that control functions, which are intended to prevent escalation, can be considered both as proactive and reactive barriers depending on how the IE is defined.

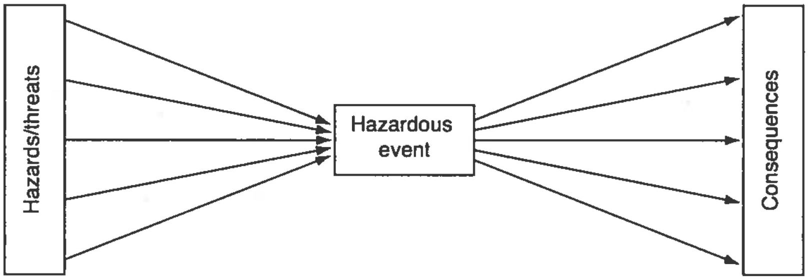


Figure 2.2: Simplified bow-tie diagram (Rausand, 2011, p. 6).

The ARAMIS-project which focuses on the release of hazardous material goes one step further, distinguishing between avoidance and prevention on the left side of the bow-tie diagram, and control and protection on the right side (Andersen et al., 2004). The frequency of an event can be reduced either by avoiding the hazard completely, or by preventing one or more of the potential causes of the undesired event. Control refers to barrier functions which help keep the operating situation in a normal state even if the undesired event occurs, such as pressure release valves, while protect refers to barrier functions which protect the environment from the consequences of the hazardous event (Sklet, 2006).

Reason (1997) classifies barriers according to more practical objectives. Seven objectives are suggested (adapted from Rausand (2011)):

- Create understanding and awareness of local hazards
- Give clear guidance on how to operate safely
- Provide alarms and warnings when danger is imminent

- Restore the system to a safe state in an off-normal situation
- Interpose safety barriers between the hazards and the potential losses
- Contain and eliminate the hazards should they escape this barrier
- Provide the means of escape and rescue should hazard containment fail

As such, it could be argued that this classification is more comparable to the ten strategies for accident prevention introduced by Haddon (1980) than the other classification schemes presented in this section.

2.3.2 Categorization by System

Taking another look at the definition of safety barriers in section 2.2, safety barriers are defined either as physical or non-physical means. This is a common classification of barrier systems. Some authors distinguish between physical and technical barriers on the physical side (Svenson, 1991, e.g.), and some distiguish between procedural/administrative barriers and human actions on the non-physical side (Neogy et al., 1996). Others distinguish between active and passive barriers (Kjellén, 2000; CCPS, 2001, e.g.). Passive barriers are inherent in the design of the workplace and do not require any sort of activation or utilities, while active barriers is dependent on an operator, an automated system, and/or other utilities to perform its function (Rausand, 2011). IEC 61511 (2003) categorizes safety measures as safety instrumented systems (SIS), other technology-related systems, or external risk reduction facilities.

Sklet (2006) presents a recommended hierarchy (See fig. 2.3) for classification of barrier systems based on the classification methods introduced above, among others. As a comment, barrier systems do not necessarily fall into only one of the suggested categories. Active barrier systems in particular tend to consist of a combination of both human/organizational and technical elements.

Hollnagel (2004) proposes a classification based on the nature of the barriers, using four categories: material, functional, symbolic and immaterial barriers. Material barriers physically prevent an event from taking place, functional barriers perform an active function (e.g. a password), symbolic barriers require interpretation (e.g. signs, instructions) and immaterial barriers are not physically present (e.g. competence, safety principles)(Rausand, 2011).

Other classification schemes include a categorization based on the barriers' ability to perform a barrier function on its own. Barriers which are able to completely prevent the progression of an accident scenario are called full barriers. Barriers which can only partially prevent the progression of an accident scenario are called partial barriers.

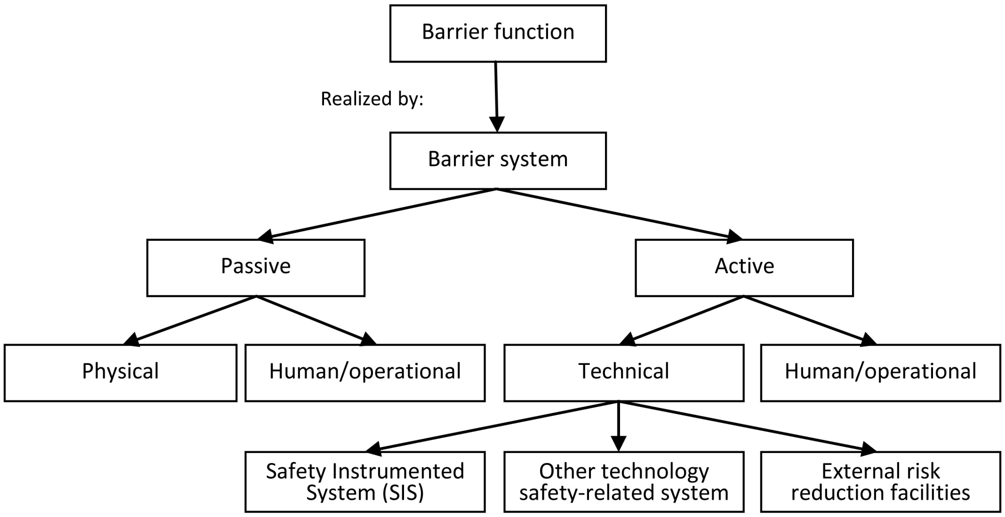


Figure 2.3: Classification of safety barriers. Adapted from Sklet (2006).

In accordance with the defense in depth principle barriers are sometimes classified according to the order in which they should be activated in case of an undesired event (i.e. primary, secondary, tertiary) (Rausand, 2011). The Norwegian Oil Industry Association (OLF, 2001) distinguishes between global and local safety functions. In addition, barrier systems may be classified with relation to time. This includes distinguishing between barriers which either perform their functions continually or on demand (Sklet, 2006). Some barriers are also temporary, which means they are only present or active during specific operations or external conditions (Hollnagel, 2004).

2.4 Barrier Performance Criteria

In his famous swiss cheese model, Reason (1990) describes safety barriers as slices of cheese. Holes in the slices of cheese represent the idea that a barrier can not be expected to perform its function with 100% success at all points in time. In order to measure and describe the ability of a barrier system to perform its intended function, a series of different performance criteria have been introduced in literature. PSA (2002) suggests that barrier performance can include, among others, the following properties:

- Capacity
- Reliability
- Availability
- Ability to withstand loads
- Integrity
- Robustness

These criteria can be categorized in three groups. Both availability and reliability describe the ability of the barrier to function when necessary. Robustness and ability to withstand loads describe the ablity of the barrier to withstand external impacts and accident loads. Capacity is a property which describes the ability of the barrier to *sufficiently* perform its intended function.

Rausand (2011) presents the following criteria for barrier performance, adapted from CCPS (1993), Hollnagel (2004) and HSE (2008):

- Specificity: The ability of the barrier to detect and prevent or mitigate the consequence of a specified hazardous event
- Adequacy: The ability of the barrier to prevent accidents within the design basis and meet regulatory requirements, as well as the capacity of the barrier
- Independence: Ideally, a barrier should be independent of all other barriers related to the specific hazardous event
- Dependability: The ability of the barrier to perform its intended function on demand
- Robustness: The ability of the barrier to withstand extreme events, and not be disabled by the activation of another barrier

- Auditability: The ability of the barrier to permit periodic validation of the barrier function (i.e. testing, maintenance)

After a comprehensive literature review of performance attributes, Sklet (2006) proposes another set of criteria recommended for the characterization of barrier performance. Which properties are relevant will depend on the type of barrier. The recommended criteria are as follows:

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

The triggering event or condition is not a property of the barrier itself, but an important key to understanding how a barrier will function.

2.5 Comments

As the NORSOK standards regulate activity in the Norwegian oil and gas industry, the definitions described in NORSOK Z-013 (2010) will also be used for the puspose of this report.

As mentioned in this chapter, the barrier concept is often used in a broad sense, and the concept can appear rather vague at first glance. As can be seen in section 2.3, a variety of different measures can fall within the definition of barriers, depending on the author's interpretation of the barrier concept. Sklet (2006) suggests that a barrier function should have a direct and significant effect on risk (i.e. the occurence and consequences of an undesired event), adding that a function which has at most an indirect effect should not be classified as a barrier function but as a Risk Influencing Factor (RIF). An element in a barrier system which can not, by itself, fulfill a barrier function is a barrier element. Because it may be difficult to determine the exact meaning of a direct and significant effect, this report will suggest a further delimitation of the barrier concept to only apply to functions which can have a direct effect on the accident *event sequence* (i.e. the release of energy). This means that this report will likely treat many non-physical barriers (e.g. organizational/operational aspects), which are classified as barriers by many authors, as RIFs. Barriers which have a direct influence on the accident sequence will usually consist of techical systems and/or human actions.

The continued use of the term *safety barrier* can be the source of some confusion. Although adequate in daily use, the distinction between barrier function and barrier system serves no purpose if standards, regulations and risk analyses continue to use the term safety barrier. In these cases it is unclear whether the term safety barrier refers to a barrier system, barrier function, both, or none of these terms. Sklet (2006) relates barriers to actions or systems, while Hollnagel (1999) states that the term is largely synonymous with barrier functions in daily language.

A further specification of the exact meanings of the related terms, and a more clear definition of which safety measures can be classified as barriers and which cannot, is needed if a common understanding of barriers is to be achieved. While many authors use the word barrier to describe virtually all types of safety measures, this report will treat barriers as a specific type of safety measure, which can have a direct effect on an event sequence leading to an undesired event or accident. This creates a distinction beween barriers and other safety related measures which both helps identify safety measures wich actually prevent an accident from happening, and facilitates barrier modeling.

Chapter 3

Safety Barriers on Offshore Oil & Gas Installations

3.1 Introduction

One of the characteristics of offshore oil and gas operations is the potential for catastrophic consequences if an accident should occur. A major accident on an offshore installation can lead to severe losses of both human life and economical resources, as well as significant environmental consequences. The main focus regarding safety barriers on offshore installations in this report is therefore on those barriers related to major accident risk. According to PSA (2011), a barrier strategy should always be based on an initial risk analysis and hazard identfication in the design phase . This is supported by Sklet (2006) who states that ”a safety barrier is related to a hazard, an energy source or an event sequence”. This section will present some of the most important barriers related to offshore oil and gas installations. Requirements regarding barriers in relevant standards and company specific guidelines will be examined.

As an example, a brief case study of barriers related to blowouts will be presented. Relevant barriers related to the accident scenario will be identified and discussed.

3.2 Barriers in NORSOK Z-013

The NORSOK Z-013 (2010) standard is the standard for risk and emergency preparedness assessment in the Norwegian petroleum industry. It was developed to support regulations issued by PSA and the Norwegian Ministry of the Environment regarding risk analysis in petroleum activities (Rausand, 2011). Clause 5.4 of the standard establishes requirements for the identification and analysis of IEs and the causes of these in risk analyses. The following IEs are listed as a minimum to be included in a QRA, as long as the scenarios are relevant for the specific hazard:

- Process accidents
- Risers/landfall and pipeline accidents
- Storage accidents (of liquid and gas)
- Loading/offloading accidents
- Blowouts and well releases
- Accidents in utility systems (e.g. leaks of chemichals, fires, explosion of transformers etc)
- Accidents caused by external impact and environmental loads (e.g. collision, falling/swinging loads, helicopter crash, earthquake, waves)
- Structural failure (including gross errors)
- Loss of stability and/or buoyancy (including failure of marine systems)

For each scenario, a number of important barriers should be in place in order to control the risk of an accident. A required minimum selection of barriers to be considered in a consequence analysis is listed in section 7.5 of the standard. The required barriers are presented in table 3.1.

Initiating Events	**Safety Barriers**
Process accidents	Detection Emergency shutdown system (ESD) and blowdown Control of ignition Control of spills Emergency power system Fire and gas system Active fire protection Passive fire protection Explosion mitigation and protection systems Evacuation, escape and rescue Segregation of main areas Structural integrity and stability
Pipeline and riser accidents	Detection Emergency shutdown system (ESD) and blowdown Control of ignition Fire and gas system Fire protection Evacuation, escape and rescue Structural integrity and stability
Accidents in utility systems	N/A
Storage accidents*	Bunds Passive and active fire protection Pressure relief system Purge gas Water curtains etc
Blowouts and well releases	Riser margin Mud balance system Pressure balance system Diverter system Control of ignition Control of spills Emergency systems related to well operations and drilling Annulus safety valves Blowout preventer (BOP) X-mas tree Down hole safety valve Barrier functions as for process accidents
External impact - Ship collisions	Planned operational restrictions for vessels Collision resistance of the facility (including risers) Planned traffic surveillance Planned emergency preparedness measures
External impact - Falling and swinging loads	N/A
External impact - Other	N/A
Helicopter accidents	N/A
Marine hazards	N/A
Environmental Consequences	Detection Drain system

Table 3.1: An overview of the safety barriers required by section 7.5 of NORSOK Z-013 (2010). N.B. The initiating events do not correspond to those listed in clause 5.4 of the same standard.
* Referred to as safety functions, not barriers.

