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Abstract

If an undesired event occurs is the possibility of escape of crucial importance for the safety of passengers and crew. It is therefore important to have good solutions on escape routes; in this matter is the design and orientation of escape routes essential. If an emergency situation occurs and the escape routes are insufficient, may this result in difficulties for passengers to escape from the area in an effective and successfully matter.

An offshore development can never be completely safe, but by selecting the optimum design may the risk be reduced to a level that is as low as reasonably practicable (ALARP). However, this requires identification of risk contributors and their assessment, which should be done by using QRA techniques early in the project life cycle (Khan & Amyotte, 2002). It is uncertain to which degree the escape routes are prioritized, evaluated and considered in such a process, and if it is the best practice used. This is due to that there are few requirements regarding how escape routes should be evaluated in a risk analysis in the legislations.

This thesis evaluates how escape routes are taken into account in two different risk analyses. This is done by the use of five success criterias; clear description of the installation, simulations, calculations, assumptions and uncertainties. The discussion indicated that there were improvement potentials for how to evaluate escape routes in the risk analysis in order to reach a robust solution.

The thesis also discusses whether the requirements to design are sufficient to reach robust escape routes solutions, or not. Some of the requirements regarding escape routes could be interpreted in different ways, and should have more explanations and guidelines.

Preface

This master thesis represents the end of my master degree in "*Risk Management – Offshore Safety*" at the University of Stavanger. The thesis was carried out in collaboration with Aker Solutions MMO in Stavanger.

I would like to take this opportunity to thank those who have given support and help during this process;

Thanks to all my classmates for many nice conversations and a good environment these last two years. It would never been the same without you guys.

I want to thank my supervisor at the University of Stavanger for constructive feedback on the structure of the thesis.

I also want to thank my supervisors at Aker Solutions, for enlightening me with their knowledge and for providing me with risk analysis documents from their database.

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1. Introduction

Risk is present in all made actions, and the most crucial risk is related to people. A risk analysis is often used as a tool for decision making, and is a process where the objective is to try to mitigate the probability and the consequences of an unwanted event. Risk analysis is applied in specific parts of the design, maintenance and modification processes; this includes the design of escape routes. If an undesired event occurs it is important to have good solutions on escape routes, in order to prevent/limit fatalities.

Emergency platform evacuation is thankfully a rare event in the offshore oil and gas sector. However, the few incidents that have occurred have demonstrated just how key the role of proper evacuation is in preventing loss of life. The possibilities of escape are of crucial importance for the safety of passengers and crew in an emergency. It is therefore important to design effective escape routes, which should provide smooth escape of passengers and crew without any congestion and confusion when they should abandon the structure in an emergency event (Yoshida, et al., u.d.). If there is an emergency and the escape routes is not sufficient will this result in difficulties for passengers to escape from the area in an effective/successfully matter.

There are developed many different standards in order to try to reach a satisfying level of safety regarding escape routes. These standards are both international and national, and could be interpreted differently from analyst to analyst. An important question to ask is if the requirements regarding escape routes are adequate in sense of making robust solutions.

One example on a disaster that did lead to more fatalities due to lack to have satisfying escape routes is the Scandinavian Star disaster in 1990. Night to 7th of aril 1990 did four different fires occur on the ship, and led to that 159 persons dies. One of the things that were defective was the signing/marking of the escape routes. A new investigation done the last years by a new special-group indicated that several fire doors where blocked in open position (Korneliussen, 2013).

This indicates how important it is to have sufficient escape routes, and it is important to include the design of escape routes from the beginning of the design-phase.

1.1. Objective

As stated by Khan, et al. (2002) can never an offshore development be completely safe, but by selecting the optimum design may the risk be reduced to a level that is as low as reasonably practicable. However, this requires identification of risk contributors and their assessment, which should be done by using quantitative risk assessment techniques early in the project life cycle. However, it is uncertain to which degree the escape routes is prioritized, evaluated and considered in such a process, and if it is the best practice used. Smaller platforms are often part of an overall construction; such platforms have a known problem to not satisfy acceptance criteria relating to escape routes. This is also true for new modules to existing installations (modification).

This brings us to the problem in focus in this thesis;

"How are escape routes taken into account in a Risk Analysis, and are the requirements regarding design of escape routes adequate for a robust solution?"