In table 3.2 the barriers are classified according to whether they have a direct impact on the accident event sequence, and how they can be modeled using traditional Event Tree (ET) and Fault Tree (FT) analysis. Most of the barriers are technical systems which directly affect the development of an accident scenario, and can be modeled directly in an ET/FT. However, modeling all these barriers explicitly would result in enormous ETs/FTs and may therefore not always be practicable or feasible. It is also worth noting that the list contains a mixture of barrier systems and barrier functions, and does not effectively distinguish between the two. When modeling barriers in risk analyses it is important to maintain a clear distinction between barrier functions and barrier systems.

Safety Barrier	**Affects Event Seq.**	**Modeling**
Detection	Directly	Directly in ET/FT
Emergency shutdown system (ESD) and blowdown	Directly	Directly in ET/FT
Control of ignition	Directly	Directly in ET/FT
Control of spills	Directly	Directly in ET/FT
Emergency power system	Directly	Directly in ET/FT
Fire and gas system	Directly	Directly in ET/FT
Active fire protection	Directly	Directly in ET/FT
Passive fire protection	Directly	Directly in ET/FT
Explosion mitigation and protection systems	Directly	Directly in ET/FT
Evacuation, escape and rescue	Directly	Directly in ET/FT
Segregation of main areas	Indirectly	RIF
Structural integrity and stability	Directly	Directly in ET/FT
Accidents in utility systems	N/A	N/A (RIF)
Bunds	Directly	Directly in ET/FT
Pressure relief system	Directly	Directly in ET/FT
Purge gas	Directly	Directly in ET/FT
Water curtains etc	Directly	Directly in ET/FT
Mud balance system/Riser margin	Directly	Directly in ET/FT
Pressure balance system	Directly	Directly in ET/FT
Diverter system	Directly	Directly in ET/FT
Emergency systems related to well operations and drilling	Directly	Directly in ET/FT
Annulus safety valves	Directly	Directly in ET/FT
Blowout preventer (BOP)	Directly	Directly in ET/FT
X-mas tree	Directly	Directly in ET/FT
Down hole safety valve	Directly	Directly in ET/FT
Planned operational restrictions for vessels	Indirectly	RIF
Collision resistance of the facility (including risers)	Directly	Directly in ET/FT
Planned traffic surveillance	Indirectly	RIF
Planned emergency preparedness measures	Indirectly	RIF
Drain system	Directly	Directly in ET/FT

Table 3.2: Barriers mentioned in NORSOK Z-013 (2010), ability to intervene in an accident sequence, and possibility of modeling in a traditional event tree/fault tree analysis. (N/A: Cannot be defined as a barrier)

3.3 Barriers in NORSOK S-001

The NORSOK S-001 (2008) standard is the standard for *technical safety* in the Norwegian petroleum industry. The standard does not address safety barriers explicitly, but describes requirements for the management of technical safety regarding implementation of technologies and emergency preparedness, in order to ensure a sufficient level of safety. The standard describes the roles, interfaces, required utilities, functional requirements and survivability requirements for 20 different safety systems/functions. The identified safety systems/functions are:

- Layout
- Structural integrity
- Containment
- Open drain
- Process safety
- Emergency shutdown (ESD)
- Blow down and flare/vent system
- Gas detection
- Fire detection
- Ignition source control (ISC)
- Human-machine interface (HMI)
- Natural ventilation and heating, ventilation and air conditioning (HVAC)
- Public address, alarm and emergency communication
- Emergency power and lighting
- Passive fire protection
- Fire fighting systems
- Escape and evacuation
- Rescue and safety equipment
- Marine systems and position keeping
- Ship collision barrier

The roles of the safety functions/systems describe the functions that the safety systems should fulfill, such as minimizing release of hazardous material, minimizing the probability of ignition or pressure relief. Interfaces are listed if a system/function interacts with one or more other systems/functions. If the safety system/function is dependent on any utilities such as uninterruptable power supply, hydraulic power or instrument air, these are listed under utilities. The functional requirements for each system/function contain general requirements and requirements for specific safety systems or system elements which must be fulfilled for the safety system to adequately perform its intended function. Survivability requirements for the safety functions/systems contain minimum requirements for safety systems or system elements to ensure that the safety systems will survive the Dimensioning Accidental Loads (DALs).

3.4 Company Internal Guidelines

Some companies have developed their own guidelines for safety systems and barriers. Norwegian operator Statoil has developed a set of proprietary performance standards for important safety systems. The Statoil performance standards contain detailed design requirements for approximately the same safety systems/functions required by NORSOK S-001 (2008) and is closely related to the Technical Conditions Safety Audit (TTS) approach which is a generalized approach for reviewing the technical condition of safety systems based on performance standards (Thomassen and Sørum, 2002). Statoil uses performance standards for 22 safety systems and barriers for offshore operations. For comparison with the NORSOK standard, a full list of Statoil performance standards can be found in appendix C (Statoil, 2009).

3.5 Human & Organizational Barriers

The focus of the standards presented in this report in terms of barriers is almost exclusively on what is often called technical barriers. However, human and organizational aspects can also have a significant impact on risk. Human actions can be important parts of barrier systems, although they rarely fulfill a barrier function on their own. Organizational or operational factors generally affect the performance of other barrier systems. In this report, these aspects will typically be considered as RIFs or as barrier elements.

As mentioned in section 2.3, active barrier systems often contain both technical and human elements. The human elements will often be human actions or inputs, such as processing and understanding information from a system, or manual activation of a safety system. Common examples of organizational ”barriers” include maintenance, testing, operational procedures, operator training and competence.

3.6 Case Study: Well Blowout

3.6.1 Introduction

In order to illustrate the importance of barriers in accident scenarios, this section of the report will present a brief case study of barriers related to blowouts. The Macondo well blowout, and subsequent explosion, on the Deepwater Horizon (DWH) drilling rig in April 2010 showed the world the catastrophic potential of blowout accidents. The failure of safety critical equipment, combined with a lack of understanding of barrier performance and integrity, was identified as a direct cause of the accident (DNV, 2011; Tinmannsvik et al., 2011). This section will present a case study identifying relevant barriers for the prevention of blowouts and related consequences. The barriers will also be classified according to the theory presented in chapter 2.

Blowouts often occur during well operations performed by a drilling rig or less frequently from platforms; situations when formation fluids are not intended to escape the well. Barriers related to drilling activities are somewhat different from those related to production platforms, such as those presented earlier in this chapter. A drilling rig is not intended to extract and store petroleum products, and while an oil production platform is usually stationary, a drilling rig is mobile and will be used for different types of drilling operations at different locations. The risk of a blowout accident is very much dependent on the specifics of the well operation, in addition to the specifics of the drilling installation. However, the methodology of classifying and modeling the barriers will be applicable for either type of accident scenario.

3.6.2 Accident Scenario & Related Barriers

In an oil or gas well, formation fluids are contained by a series of barriers. If formation fluids unintentionally start flowing into the well, this is called a kick. A blowout occurs when a kick cannot be contained by the barriers in place to seal the well, and formation fluids are released uncontrollably. The technical and physical barriers present in order to prevent a blowout will vary depending on the type of well operation performed. Holand (1997) describes six types of blowouts. NORSOK D-010 (2004) uses a different, slightly more detailed set of activities. Both classifications of blowouts are presented in table 3.3. Shallow gas blowouts, as defined by Holand, are blowouts occuring at shallow drilling depths when the mud column is the only barrier preventing an unwanted release.

Holand (1997)	**NORSOK D-010 (2004)**
Exploration drilling blowouts which may be:	Drilling activities
• Shallow gas blowouts	Testing activities
• Deep blowouts	Completion activities
Development drilling blowouts which may be:	Production activities
• Shallow gas blowouts	Sidetracks, suspension & abandonment activities
• Deep blowouts	Wireline operations
Completion blowouts	Coiled tubing operations
Workover blowouts	Snubbing operations
Production blowouts	Under balanced drilling & completion operations
Wireline blowouts	Pumping operations

Table 3.3: Activities during which a blowout may occur according to Holand (1997) and NORSOK D-010 (2004)

During these operations, the barrier situation may be dynamic or relatively static.

NORSOK D-010 (2004) covers barrier systems related to well integrity (ie. the barriers which prevent the release of fluids), and groups barrier elements into two barrier systems: The primary and secondary well barrier. Two independent well barriers has long been a PSA requirement (Holand, 1997). For simplicity, this case study will focus on just one type of activity: Drilling, coring and tripping with shearable drill string. The well barriers required for this type of equipment are shown in table 3.4

Barrier Elements	**Comments**
Primary Barrier	
Fluid column	
Secondary barrier	
Casing cement	
Casing	Last casing set
Wellhead	
High pressure riser	If installed
Drilling blowout preventer (BOP)	

Table 3.4: Well barriers for "Drilling, coring and tripping with shearable drill string" under drilling activities. Adapted from NORSOK D-010 (2004)

If the drill string cannot be sheared by the BOP, the drill string and stab-in safety valve will act as elements in the secondary barrier (NORSOK D-010, 2004).These barrier systems can be defined as frequency-reducing or proactive barriers with reference to a blowout as the initiating/top event, and fulfill the barrier function *containment*. As a comment, these barriers fall within a very traditional definition of barriers in that they physically prevent formation fluids from escaping the well. If these barriers fail and a blowout occurs, consequence-reducing or reactive barriers will be necessary. A set of reactive barriers found in relevant standards are presented in table 3.5. The barrier functions identified can be realized by different types of barrier systems.

Reactive Barriers	
Diverter system	System
Gas detection	Function
Ignition control	Function
Fire detection	Function
Layout (Separation)	Function
Explosion protection	Function
Active fire protection	Function
Passive fire protection	Function
Control of spills	Function

Table 3.5: Reactive barriers related to blowouts during drilling from rig. Loosely based on NORSOK Z-013 (2010); NORSOK S-001 (2008)

After the DWH accident, BP (2010) identified a number of barriers which failed and contributed to the development of the accident scenario. These barriers are presented in figure 3.1. The accident occured while the well was being sealed for temporary abandonment, awaiting completion as the exploration well was being converted to a production well, which means the well barriers were slightly different than those presented above.

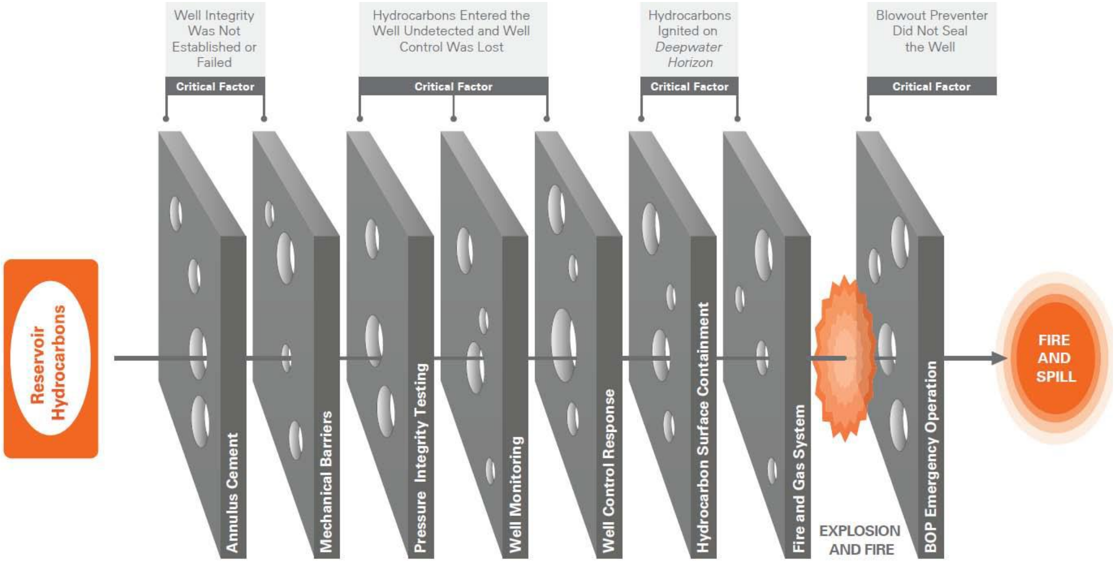

Well Integrity Was Not Established or Failed
Critical Factor
Hydrocarbons Entered the Well Undetected and Well Control Was Lost
Critical Factor
Hydrocarbons Ignited on Deepwater Horizon
Critical Factor
Blowout Preventer Did Not Seal the Well
Critical Factor
Reservoir Hydrocarbons
Annulus Cement
Mechanical Barriers
Pressure Integrity Testing
Well Monitoring
Well Control Response
Hydrocarbon Surface Containment
Fire and Gas System
EXPLOSION AND FIRE
BOP Emergency Operation
FIRE AND SPILL

Figure 3.1: BP list of barriers which contributed to the Deepwater Horizon accident presented as a swiss cheese diagram. BP (2010, p. 32).

The barriers presented in this figure are different than those presented previously in this section, and is not very intuitive using the logic presented in this report. Rather, it appears to be presented in the order of the specific nature of the DWH accident sequence. BP lists Pressure Integrity Testing, Well Monitoring, Well Control Response and BOP Emergency Operation as critical barriers. These are examples of human/organizational or operational barriers, which have not yet been addressed in this case study. The operation of the BOP may certainly have been an important factor in the DWH accident, but the BOP is part of the mechanical barrier system which is included further to the left in the diagram. The emergency operation may have affected the performance of the BOP, but can hardly be considered an independent barrier within the scope of this report. Well monitoring and pressure integrity testing will not be able to directly affect the frequency or the consequences of a blowout, but will affect the performance of well barriers and facilitate risk-informed decision-making. While they are certainly important factors affecting risk, this type of measures does not meet the critera for being defined as a barrier in this report, presented in chapter 2. They will therefore not be treated as barriers in this report.

Also, activities related to emergency perparedness such as escape, evacuation and rescue will affect the likelihood of fatalities, but are not considered barriers for the purpose of this case study.

3.6.3 Classification

Because the concept of barriers in this report is more narrow than the concept of barriers used in most modern literature on the subject, a classification of barrier systems based on the schemes presented in section 2.3.2 will not be particularly meaningful. Many of the types of barriers mentioned in this section are not considered barriers in the narrow sense recommended in this report. Rather, this report will focus more on the distinction between barrier function and barrier systems with relation to risk analysis. It is therefore important to distinguish between barrier systems and functions, and begin by identifying relevant barrier functions. Table 3.5 has identified a set of barrier functions, along with one barrier system. If this system is assumed to fulfill the barrier function *pressure relief*, the barrier functions identified in this case study are as follows: containment, pressure relief, gas detection, ignition control, fire detection, layout (separation), explosion protection, passive fire protection, active fire protection and control of spills. Barrier functions may be identified either as high-order functions or low-order functions, as high-order barrier functions can often be broken down into sub-functions. If there is a desire to avoid large event trees in risk analysis, using barrier functions of a higher order is recommended. For each barrier function, an analysis of relevant barrier systems can then be performed at an appropriate level of detail.

Proactive Barriers	**Reactive Barriers**
Containment	Pressure Relief Gas detection Ignition control Fire detection Layout (Separation) Explosion protection Active fire protection Passive fire protection Control of spills

Table 3.6: Classification of barrier functions as proactive or reactive.

Depending on how barriers are analyzed and how the IE is defined, it may also be helpful to identify which barriers are proactive and which are reactive. This will also facilitate risk analysis in accordance with NORSOK Z-013 (2010), which distinguishes between analysis of IEs and analysis of consequences. In this case study, the blowout was identified as the IE. The proactive and reactive barrier functions for this scenario are listed in table 3.6

3.7 Comments

The standards presented in this chapter present a list of important barrier functions and barrier systems that will normally be found on offshore installations, as well as a small case study related to blowouts. There is an evident focus on technical barriers in the standards, and the human/organizational perspective is not emphasized. The lists also contain both barrier functions and barrier systems, with no apparent distinction between them. This can cause considerable confusion, which could be prevented if theory and practice in these standards were made more consistent. In risk analysis, a functional requirement will often be given for barrier function which can be included in relatively simple event trees. These functions can be divided into sub-functions and be realized by a number of barrier systems. A clean-up of NORSOK Z-013 (2010) in particular, consistent with the definitions of barrier functions and system, could be in place. Requirements for barrier functions to consider in a QRA could be listed for each scenario. Where a certain barrier system is of special importance this could be stated, but the system should always be related to a barrier function to avoid confusion.

This chapter has presented a selection of important safety barriers for offshore oil and gas operations. However, because the classification of barrier functions and systems depend heavily on the definitions of the barrier concept and accident scenarios, this selection should not in any way be considered as a complete list of important barriers. For each specific installation or operation, the specific risk should always be considered, and appropriate barriers should be applied. It is important to note that different barrier systems may be suitable given the characteristics of each specific installation.

Chapter 4

Barrier Performance Modeling in Risk Analysis

4.1 Introduction

In chapter 2 and chapter 3 of this report, a basic understanding of the roles of safety barriers on offshore installations was established. This chapter will address the issues related to accounting for safety barriers in QRAs. At first, in order to establish the requirements of the QRAs performed, common objectives of risk analyses will be identified and discussed. Important barrier properties which contribute to risk will also be identified. How barriers can be made more visible in risk analyses (i.e. how the QRA can be structured to include safety barriers more explicitly) and how these barriers can be analyzed quantitatively will be discussed. Special attention will be given to how the technical and human/organizational condition of barriers can be taken into account in the QRAs. A selection of methods for analysis and quantification of barrier performance will be reviewed and discussed briefly. The results of this review will then be compared with the current practice in DNV Safety Risk Assessment, and comments and suggestions for improving the current QRA methodology with respect to barriers will be presented.

4.2 Objectives of Risk Analyses

NORSOK Z-013 (2010) defines the following general objectives for risk analyses:

- identify hazardous situations and potential accidental events
- identify initiating events and describe their potential causes
- analyse accidental sequences and their possible consequences
- identify and assess risk reducing measures
- provide a nuanced and overall picture of the risk, presented in a way suitable for the various target groups/users and their specific needs and use

In addition to this, QRAs can be performed with a number of different objectives, for a number of different applications. Depending on which decision making processes an analysis should support, the analysis should be tailored to provide the information which will facilitate those processes. For offshore oil and gas installations, the scope of an analysis will often be limited (e.g. with respect to life-cycle phases, specific operations or specific equipment). Risk analyses can be performed during the design phase, during operation, for special operations or interventions (repair etc) where there will be an altered risk picture, or decommissioning. If a QRA is performed of an installation in the design phase, it will have a predominant focus on technical issues and design parameters in order to provide support to the design process. A QRA of an installation in the operational phase will require an increased focus on technical and operational conditions on the specific installation, in order to provide input to operational safety processes. This report suggests a distinction between three main categories of QRAs, described in table 4.1.

Section 5.2 of NORSOK Z-013 (2010) describes the process of defining the objectives and scope of a QRA, and how this should be reflected in the analysis. Typical main objectives of QRAs performed by DNV for customers operating on the NCS include the following:

- To identify major hazards of the present design that may constitute a risk to personnel, main safety functions, the environment or assets.
- To establish a total risk picture, expressed in terms of personnel, impairment of main safety functions, frequency of oil spill to the environment and asset loss.

- To compare and assess the risk versus Norwegian Authority Requirements and Company requirements.
- To provide DALs as input to the platform design process.
- To provide advice to customer on potential risk reducing measures.

These objectives are deemed to be representative for the bulk of QRAs performed by DNV Safety Risk Assessment, and this type of analysis will be used as a basis for discussion in this chapter. However, the third objective is found to be somewhat beside the scope of this report, and will not be treated in detail.

The first objective can be met in a qualitative or semi-quantitative manner, by identifying obvious major hazards and/or relative differences between the contribution to risk of different hazards. This will not necessarily require a high level of detail, as the important outcome is to identify the major risk contributors and areas for improvement. The most detailed analysis will be required to meet the second and third objectives, which include the calculation of important risk-related indicators and comparing these with legal requirements. However, the level of detail will often be limited by the scope and objectives of the analyses, among other factors. While modeling can be done at a very high level of detail, it may not be feasible to create such models which represent the total risk picture of an installation. In practice, a trade-off between sufficient detail and computational ability, resources, and/or available data usually has to be made. Different modeling tools are suitable for different types of analyses, and the appropriate tools should be selected based on the data and resources available, the required level of detail and the objectives of each analysis (Røed et al., 2009).

Design Phase QRA	**Operational Phase QRA**	**Situational QRA**
Should give design support: Assess whether the design is safe (ie. within legal requirements), highlight areas which particularly affect risk, determine design loads etc.	Usually assesses the risk level of an installation in operation, and should take the specific technical and operational condition of the installation into account	Usually either an analysis of a specific operation or specific equipment, or an update of a QRA due to a change in risk picture (e.g. installation of new equipment, defective barrier systems/elements)

Table 4.1: A suggested distinction between three main categories of QRAs

4.3 The Effect of Barrier Properties on Risk

In a strict sense, every property related to a barrier can be argued to have an effect on risk, either directly or indirectly. In a QRA, the risk usually determined based on the probability of barrier functions being fulfilled by barrier systems, for instance using the performance measures described in chapter 2. Ultimately, these likelihoods form the basis of a QRA. It is important that the different performance measures are taken into consideration. As an example, the reliability of a gas detection system will describe the probability of the system being in working order. However, a working gas detection system will only detect a leak if a sufficient amount of gas reaches the sensors. In order to obtain these figures, we may have to use models which describe how barrier systems work and how they might fail. This can include traditional failure analysis, RIF analysis and/or fire and gas modeling (e.g. using Computational Fluid Dynamics (CFD)). Depending on the level of detail in the analysis, generic failure data will often be used in place of detailed modeling of the failure mechanisms of barrier systems. In operational phase QRAs, an important yet challenging objective is to include the effect that RIFs have on barrier performance. Possible methods for doing this will be discussed later on in this chapter.

While it can be argued that barriers may actually also introduce risk to a system, it will be assumed for the purpose of this report that the effect barriers have on risk is limited to risk reduction. Properties such as those proposed by Sklet (2006) and presented in chapter 2 will affect the probability of a barrier system performing its barrier function in an adequate manner. If barriers are to be included in a QRA, it is these probabilities which will be relevant for the modeling of accident scenarios.

4.4 Barrier Modeling in Risk Analyses

Traditionally, a QRA is performed by modeling total risk as the combined likelihood of a set of accident scenarios, which in turn are modeled based on the bow-tie principle. This is also how risk analyses are performed in accordance with NORSOK Z-013 (2010). Accident scenarios are usually modeled using traditional ET/FT methods. ETs are used to represent the accident scenarios, while FTs usually describe the failure modes of technical systems. Failure frequencies (e.g. leak data) for different equipment types are usually based on generic industry averages, multiplied by the number of equipment units on the specific installation. In recent years, a number of QRA approaches have been developed which include human/organizational factors as well as the technical properties of barriers. Three similar and somewhat related approaches will be presented in this section: Barrier & Operational Risk Analysis, Hybrid Causal Logic in Offshore Risk Analysis and Risk_OMT. The applicability of these methods for DNV QRAs will be discussed further in section 4.6.

4.4.1 The Barrier & Operational Risk Analysis Project

The Barrier and Operational Risk Analysis (BORA) Project was an extensive research project on barriers and operational risk analyses carried out between 2003 and 2006. The project focused on hydrocarbon release, and attempted to develop a methodology for barrier analysis addressing some of the issues presented in section 1.1 of this report. A detailed description of the generalized methodology can be found in Vinnem et al. (2009).

According to Vinnem et al. (2009), around half of the hydrocarbon leaks on the NCS occur as a result of human interventions where barriers are either inhibited or deactivated. The intention of the BORA approach is therefore to consider how deviations from normal operation, including human intervention, may affect barrier performance and cause hydrocarbon leaks.

The BORA methodology differs from traditional analysis in that it views initiating events as conditions deviating from normal, either technically or organizationally, in place of the traditional IE ”hydrocarbon release”. The starting point of the model is a set of generic work operations and equipment types, such as ”corrective maintenance on depressurized hydrocarbon containing equipment”. A set of errors related to these working operations are defined as the IEs. The IEs can be related directly to the manual intervention or to technical causes (e.g. ”incorrect fitting of flanges or bolts during replacement of a flange gasket”, or ”degradation of flange gasket”). Barriers which are intended to prevent the IE leading to a hydrocarbon release are modeled in Barrier Block Diagrams (BBDs). BBDs are diagrams similar to ETs, in which all nodes represent barrier functions realized by barrier systems (Vinnem et al., 2009). The modeling principles of BORA is similar to those used in

Risk_OMT, which will be presented in section 4.4.3 (see fig. 4.4).

Barrier performance is modeled using FT analysis, where the top event is defined as a failure or degradation of a barrier system. These failures are categorized in three groups: insufficient or inadequate functionality, technical failures and human errors. Often, industry average frequencies or probabilities of IEs and basic events in FTs can be found in data sources. In order to reflect the specific nature of each installation, the probability of the IEs and basic events are influenced by a set of RIFs. RIFs are modeled using risk influence diagrams which were developed as part of the BORA project. The generic RIFs are categorized in five groups. The RIFs associated with each group are shown in table 4.2. Different RIFs will be relevant for the different generic IEs.

RIF Groups	**Generic RIFs**
Personal characteristics	Competence Working load/Stress Fatigue Work environment
Task characteristics	Methodology Task complexity Time pressure Tools Spares
Characteristics of the technical system	Equipment design Material Properties Process complexity HMI (labels, alarms, ergonomic factors) Maintainability/accessibility System feedback Technical condition
Administrative control	Procedures Disposable work descriptions
Organizational factors/ Operational philosophy	Programs Work practice Supervision Communication Acceptance criteria Management of changes

Table 4.2: Generic RIFs categorized by groups in BORA (Aven et al., 2006a).

For each IE and basic event, Risk Influence Diagrams (RIDs) are used to model the effect of the RIFs on the event in question (see fig. 4.1). In order to assess the RIFs, each RIF is given a score. The scoring system is based on the TTS approach (Thomassen and Sørum, 2002), with scores ranging from A to F where A is the best industry standard and F is worst practice. The scoring can be based on different sources, such as expert judgement or TTS data.

In order to determine the effect each RIF has on the event, the RIFs are weighted according to the relative difference between the frequencies or probabilities of the basic event if the RIFs score is changed from the best standard to worst practice (Aven et al., 2006a,b). This is done based on expert judgement. The most important RIF is given a weight of 10, and the rest is given relative weights compared to this, on the scale 10-8-6-4-2. The weights are then normalized so the sum of weights is equal to 1.