The purpose of this assignment is to take a closer look at how the results of a risk analysis are used in order to design and evaluate escape routes. This is due to both the fundamental of the assessment, how the analysis is performed in relation to regulations, and technical aspects. The thesis will include a review of both the Norwegian and international legislations regarding requirements to specific escape routes design, in order to evaluate if these are met in the risk analysis analyzed and if they is satisfying in order to reach a robust solution. Two different case studies have been used, in order to determine how escape routes and is evaluated in risk analysis.

The thesis also aims to identify improvements potentials related to the evaluation of the escape routes by the use of risk analysis, in order to reach the most robust solution.

1.2. Limitations

- Only had access to two risk analysis; which may limit the thesis; the thesis will therefore only be based on two different platforms and their risk analysis. Which may lead to those aspects studied might be different in other cases.

- For simplification is the evaluation of the analysis process based on five success criteria's, other aspects will therefore not be evaluated even though there are other aspects that affect the efficiency of a Quantitative Risk analysis.

1.3. Structure

Chapter 2 consists of the theory considered as relevant to solve the problem. This includes risk, risk analysis, quantitative risk analysis, Emergency preparedness, barriers, risk acceptance criteria, ALARP principle, Escape, evacuation and rescue, and human behavior.

Chapter 3 consists of an introduction to the risk analysis in the two cases used in this thesis; Yme MOPUstor and modification on Troll A. This includes a brief presentation of the fields. Design specification with respect on main areas and escape routes.

Chapter 4 form a discussion which is divided into two sub-chapters; success factors and technical aspects.

Chapter 5 consists of the writer's opinion on improvement potentials regarding the use of risk analysis for evaluating escape routes, as well as a discussion on the requirement of the escape routes.

Chapter 6 contains the conclusion that can be extracted from the discussion.

1.4. Abbreviations

ALARP	As Low As Reasonably Practicable
CRA	Concept Risk Analysis
EER	Evacuation, Escape and Rescue
EERS	Evacuation, Escape and Rescue Strategy
ER	Emergency Response
EPA	Emergency preparedness analysis
FAR	Fatal Accident Rate
IR	Individual Risk
ISO	International Organization for Standardization
NORSOK	NORsk Sokkels Konkurranseposisjon
PDO	Plan for Development and Operation
PLL	Potential Loss of Life
QRA	Quantitative Risk Assessment
RAC	Risk Acceptance Criteria
TPK	Existing pre-compression module
TRA	Total Risk Analysis

2. Theory

This chapter includes theory relevant to answer the problem of this thesis. The theory is partly based on legislations, from both international and Norwegian standards. The section will present basic knowledge regarding risk, risk analysis, Quantitative risk assessment, barriers, risk acceptance criteria, and escape routes with legislations.

2.1. Risk

The concept of risk is defined in many ways; for instant by distributions, expected values and single probabilities of specific consequences. In the financial context may the risk be defined as the probability that an actual return on an investment will be lower than the expected return (business dictionary, u.d.). Whilst in engineering context, risk is often linked to the expected loss/consequences (Vinnem, 2007). There are several concepts and perspectives on risk. Risk can be seen as expected values (C * P), through probability (C, P), and through uncertainties (C, U).

NORSOK standard Z-013 (2010) defines risk as the combination of the probability of occurrence of harm and the severity of that harm. Where risk may be expressed qualitatively as well as quantitatively where the probability of occurrence is set between 0 and 1 or as a frequency, with the inverse of time as dimension.

Whereas, ISO standard 13702 (1999) explains risk as the combination of the chance that a specified undesired event occurs and that the severity of the consequences of that event are taken into consideration.

2.1.1. (C * P) perspective

This perspective link the risk to expected values. Equation 2.1 is an operational expression for practical calculation of risk, which underlines how risk is calculated by multiplying probability (P) and numerical value of the consequences (C) for each accident sequences *I*, and summed over all (*I*) potential accident sequences (Vinnem, 2007).

$$R = \sum_i (P_i \cdot C_i) \tag{1}$$

Equation 2.1 is often referred to as “real risk” or “objective risk, Vinnem (2007) says that these two terms give misleading impression of the interpretation of risk. “Risk” is reflecting interpretations and simplifications made by, for instance the analyst and as such to some extent subjective. It is therefore misleading to give the impression that some expressions are more objective than others. Vinnem (2007) further states that it should be noted that the expression of risk as expected consequences is a statistical expression, which often implies that the value in practice may never be observed.