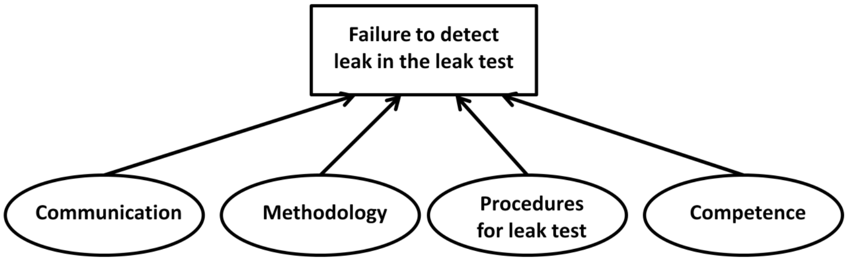


Figure 4.1: Risk influence diagram (Aven et al., 2006b).

The RIFs can then be used to adjust the industry average frequencies identified in the analysis using the following equation:

$$P_{rev}(A) = P_{ave}(A)\sum_{i=1}^{n} w_i Q_i \tag{4.1}$$

Where $P_{rev}(A)$ is the revised probability of event A, $P_{ave}(A)$ is the industry average probability, w_i is the respective weights of the RIFs, and Q_i is an expression reflecting the score of each RIF. In the BORA methodology a triangular distribution is assumed for each RIF, where Q_i is P_{low}/P_{ave} for the best standard, Q_i is 1 for the industry average, and Q_i is P_{high}/P_{ave} for worst practice. Here, P_{high} and P_{low} are the highest and lowest imaginable probabilities or frequencies as decided by expert judgement. The revised probabilities or frequencies can then be included in the risk model.

The BORA approach as an alternative to traditional QRAs has both strengths and weaknesses. The most important difference from the traditional approach is the modeling of IEs as a function of the number or manual operations performed on the equipment. As a significant part of leaks on the NCS occur during this type of operations, this approach appears to have significant potential. This is, however, somewhat outside the scope of this report which will discuss the treatment of barriers. As part of its generalized methodology, the BORA approach uses BBDs to model barriers between the IE and the end state, which is hydrocarbon release. Using barrier functions realized by barrier systems in the ET provides a robust approach to accident modeling, less dependent on the actual event sequence of the accident. BORA provides a relatively simple, generalized methodology for adjusting industry average frequencies based on installation-specific survey data or expert judgement, with RIFs including both technical and human/organizational factors (Aven et al., 2006b). However, the adjustment scheme will be based on assumptions about the distribution of the RIFs which, while intuitive, may have a weak relation to actual risk. In addition, the BORA approach describes only one level of RIFs, and RIFs which influence other RIFs are not included.

It should be noted that BORA is an approach specifically designed for calculating leak frequencies based on a set of generic scenarios, and is therefore not applicable for other QRA purposes. In addition, some of the operational barriers included in the BORA approach might not fall within the strict definition of safety barriers suggested in this approach. This does not mean that the modeling approach introduced by BORA is incompatible with the ideas of this report, but simply that the concept of barriers is slightly different.

4.4.2 Hybrid Causal Logic in Offshore Risk Analysis

A Bayesian Belief Network (BBN) is a network of nodes connected by arrows which indicate a statistical influence on the following node. BBNs have become more popalur in recent years, because of their ability to model non-deterministic causal relationships such as human and organizational factors. However, the use of BBNs in practice has been limited because of the significant amount of conditional probabilities required to calculate even relatively small networks (Røed et al., 2009). Large BBNs are challenging both in terms of describing the relationships between RIFs and in terms of computational ability. BBNs will not be explained in detail in this report, but information on the subject is readily available in literature (Jensen, 2001; Rausand, 2011, etc.). A small example of a BBN is presented in fig. 4.2.

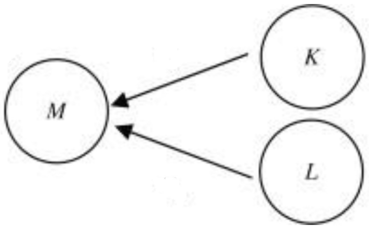


Figure 4.2: Example BBN (Røed et al., 2009).

In order to combine the modeling ability of BBNs and the intuitiveness and relative simplicity of ET/FT methods, a framework known as Hybrid Causal Logic (HCL) has been developed (Wang, 2007; Mohaghegh et al., 2009). The HCL framework consists of three integrated levels of analysis, illustrated in figure 4.3 (Wang, 2007):

1. Analysis of the accident scenario, using ET or Event Sequence Diagram (ESD) methods
2. Analysis of the system failures identified in the ESD, using FTs
3. Analysis of potential human and organizational factors which may contribute to the likelihood of events in the ET or failures in the FTs, through the use of BBNs.

Røed et al. (2009) proposes an adapted framework for the offshore oil and gas industry based on HCL. The method attempts to reconcile parts of the BORA approach and the TTS approach with the HCL framework. The TTS method is suggested for determining the states of the RIFs in the BBNs. The Operational Condition Safety (OTS, Sklet et al., 2010) approach was not part of the study, but is suggested as a possible method for determining the states of operational RIFs. Røed et al. (2009) proposes and describes a six-step process for applying HCL in the offshore industry:

1. Define RIFs and causal relationships for the relevant basic events of FTs
2. Identify concurrent RIFs
3. Build a BBN
4. Assign conditional probability tables
5. Evaluate performance, and assign a state for (some) RIFs
6. Calculate results

According to Røed et al. (2009) the RIFs, BBNs and conditional probability tables should be developed only once. Then, steps 5 and 6 can be performed for different operational conditions. Establishing the causal relationships in BBNs requires a fundamental understanding of the system in question, and a process involving teams of experts will often be necessary. Another idea is therefore to develop generic RIFs and BBNs for use in QRAs of similar installations. It is important that each RIF is defined in a way which ensures that the same factor is not represented more than once in the BBN.

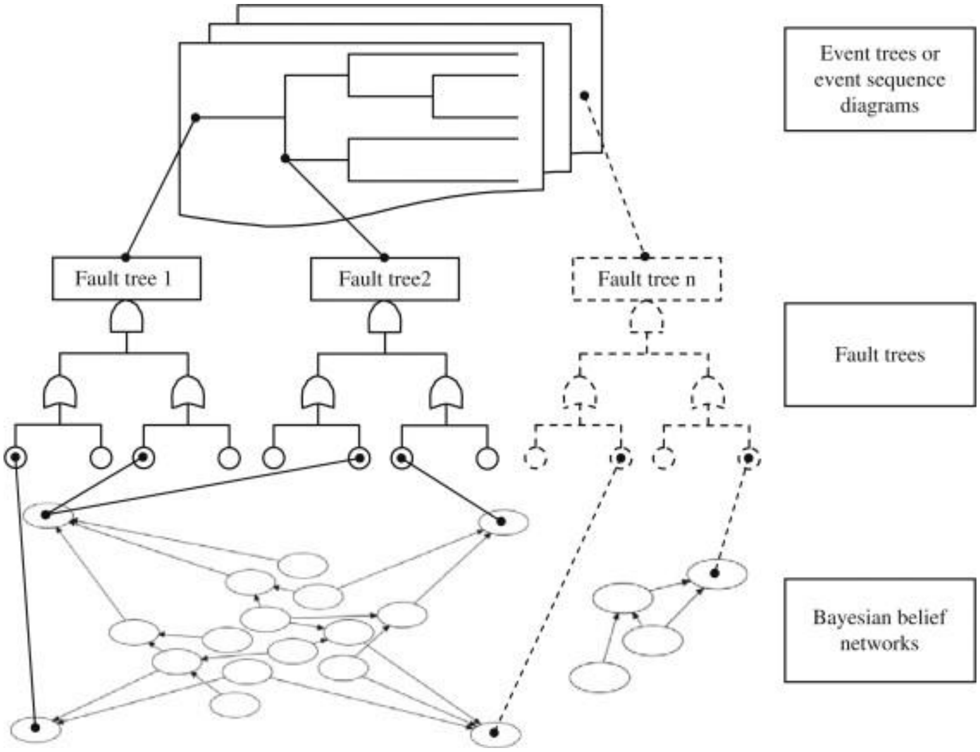


Figure 4.3: The HCL framework (Røed et al., 2009).

When assessing BBNs, knowledge about technical or operational conditions can be used to assign states to a number of RIFs, for instance using the TTS-based system introduced in BORA. These RIFs will be ”locked” in this state, and will work as parent nodes to other RIFs. The probability distribution of these nodes will depend on the state of the parent nodes. Because a large number of conditional probabilities have to be assigned even for small

BBNs, a semi-mechanistic method of assigning these probabilities is proposed by Røed et al. (2009). A probability distribution is assumed, where the probability of the RIF being in a state j is expressed as:

$$P_j = \frac{e^{-RZ_j}}{\sum_{j=a}^{f} e^{-RZ_j}} \qquad P_j \in [0,1] \tag{4.2}$$

Here, Z_j is a measure reflecting the distance between the RIF in question and the weighted average state of the parent RIFs, expressed as:

$$Z_j = \sum_{i=1}^{n} |Z_{ij}| w_i \qquad Z_j \in [0,6] \tag{4.3}$$

Where Z_{ij} is the distance (i.e. number of states) between the parent node and the RIF in question. w_i is the weight of the parent RIF i, assigned using the same approach as in BORA (see sec. 4.4.1).

R in eq. 4.2 is a shaping factor. The distribution will become narrower as R increases. A method for assigning a value to R based on expert judgement is suggested by Røed et al. (2009).

The approach for adjusting generic probabilities introduced in BORA is suggested for calculating the probablility of the binary events (i.e. events in the ET/FT structure). However, because the probability of the binary events are conditional on the states of the RIFs, the calculation of the revised probability is slightly different:

$$P_{rev} = P_{basis} \sum_{i=1}^{n} w_i \sum_{k=a}^{f} P_{ik} Q_{ik} \qquad P_j \in [0,1] \tag{4.4}$$

Here, P_{ik} are the probability of RIF i being in a state k, and Q_{ik} is the adjustment factor used in the BORA approach.

The HCL approach takes advantage the strengths of BBNs without having to face the challenges related to full BBN implementation for accident scenarios. The use of BBNs in RIF models enables a more detailed analysis of RIFs than the RIDs used in BORA, as interactions between RIFs can be included in the model. A problem with the hybrid approach is that when small BBNs are assumed to influence basic events independently, the same RIFs will often be used in several BBNs. This creates dependencies between events which are not accounted for statistically in the model. To avoid this, a few larger BBNs should be developed which are linked to several events in the ET/FT structure (Røed et al., 2009). Algorithms and techniques for the calculation of hybrid models, which account for these dependencies, have been developed as part of the HCL approach (Groth et al., 2010; Mohaghegh et al., 2009). In general, the exact approach will give a more conservative estimate, and will amplify the effect of the RIFs on risk compared to the simplified approach (Vinnem et al., 2012).

4.4.3 The Risk_OMT Approach

The Risk_OMT (Risk Modelling - Integration of Organizational, Human and Technical Factors) approach is a further development of the BORA approach, including elements from the HCL approach and the OTS program (Vinnem et al., 2012). A comprehensive approach for modeling leak frequencies is developed, through the identification of generic scenarios related to work operations, as introduced in BORA. One of the biggest differences between BORA and Risk_OMT is the introduction of BBNs in RIF modeling. With its relation to the OTS approach, Risk_OMT has a more detailed focus on the effect of human and organizational factors than BORA. Scenarios are modeled using BDDs and FTs like in BORA, but these are developed with a more elaborate and detailed focus on human error and operational barriers (see fig. 4.4).

Two modeling approaches are suggested by Vinnem et al. (2012). One is similar to that described by Røed et al. (2009), while the other approach describes a method of combining the FT and BBN logic of HCL in one large BBN . Barrier systems are initially modeled using FT analysis, and BBNs describe the effect of RIFs on the basic events. The FTs in Risk_OMT are generally given the top event ”failure or degradation of . . . the barrier system”, which is then classified in two groups (Vinnem et al., 2012):

- Inadequate or insufficient functionality of the barrier system
- Human failure

The taxonomy of human failures used in Risk_OMT is based on the theories of Reason (1990), and covers *violations*, *mistakes* and *slips and lapses*. These failures are called failures of execution, while failures of omission describe activities which are simply not carried out. The process of developing this taxonomy is described in section 3 of Vinnem et al. (2012).

A BBN model is suggested with RIFs structured in two levels, where the first level RIFs have a direct influence on binary events and second level RIFs influence the factors on the first level. The RIFs for all the generic scenarios in the method are grouped into two generic RIF structures: One for planning activities and one for execution and control activities. However, the generic structures may have to be adapted somewhat for each scenario. The same scoring practice is used as in BORA (taken from OTS and TTS), assigning scores from A to F, using these scores to update the probability distributions of RIFs.

Risk_OMT represents an improvement of the BORA approach with respect to the detailed modeling of human and operational factors. With its extensive use of BBNs, and human and operational failure data, it also requires significantly more work than the BORA method. If the distributions of each RIF is assigned individually, for instance using bayesian updating, the work load will also be considerably higher than that introduced for the HCL approach by Røed et al. (2009). The application of Risk_OMT is limited to the calculation of leak frequencies focusing on human and operational factors, but the approach introduces methods for analyzing barrier performance and RIFs which can potentially be extended to other purposes. As an example, similar methods could be developed which take into account the effect of operational RIFs on technical barrier systems.

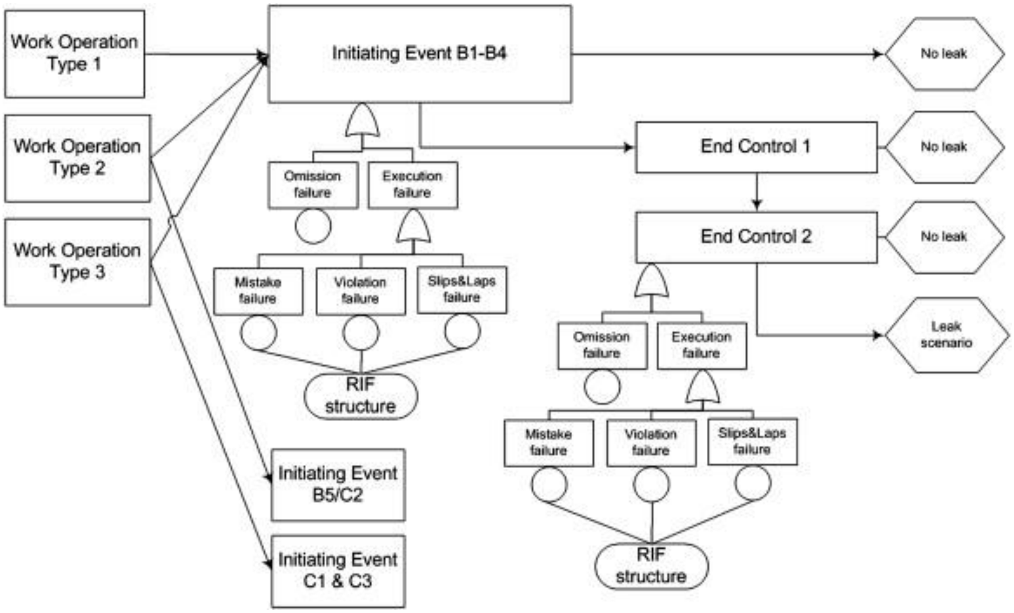


Figure 4.4: The basic principles of modeling in Risk_OMT (and similarly in BORA). (Vinnem et al., 2012).

4.5 Current Practice in DNV

In accordance with regulations for operations on the NCS, risk analyses in DNV are performed using the general methodology and process described by NORSOK Z-013 (2010). Accident scenarios are developed using ETs, and fire and explosion scenarios are modeled using CFD, or simplified modeling tools. A typical event tree in a QRA is developed to be applicable for a class of accident scenarios. For instance, a single ET will be developed for process accidents initiated by hydrocarbon release. Similar ETs can be used for process accidents, riser and pipeline accidents and blowout accidents. An ET like this will generally contain the following or similar branches:

- Leak (IE)
- Immediate ignition
- Early detection
- Delayed ignition
- Explosions escalating to other areas
- Explosions escalating to other equipment given no escalation to other areas

- Isolation failure
- Escalation to Equipment
- Escalation to adjacent areas

Here, early detection and isolation represent barrier functions. Other barriers are usually covered more indirectly, or assumptions are made regarding their functionality. As an example, leak frequencies are based on reliability data for hydrocarbon containing equipment which fulfill the barrier function *containment*. Table 4.3 describes how the safety barriers related to process accidents in NORSOK Z-013 (2010) are currently treated in QRAs. Usually, the most important technical barriers are accounted for, at least implicitly, while operational factors are not accounted for.

Safety Barrier	**Treated in QRA**
Detection	Gas detection modeled as part of ignition modeling (e.g. using CFD) and takes into account amount of detectors etc. It is often assumed that leaks will be detected either automatically or manually. Detection is normally assumed for fires.
ESD and blowdown	Modeled as barriers both with respect to reliability, response time etc.
Control of ignition	Part of ignition probabilities. Includes no. of ignition sources, shut-down time etc
Control of spills	Taken into account for environmental risk, and in pool size calculations for fire/explosion modeling
Emergency power system	N/A
Fire and gas system	Ventilation included in CFD models (For other systems, see detection and active/passive fire protection)
Active fire protection	Often not included due to PSA requirements for DAL calculation, but can be modeled including reliability, capacity etc.
Passive fire protection	Included in CFD models and escalation probabilities
Explosion mitigation and protection	Included in CFD models and escalation probabilities
Evacuation, escape and rescue	N/A
Segregation of main areas	Included in CFD models and escalation probabilities
Structural integrity and stability	Usually not modeled ind detail, but assumptions for the integrity of structures are included

Table 4.3: Barriers related to process accidents according to NORSOK Z-013 (2010), and how they are currently treated in DNV QRAs.

4.6 Comments and Suggestions

While most barrier functions are accounted for at least partly in DNV QRAs, not all barriers are modeled with the same level of detail. Some barriers are only accounted for in consequence modeling, while assumptions are made for the reliability and functionality of the barriers. Many types of barrier systems usually have a very low probability of failure, and the probability of success of these barriers is often assumed to be one. This might not always be a sound assumption, especially in the operational phase when barrier systems may have deteriorated. Other barriers are taken into account in risk models, but this is not visible from the ET scenarios. The QRAs in general, and ETs in particular, could be designed to provide more information about the impact of safety barriers on major accident risk. In order to include the effect of different barriers in the ET models, the first suggestion for improvement identified in this report can be defined as:

1. *Include relevant barrier functions for each scenario as events in ET models.*

By including barrier functions more systematically as nodes in the ETs, a much more robust scenario model can be developed. The end states developed will be dependent on the success or failure of relevant safety barrier functions, providing a more nuanced risk picture. Inferences can be drawn about the importance of barriers simply by looking at the ET, and changes in the barrier situation (e.g. loss of a barrier function/system) can easily be accounted for in the ET model. As an example of how this can be done, a new tree for process accidents is proposed and illustrated in appendix D. When creating ETs with barrier functions as nodes, the risk analyst should be aware that dependencies may be introduced if the same barrier system contributes to more than one barrier function in the ET.

These ETs will account for barriers on the right side of the bow-tie model. Depending on the definition of the IE, barriers on the left side of the bow-tie can also be modeled explicitly. As an example, BORA describes how barriers can be taken into account for hydrocarbon release rates, and FT models for well barriers can be used to synthesize blowout frequencies.

Another advantage of including safety barriers explicitly in ETs is that it allows for systematic modeling of safety barrier performance, including both technical and human/organizational factors. A combination of FTs and RIDs/BBNs can be used to model the performance and condition of the barrier systems which realize each barrier function.

The level of detail of these models can be adjusted based on the specific requirements and objectives of the QRA. In some cases, additional modeling may not be necessary and a standard event frequency can be applied. If there is uncertainty related to the appropriateness of these frequencies, further analysis can be performed. Methods such as those described in the HCL approach proposed by Røed et al. (2009) or in BORA can be applied to account for both technical and human/organizational factors. This may be particularly useful in the operational phase, when there is a need to model the specific technical and operational condition of barriers on an installation. The second suggestion for improvement identified in this report will be the following:

2. *When appropriate and practicable, the technical and human/organizational condition of barriers should be taken into account using FT or RID/BBN models.*

Approximate methods for adjusting standard frequencies, such as that proposed by Røed et al. (2009), are recommended as a feasible addition to the current QRA approach. While not as accurate as the approach described in the Risk_OMT framework (Vinnem et al., 2012), these methods can give valuable input regarding installation specific conditions. For most applications, the amount of system knowledge, data and work required to implement the full BBN approach suggested by Vinnem et al. (2012) makes it unlikely to be practicable for QRAs today.

It can be argued that this type of analysis will introduce uncertainty to the models, as the use of non-deterministic causal relationships and expert judgement make it difficult to know whether the adjusted probabilities reflect the ”true likelihood” of an event (Røed et al., 2009). It may seem inappropriate to tamper with numbers based on historical data, as the data can be argued to reflect ”reality”. While this criticism is valid, the alternative is to simply ignore the effect of RIFs and use historical data which may not be appropriate. If inappropriate numbers are applied, these numbers will describe a different reality than that of the object under analysis If conditions deviate from the industry average, the industry average numbers will not reflect the reality of the specific installation. Even a qualitative discussion of installation-specific conditions will give important input on whether the historical data used in QRAs are appropriate for each specific application. The tools suggested in this report provides a systematic approach to RIF modeling which will be less subjective than a purely qualitative, high-level discussion of barrier conditions. Especially for situations where barrier conditions are assessed to be worse than the industry average, it will be more appropriate to use an adjusted estimate than an optimistic industry average probability. The adjusted average probability will then be a conservative estimate.

While the objective of this report is to examine how safety barriers can be taken into account to improve QRAs, it should be noted that the concept of safety barriers is not entirely undisputed. The energy-barrier perspective has received criticism from some researchers because it is based on linear causal chains, and does not account for complex interactions in larger socio-technical systems. The term ”organizational accidents” is often used to describe major accidents which have several contributing causes, involving interactions between people and technology at different levels within an organization (Reason, 1997). Researchers such as Hollnagel et al. (2006) and Rasmussen (1997) have argued that the traditional approach does not sufficiently account for the mechanisms that cause such accidents, and have developed alternative approaches. However, all models represent a simplification of reality, highlighting certain aspects of problems which are often too complex to understand without simplification. Rosness et al. (2010) discusses how alternative approaches can be used to highlight different aspects of an accident. Røed et al. (2009) argues that while critical discussion of the causal chain and event modeling approach is important, these methods are suitable and useful for a number of applications. Also, possibilities of including organizational factors in these models have been enabled through the introduction of BBNs and hybrid approaches.

Chapter 5

Summary and Recommendations for Further Work

5.1 Introduction

In the previous chapters of this report, the many aspects of safety barriers have been presented and discussed, and potential ways of modeling barriers in QRAs have been examined. This final chapter will provide a brief summary and the conclusions of the report. In addition, a brief list of recommendations for further work on the subject will be presented, based on the findings of this report.

5.2 Summary

In chapter 2, the concept of safety barriers was presented and discussed based on a comprehensive literature review on the subject. Because the concept of safety barriers is often loosely defined and used interchangeably with similar terms, there is a need for a common understanding of the term within the Norwegian oil and gas industry. In accordance with the NORSOK Z-013 standard, safety barriers are defined as:

- *Safety barrier:* Physical or non-physical means planned to prevent, control, or mitigate undesired events or accidents.

In addition, a distinction between *barrier function* and *barrier system* is suggested. A barrier function is a function which is planned to prevent, control, or mitigate an undesired event or accident. A barrier system is a system which is designed to perform one or more barrier functions.

A number of methods for categorizing safety barriers exist. Sometimes barriers are categorized by function, and sometimes they are categorized by system properties. When safety barriers are categorized by function, it is often related to the effect the barrier function has on the accident scenario. A common categorization is based on the bow-tie model, distinguishing between frequency-reducing and consequence-reducing barriers. Frequency-reducing barrier functions can be further divided into avoidance and prevention, while consequence reducing barrier functions can be divided into control and protection or mitigation. Barrier systems are often classified as either physical or non-physical, or as passive or active.

Several properties have also been suggested to measure the performance of safety barriers. Common performance measures, which describe different aspects of barrier performance, inlude functionality/effectiveness, reliability/availability, response time and robustness.

An introduction to common safety barriers in offshore oil and gas operations on the Norwegian Continental Shelf was presented in chapter 3. Important relevant safety barriers in standards for offshore operations were identified, and a brief case study of barriers related to blowout accidents was performed. In the standards, even though there is a formal distinction between the terms, barrier functions and barrier systems are often mentioned interchangeably.

In chapter 4, possible ways of modeling safety barriers in risk analyses were examined. The specific requirements and objectives of different types of risk analyses were discussed, and three main categories of risk analyses was suggested: Design phase QRAs, operational phase QRAs, and situational QRAs. The relevant barrier properties for risk analyses were discussed briefly. Three relatively new QRA approaches, which include methods for analyzing safety barriers, were presented. The BORA approach was developed as a method for synthesizing process leak frequencies based on human interventions to hydrocarbon containing systems. The approach is based on generic accident scenarios, initiated by a deviation from normal condition, with safety barriers modeled in barrier block diagrams. A method for modeling RIFs, based on the TTS approach, is suggested. The TTS approach is used to give scores to

RIFs, which are modeled in risk influence diagrams. A mathematical algorithm for adjusting industry average frequencies based on these scores is proposed.

A framework known as HCL has been developed, which combines the ability of BBNs to model non-deterministic causal relationships between RIFs, and the intuitiveness and relative simplicity of ET/FT methods. The framework uses BBNs to model RIFs for binary events in ETs/FTs. A method attempting to apply HCL to the oil and gas industry, building on elements from the BORA and TTS approaches, has been developed. An algorithm for adjusting average probabilities similar to that proposed in BORA is suggested, applying BBNs for more detailed RIF modeling.

Risk_OMT is a further development of the BORA approach, including elements of HCL and the OTS program. The Risk_OMT approach introduces BBNs both for modeling RIF structures and the traditional FT structures. Detailed methods for modeling human and operational errors are described. The extensive use of BBNs and human and operational failure data makes the approach require significantly more work than the simplified methods presented in this report.

The current approach for risk analysis in DNV was also discussed. Technical barriers are usually accounted for in DNV QRAs today, but not all barriers are modeled explicitly in ET models, or with the same level of detail. Human and organizational aspect are often not modeled explicitly. Suggestions for improvement of the current approach were identified, based on the theory reviewed.

The conclusions of the report will be summarized below, in section 5.3.

5.3 Conclusions

This report has identified the following suggestions for improvement of QRAs with respect to safety barrier analysis:

1. *Include relevant barrier functions for each scenario as events in ET models.*
2. *When appropriate and practicable, the technical and human/organizational condition of barriers should be taken into account using FT or RID/BBN models.*

It is suggested that only functions or systems which have a direct effect on the accident scenario should be classified as safety barriers. This means that some non-physical measures which are often classified as barriers, such as operational barriers, may not be classified as barriers in this report. Functions which only have an indirect effect on the accident scenario should be treated as RIFs. Barriers which have a direct effect on accidents can be modeled in ETs, while influencing factors can be modeled as RIFs. It is also important to maintain a clear distinction between barrier functions and barrier systems. This could be facilitated by improving relevant standards for risk analysis with respect to barriers.

Including barriers in ETs helps illustrate the effect of barriers on major accident risk, and allows for explicit modeling of the barrier systems implemented to perform each barrier function, as well as RIFs which affect barrier performance. FT and BBN models can be applied to analyze both the technical and human/organizational condition of barrier systems.

It is suggested that simplified methods for adjusting industry average probabilities such as those introduced in BORA or the HCL approach for the oil and gas industry are applied for RIF modeling, as these methods will require a more practicable workload than the detailed approach suggested in Risk_OMT.

While it may seem inappropriate to tamper with probabilities which are based on historical data, it is important to consider whether the historical data accurately reflects the object under analysis. If conditions deviate from the industry average, industry average numbers will not reflect the reality of the specific installation. Using adjusted probabilities will be particularly useful when RIFs have a lower score than the industry average, because the average frequencies will be artificially optimistic. An adjusted probability will be a conservative estimate.

It should be mentioned that the energy-barrier perspective has received criticism from some researchers because it is based on linear causal chains, and does not account for complex interactions in larger socio-technical systems. While the approach does have its shortcomings, methods based on the barrier approach have proved to be useful and suitable for a number of applications. In addition, the approach is continuously improved with respect to more complex causal relationships, for instance through the development of BBNs.

5.4 Recommendations for Further Work

This report has identified a set of suggestions for how safety barriers can be modeled in risk analyses, but a complete approach for doing this has not been developed. In order to further examine how barriers can be successfully modeled in QRAs, the following recommendations for further work have been identified:

- Event trees with focus on barrier functions, like that proposed in this report, should be developed for all relevant accident scenarios. The ET proposed in this report is indended as an illustration, and should also be developed further.
- BBNs and/or RIDs should be tested in pilot projects. An appropriate method for integrating these models in DNV QRAs should be developed. Appropriate RIFs for different accident scenarios and events should be identified, and data sources should be identified or developed.

Appendices

Appendix A

Definitions

Barrier element Physical, technichal or operational component in a barrier system (NORSOK Z-013, 2010).

Barrier function Function planned to prevent, control, or mitigate undesired or accidental events (NORSOK Z-013, 2010).

Barrier system System designed and implemented to perform one or more barrier functions (NORSOK Z-013, 2010).

Hazard Potential source of harm (NORSOK Z-013, 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 Z-013, 2010).

Safety barriers Physical or non-physical means planned to prevent, control, or mitigate undesired events or accidents (NORSOK Z-013, 2010).

Safety function Physical measures which reduce the probability of a situation of a hazard and accident occuring, or which limit the consequences of an accident (NORSOK Z-013, 2010).

Technical safety Technical safety management in project development and design processes comprises activities to identify risks, develop safety strategies and performance requirements for safety systems and barriers. Technical safety management shall also facilitate the design process to ensure that studies, analysis and reviews are performed in due time and properly documented with due consideration of the needs for timely input to design and procurement processes (NORSOK S-001, 2008).

Appendix B

Acronyms

ALARP As Low As Reasonably Practicable

BBD Barrier Block Diagram

BBN Bayesian Belief Network

BOP Blowout Preventer

BORA Barrier and Operational Risk Analysis

CFD Computational Fluid Dynamics

DAL Dimensioning Accidental Load

DNV Det Norske Veritas

DWH Deepwater Horizon

ESD Emergency Shutdown

ET Event Tree

FT Fault Tree

HCL Hybrid Causal Logic

HMI Human-Machine Interface

HSE Health, Safety and Environment

HVAC Heating, Ventilation and Air Conditioning

IAEA International Atomic Energy Agency

IE Initiating Event

ISC Ignition Source Control

IPK Department of Production and Quality Engineering

NCS Norwegian Continental Shelf

NTNU Norwegian University of Science and Technology

OLF Norwegian Oil Industry Association

OTS Operational Conditions Safety Audit

PSA Petroleum Safety Authority Norway

QRA Quantitative Risk Analysis

RAMS Reliability, Availability, Maintainability and Safety

RID Risk Influence Diagram

RIF Risk Influencing Factor

SIS Safety Instrumented System

TTS Technical Conditions Safety Audit

Appendix C

List of Statoil Performance Standards

1 Containment

2 Natural ventilation and HVAC

3 Gas detection

4 Emergency shut down (ESD)

5 Open drain

6 Ignition source control

7 Fire detection

8 Emergency depressurisation and flare/vent system

9 Active fire protection

10 Passive fire protection

11 Emergency power and lighting

12 Process Safety

13 Alarm and communication system for use in emergency situations

14 Escape, evacuation and rescue (EER)

15 Layout design principles and explosion barriers

16 Offshore cranes

16 (B) Drilling hoisting system

17 Well integrity

18 Ballast water and position keeping

19 Ship collision barriers

20 Structural integrity

21 N/A

22 Human machine interface & alarm management

Source: Statoil (2009)

Appendix D

Suggested Event Tree for Hydrocarbon Release

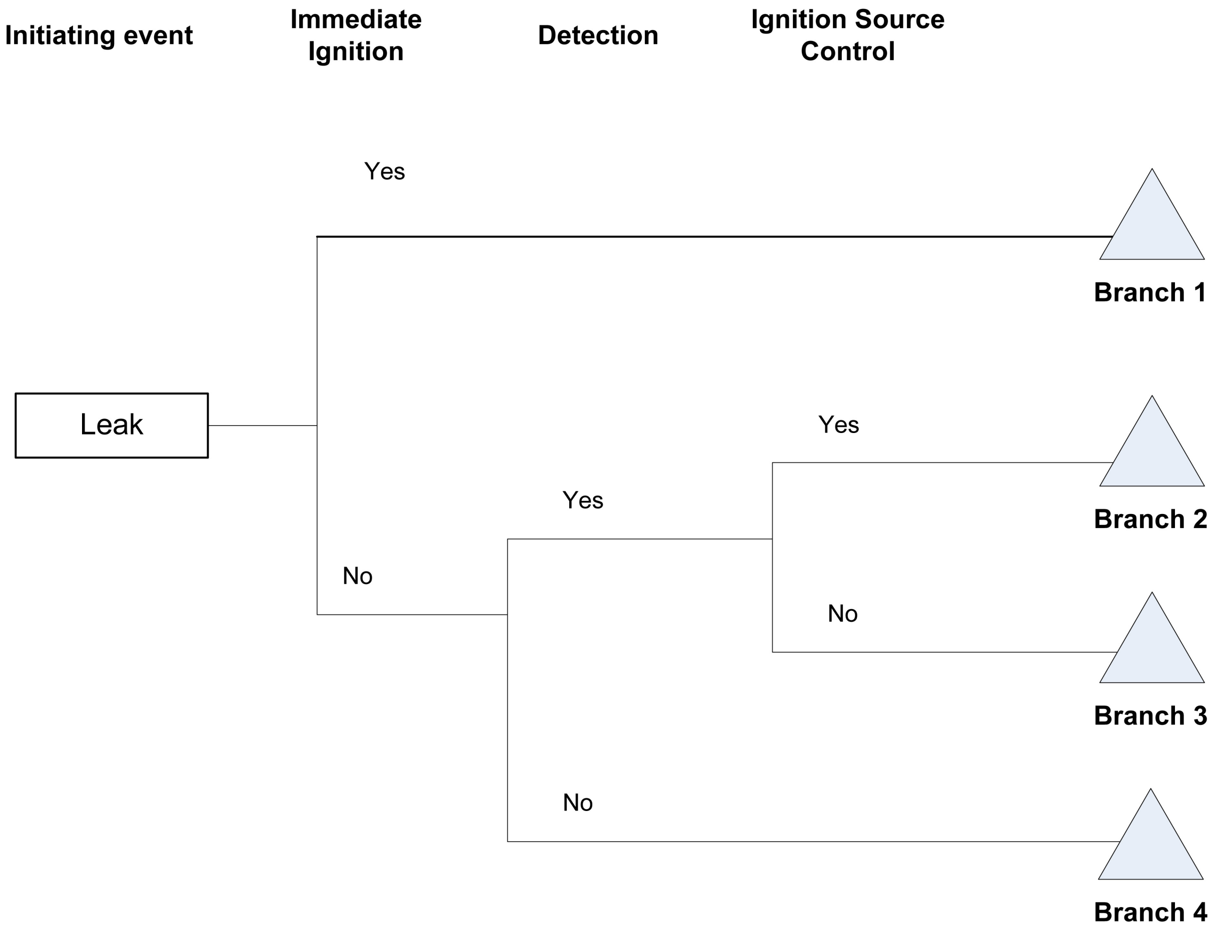
As an example of how barrier functions can be included in models, an ET has been developed for the scenario of hydrocarbon release. The new ET is based on the tree described in section 4.5, and has been altered to more explicitly contain barrier functions. The tree is intended to contain the same information about the scenario as the current tree. The end states of the ET will reflect the possible consequences of a leak, dependent on the performance of relevant safety barriers.

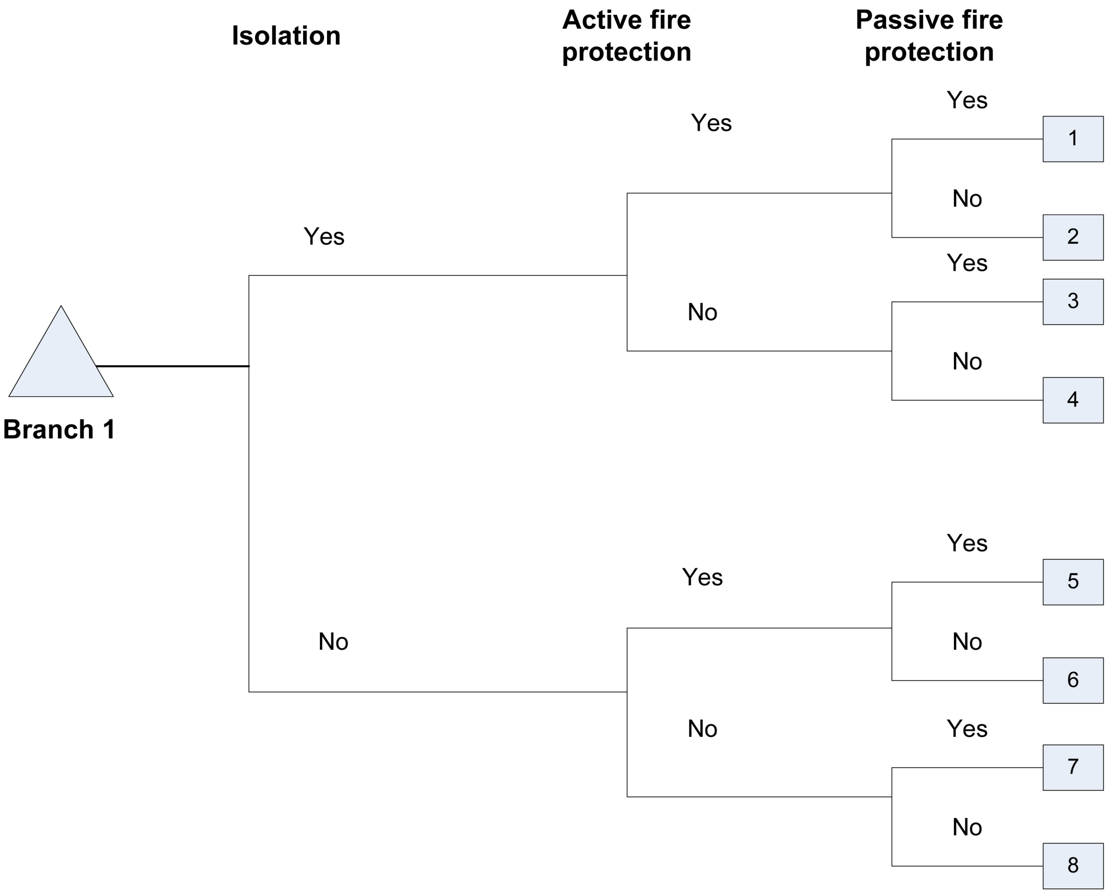
It should be noted that delayed ignition is placed in different places in the ET branches. If detection is successful, isolation will hopefully be attempted before ignition. If there is no detection, isolation will not be attempted until after ignition. The probability of successful isolation will then be dependent on delayed ignition. Conversely, if detection is successful, the probability of delayed ignition might be dependent on isolation.

In order to simplify the ET, a number of assumptions has been made for the scenario:

- It is assumed that immediate ignition will not have the potential to cause an explosion. Fire will be assumed as the only hazardous consequence of immediate ignition. Because of the amount of flammable material in the area, delayed ignition will be assumed to cause an explosion (of a size dependent on leak rate, response time etc.).
- Immediate ignition is assumed to be independent of Ignition Source Control. Delayed ignition, however, is assumed to be dependent on Ignition Source Control. Ignition Source Control is assumed not to be relevant when detection fails.
- There is no specific branch for escalation in the new tree. However, it is assumed that the probability of escalation due to explosions is the same as the probability of failure of the barrier function *explosion mitigation and protection*.
- The availability of data was not considered during the development of the tree. It is assumed that sufficient data will be available for the modeling of each basic event.

These assumptions have been made in order to simplify the ET, and have not been verified for any type of application. In addition, several barrier functions are not included in the tree. As such, this ET should only be viewed as an illustration for the purpose of this report. Before the ET can be put into use, the assumptions should be tested and verified. Further development of the tree might then be required.


Initiating event
Immediate Ignition
Detection
Ignition Source Control
Yes
Branch 1
Leak
Yes
Yes
Branch 2
No
No
Branch 3
No
Branch 4


Isolation
Active fire protection
Passive fire protection
Branch 1
Yes
No
Yes
No
Yes
No
Yes
No
Yes
No
Yes
No
Yes
No
Yes
No
1
2
3
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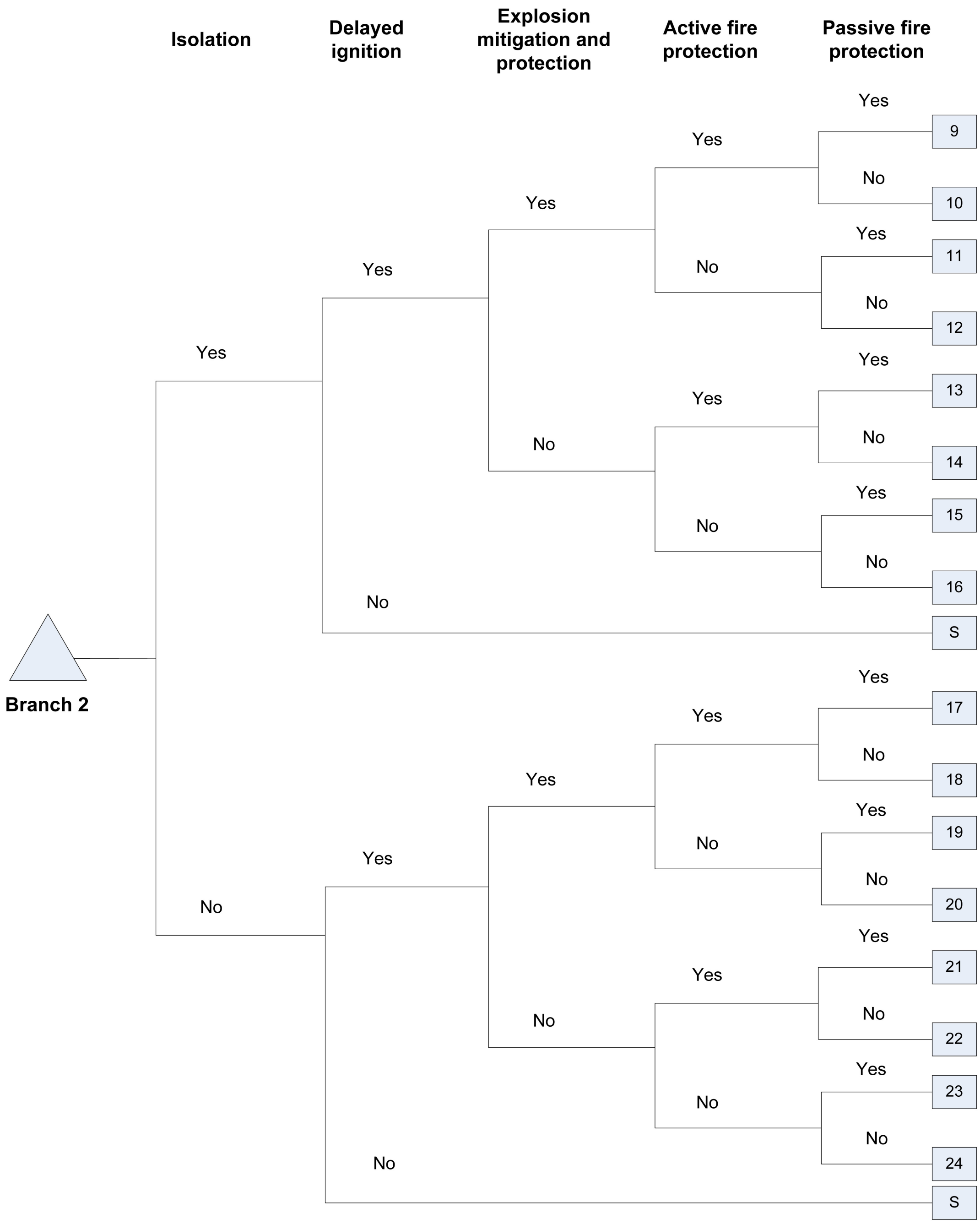
Isolation
Delayed ignition
Explosion mitigation and protection
Active fire protection
Passive fire protection
Branch 2
Yes
No
Yes
No
Yes
No
Yes
No
Yes
No
9
10
11
12
13
14
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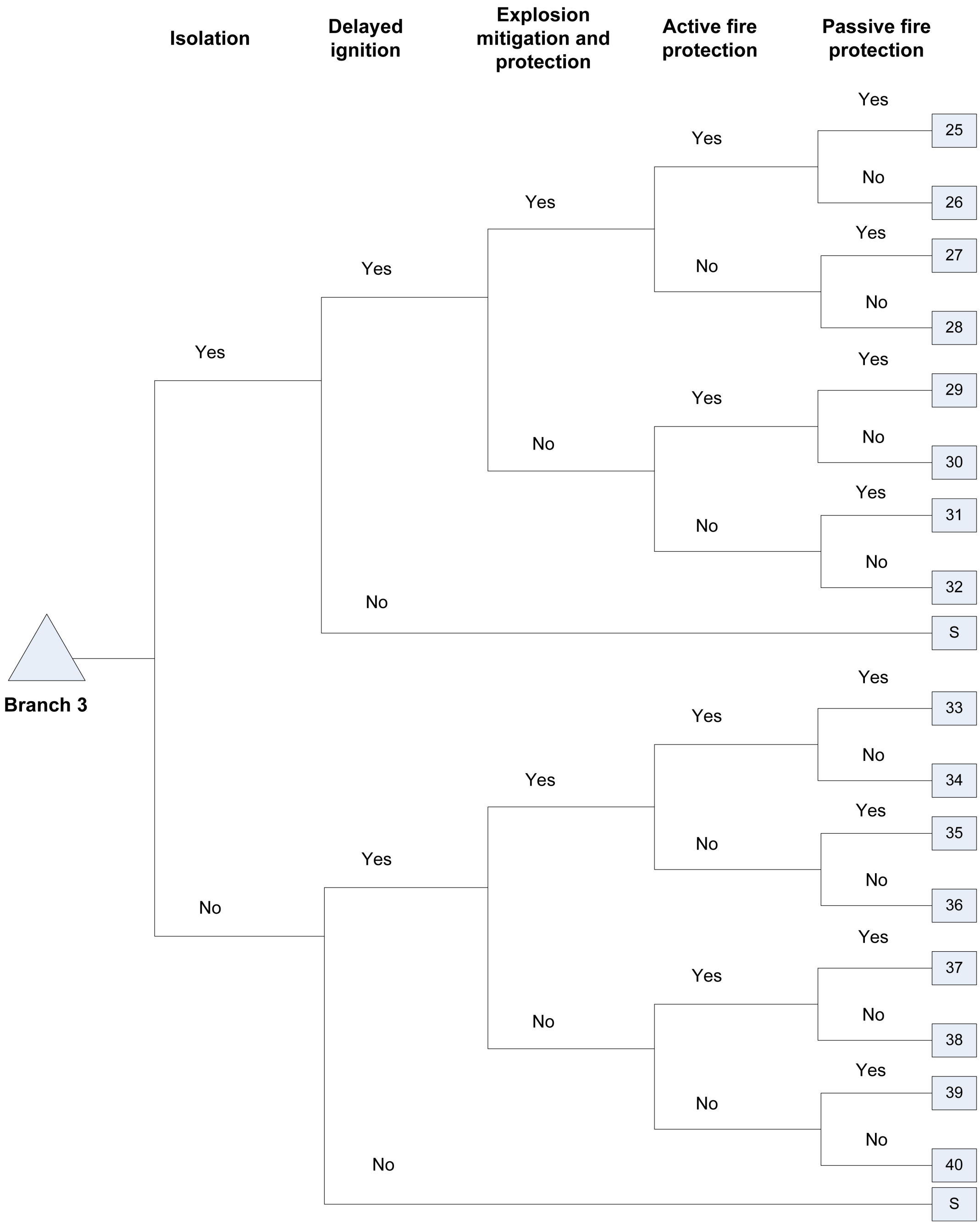
S
17
18
19
20
21
22
23
24
S

S: Safe state


Isolation
Delayed ignition
Explosion mitigation and protection
Active fire protection
Passive fire protection
Yes
No
25
26
27
28
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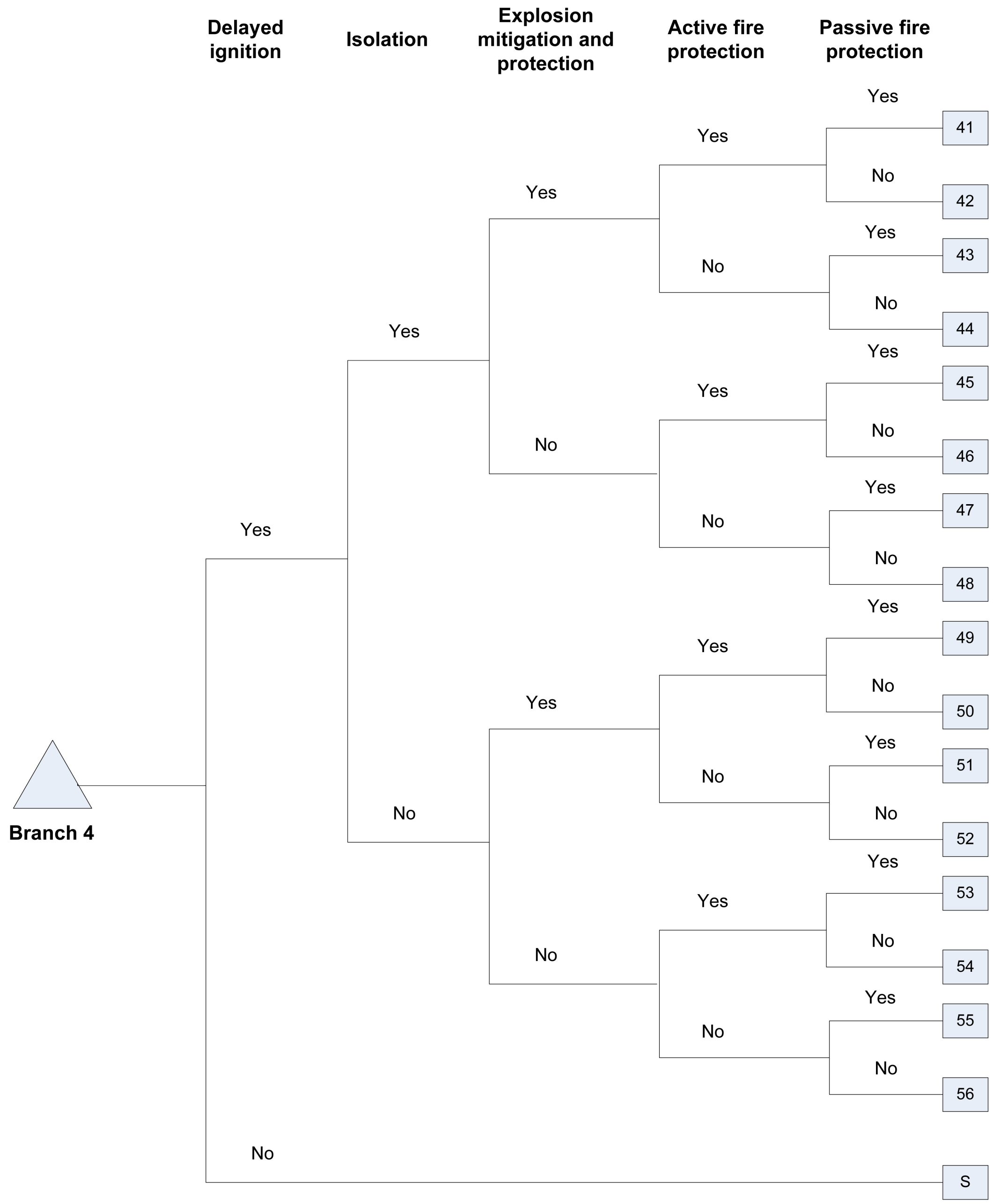
31
32
S
33
34
35
36
37
38
39
40
S
Branch 3

S: Safe state


Delayed ignition
Isolation
Explosion mitigation and protection
Active fire protection
Passive fire protection
Branch 4
Yes
No
Yes
No
Yes
No
Yes
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Yes
No
Yes
No
Yes
No
Yes
No
Yes
No
Yes
No
Yes
No
Yes
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53
54
55
56
S

S: Safe state

Appendix E

Pre-Study Report

Modeling of Safety Barriers in Risk Analyses - Pre-study Report

Kjetil Holter Næss

January 31, 2012

1 Preface

This is the pre-study report for the the master thesis *Modeling of Safety Barriers in Risk Analysis*, written as part of the Master of Science (MSc) program in mechanichal engineering at the Department of Production of Production and Quality Engineering (IPK) at the Norwegian University of Science and Technology (NTNU). The thesis will be written in cooperation with IPK and Det Norske Veritas (DNV), under the supervision of professor Stein Haugen at IPK, and Astrid Folkvord Janbu at DNV.

2 Introduction

There are requirements from both the Petroleum Safety Authority Norway (PSA) and companies in the oil and gas industry that the condition of technical and human/organizational safety barriers on an installation should be reflected in the risk analysis of the installation. However, implementing this using existing methods, in a way that supports appropriate analysis- and decision making processes, has proved to be a challenge.

The master thesis will be performed in cooperation with DNV, provider of services for risk management, with the objective of examining how safety barriers can be modeled in risk analyses, and to which level of detail this can be done.

This pre-study report is intended as a preliminary work plan and break-down of the master thesis assignment. The pre-study report will present an analysis of the assignment objectives, a description of the tasks to be performed presented as a work breakdown structure, and a work schedule including deadlines and important milestones presented as a Gantt chart. This will serve as a foundation and work plan for the thesis work, and as a basis for subsequent progress reports.

3 Thesis Obejctives

The main objective of the master thesis is to examine how safety barriers can better be modeled in risk analyses, and to which level of detail this can be done. In order to acheive this main goal, the assignment has been divided into the following objectives:

1. Literature study - What does the safety barrier concept entail? Identify relevant literature and summarize briefly.
2. Which barriers are relevant for offshore installations? A specific case (a major accident scenario) is chosen and used as an example. The barriers are classified in different ways to allow for quantification.
3. Which decision processes affecting barriers should the risk analyses provide input to? Decisions are classified into groups/categories.
4. What are important properties of barriers which affect the risk/risk analysis?
5. Which of these can be quantified, how can they be quantified, and how can they be modeled in risk analyses? Possibilities of doing this both within the scope of existing analyses and other methods shall be considered.

The work on these objectives will be based on relevant standards and practical guidelines which exist and are recommended in use, in addition to theory identified in the literature study.

An analysis with additional comments to the objectives is presented below:

1. The literature study should identify important literature on the subject of safety barriers and present a summary of this literature, along with a short discussion of which issues are being discussed today and which questions remain unsolved. This should include a discussion on the definition of safety barriers and related concepts.
2. A list of important barriers on offshore installations should be developed before the case study is performed, preferably in cooperation with DNV. This could be founded in barrier functions defined by the PSA, company sepecific definitions and/or national or international standards. A typical major accident scenario should be investigated. The barriers identified in the case study should then be classified in different ways to allow for quantification, and a discussion of which type of classification is most suitable for integration with risk analyses should be performed. For instance, the effect of human and organizational barriers compared to technical barriers could be investigated.
3. The decision processes regarding barriers which should be supported by the risk analyses, both as intended in current DNV practices and ideally should be considered.

4. Determining which barrier properties affect risk/risk analyses could require a combination of analytical thinking, discussion with DNV, as well as studying literature. It is important to determine the relevance of each property for the risk under assessment.

5. After the relevant barrier properties have been determined, possible ways of quantifying these properties, and how they can be integrated into the risk analyses, should be examined. This is perhaps the most challenging objective in terms of generation of knowledge, and should therefore rely on a thorough review of existing methods and methods under development in the field of risk assessment. Several methods are in use and under development today, and these should be presented in detail. If possible, the case study could be compared with a typical DNV risk assessment to investigate how the analyses account for the condition of safety barriers, and if this can be done in a sufficient manner. A recommendation of further research required on the subject should be presented.

4 Approach

The work will begin with a literature study, which will provide a foundation for the subsequent tasks. The report will be written as a scientific report, based both on theory in literature and standards and cooperation with DNV. Work on the objectives presented in this pre-study report will tentatively be performed in the order presented in this pre-study report, involving both supervisors from DNV and IPK as necessary.

5 Work Description

This section of the pre-study report will provide a description of the tasks necessary to acheive the aforementioned objectives. The work on each objective is broken down into subtasks. In addition to this, the actual writing of the report document will be a continuous process throughout the semester, where finished work can be revisited and revised to ensure that a coherent, intuitive report is produced.

A break-down of tasks to be performed is presented below, in table 1:

	Tasks	**Subtasks**
1	Literature study	- Literature search - Literature review - Write summary
2	Case Study	- Case selection & review - Barrier identification - Barrier classification
3	Decision Analysis	- Identify relevant decisions - Classify in appropriate groups
4	Barrier Properties	- Identify relevant barrier properties
5	Quantification & Integration With Risk Analyses	- Identify quantifiable properties - Identify techniques & methods for quantification & modeling - Discuss possibilites of quantification & integration with risk analyses
*	Text Production and Formatting	- Produce introduction, main body, conclusions & summary - Format Document (ToC, Figures, Tables, References, Appendices etc.)
**	Project Management	- Pre-study report - Progress reports - Supervision meetings, DNV & IPK
***	Proof Reading	

Table 1: Break-down of tasks into subtasks required to acheive the objectives listed in section 3. Tasks are numbered by their respective objectives. Tasks related to the production of the actual report are numbered using asterisks.

6 Work Schedule

In order to ensure that the tasks presented in section 5 are performed in a timely manner, a tentative schedule for completion of the respective tasks is presented in the following Gantt chart:

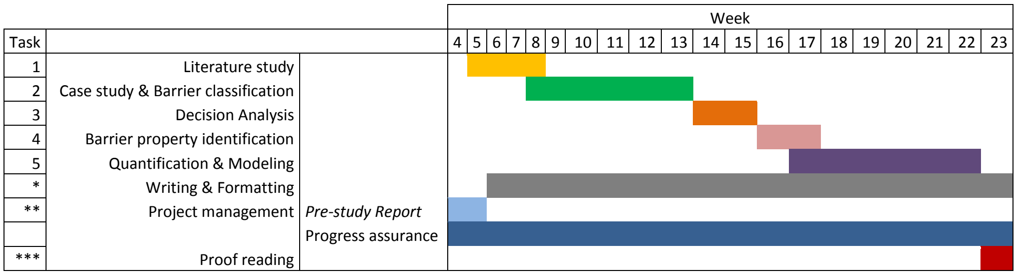

Figure 1: Gantt chart describing the proposed work schedule.

Important milestones with absolute deadlines:

- Pre-study report due: January 6.
- Progress reports due: To be determined.
- Thesis due: June 11.

Deadlines for the respective tasks are tentatively set at the end of the weeks as presented in the Gantt chart in figure 1.

The master thesis course is worth 30 ECTS credits which equals a full course load per semester. This means an estimated 48 hours of work should be required per week throughout the semester. Each planned week of work is therefore assumed to be 48 hours. Where two tasks are planned in parallel, work should be split between the tasks as necessary.

7 Potential Challenges

The most important challenges in acheiving the objectives set forth in this pre-study report include the difficulties of including human and operational barriers, as well as human and operational factors in technical barriers, in risk analyses. In addition to this, a key question is how the condition of barriers, which is currently assessed mostly as ”still frames” taken at a specific point in time, can be appropariately accounted for in risk analyses which should analyze the risk associated with the installation throughout a defined period of time.

Appendix F

Progress Report

Modeling of Safety Barriers in Risk Analyses - Progress Report

Kjetil Holter Næss

April 13, 2012

1 Preface

This is the progress report for the the master thesis *Modeling of Safety Barriers in Risk Analysis*, written as part of the Master of Science (MSc) program in mechanichal engineering at the Department of Production of Production and Quality Engineering (IPK) at the Norwegian University of Science and Technology (NTNU).

2 Introduction

The objective of this report is to provide an update on the progress of writing the masters thesis, as outlined in the pre-study report, as per April 13, 2012. The progress report will discuss the development of the report compared to the original scope and objective, as well as the progress with regards to time. Deviations from the plan will be discussed, and measures taken to address the deviations will be presented.

3 Thesis Obejctives

The thesis objectives and the scope of the report as described in the pre-study report remains unchanged:

1. Literature study - What does the safety barrier concept entail? Identify relevant literature and summarize briefly.
2. Which barriers are relevant for offshore installations? A specific case (a major accident scenario) is chosen and used as an example. The barriers are classified in different ways to allow for quantification.
3. Which decision processes affecting barriers should the risk analyses provide input to? Decisions are classified into groups/categories.

4. What are important properties of barriers which affect the risk/risk analysis?
5. Which of these can be quantified, how can they be quantified, and how can they be modeled in risk analyses? Possibilities of doing this both within the scope of existing analyses and other methods shall be considered.

The key points discussed in the pre-study report in relation to these objectives have been followed according to plan, with the exception of parts the second and third objective. It was intended that the barriers identified in fulfilment of the second objective should be classified and categorized in groups. Due to a delimitation of the barrier concept, it became apparent that this specific task would have limited value. This issue is discussed in the report.

The third objective was found to be somewhat unclear. It was agreed between the supervisor and the author that the report should should perhaps contain a discussion of the different objectives of risk analyses, rather than a dicussion and classification of the decisions themselves.

The scope has not been delimited further, but has been specified in order to make it clear that:

- While the report contains a general discussion of possibilities for improving QRAs with regards to barriers, the findings of the report will be specific to the needs of DNV for their QRAs.
- The report has a clear focus on major accident risk, and does not discuss other elements of risk such as occupational risk in any specific detail.
- Issues related to safety barrier management is outside the scope of the report. The report focuses on analysis of barriers in QRAs (which can be used as decision support for barrier management processes).

4 Approach

The work related to the development of the masters thesis has, to this point, consisted of:

- A literature study of literature on safety barriers, barrier analysis, and relevant standards and regulations for oil and gas activities on the NCS
- A case study of barriers relating to blowouts
- Informal meetings with DNV personnel and review of a DNV QRA report

5 Work Description

A break-down of tasks was presented in the pre-study report, and is included here in table 1:

	Tasks	Subtasks
1	Literature study	- Literature search - Literature review - Write summary
2	Case Study	- Case selection & review - Barrier identification - Barrier classification
3	Decision Analysis	- Identify relevant decisions - Classify in appropriate groups
4	Barrier Properties	- Identify relevant barrier properties
5	Quantification & Integration With Risk Analyses	- Identify quantifiable properties - Identify techniques & methods for quantification & modeling - Discuss possibilites of quantification & integration with risk analyses
*	Text Production and Formatting	- Produce introduction, main body, conclusions & summary - Format Document (ToC, Figures, Tables, References, Appendices etc.)
**	Project Management	- Pre-study report - Progress reports - Supervision meetings, DNV & IPK
***	Proof Reading	

Table 1: Break-down of tasks into subtasks required to acheive the objectives listed in section 3. Tasks are numbered by their respective objectives. Tasks related to the production of the actual report are numbered using asterisks.

This work break-down remains unchanged, with one exception: The work packages related to the case study have been altered slightly. Important barriers for oil & gas installations have been identified and presented based on relevant standards and guidelines, separately from the case study. The scope of case study has been reduced slightly, and the classification of barriers in groups has been excluded.

6 Work Schedule

In the pre-study report, a Gantt chart of the work schedule for the development of the report was presented:

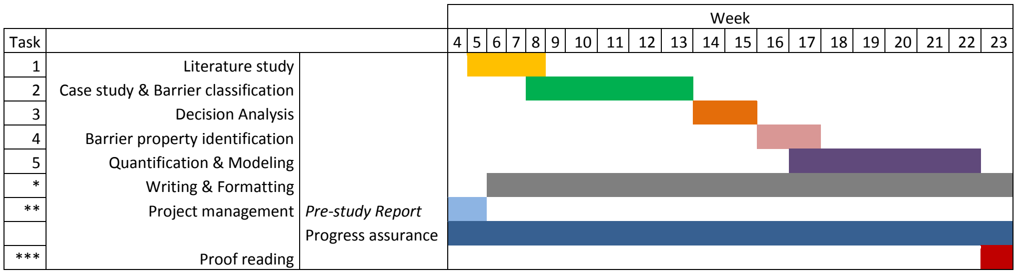

Figure 1: Gantt chart describing the proposed work schedule.

The first two work packages were finished on time. As per April 13, work on the decision analysis part of the report is not entirely finished, but work on work packages 4 and 5 has already started. As a whole, the project is running ahead of time. It is however possible that work related to the completion of the report will be more comprehensive than planned, and this extra time could be needed as the deadline comes closer.

Important milestones with absolute deadlines were identified in the pre-study report:

- Pre-study report due: January 6.
- Progress reports due: To be determined.
- Thesis due: June 11.

No due date was set for the delivery of the progress reports. This progress report describes the status of the project on April 13, 2012, the end of week 15. It, along with potential new progress reports will be handed in as part of the main report on June 11, 2012.

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