Example (based on example provided by (Aven, 2010, p. 3):

You are offered to play a game, using a dice with 8 outcomes. If you get 4 or 5 on the dice, you win $20 million. If it you get another value on the dice, you lose $8 million. As the probability of losing $10 million is 2/8, and of winning $3 million is 6/8, the expected gain is given by:

$$-20 \times \frac{2}{8} + 8 \times \frac{6}{8} = -5 + 6 = 1$$

In this perspective is there no distinction between situations with potential large consequences and small probabilities, and the situations involving minor consequences with large probabilities. This perspective can be misleading since it may lead to that extreme events with millions of fatalities is overlooked, because the expected loss might be small due to that the probabilities for minor accidents are large (Aven, 2011). Therefore is it important to look beyond expected values.

2.1.2. (A, C, P) Perspective

In the Offshore QRA industry is the most frequent used risk perspective the (A, C, P) perspective. This perspective uses probabilities as an expression for risk, and the definition of risk may be;

$$\text{Risk} = (A, C, P)$$

Where A represent the events (initiating events, scenarios), C represent the consequences of A, and P is the associated probabilities. This definition of risk is, however, not meaningful without an interpretation of the probability P. There are basically two ways of interpreting a probability (Aven, 2011);

- A probability is interpreted as a relative frequency Pf: the relative fraction of times the event occurs if the situation analyzed were hypothetically “repeated” an infinite number of times; Pf is referred to as a frequentist probability (Aven, 2011, p. 18),
- The probability is a subjective measure of the uncertainty about future events and consequences seen through the eyes of the assessor and based on some background information and knowledge (Aven, 2011, p. 18).

Schofield (1998) states that the relative frequency interpretation is the most used perspective in the offshore QRA (Schofield, 1998). However, this thesis will focus on the interpretation that is referred to as a subjective or knowledge-based probability P(A|K). This perspective of probability states that there are no uncertainties related to the assigned probability, because it is an expression of uncertainty. This is because the probability is conditional on background knowledge. The background knowledge could be based upon hard data and/or expert judgment; this also includes assumptions that are made. The background knowledge needs to be reported along with the assigned probabilities (Aven, 2011).

Example (based on example provided by (Aven, 2010, pp. 23-24)):

You are playing the same dice game as the last example. This time you suspect that the dice is unfair and you design a probability equal to 0.80 that the dice is unfair. You compare the uncertainty about the unfair dice with drawing a random red ball from an urn having 10 balls of which 8 are red.

$$P(unfair\ dice\ |K) = 0.80$$

However, Probabilities are just a tool, not a “perfect” tool, used to represent or express the uncertainties. The assigned probabilities are conditioned on a number of assumptions and suppositions. They depend on the background knowledge of the system in mind. Uncertainties are often hidden in background knowledge, and restricting attention to the assigned probabilities could camouflage factors that could produce surprising outcomes. By jumping directly into probabilities, important uncertainty aspects are easily truncated, meaning that potential surprises could be left unconsidered (Aven, 2011; Aven, 2010).

There are two types of uncertainties involved in probability; aleatory and epistemic. Aleatory uncertainty is referred to as the uncertainty described by P(A), and cannot be reduced and will always be present. Whilst epistemic uncertainty is the lack of knowledge about the true value of P(A), and can be reduced with more knowledge (Aven & Flage, 2009).

2.1.3. (A, C, U) Perspective

The (C, U) risk perspectives intend to describe the uncertainties about the unknown quantities of interest. Aven (2011) define the (A, C, U) perspective risk as a two dimensional combination of

i) events A and their consequences C, and
ii) the associated uncertainty U about A and C.

Where *event* (A) may be defined as the occurrence of a particular set of circumstances, According to Aven & Flage (2009) some main categories of events in QRA may be identified as Initiating events or Barrier failures. An event is referred to as undesirable, unwanted or accident when there is a clearly negative consequence (Aven & Flage, 2009).

The *consequences* (C) may be defined as the outcome of an event. In the QRA context there is sometimes useful to distinguish between two levels of consequences; Physical quantities and losses. Examples of physical quantities in an offshore QRA may be fires and explosions, whilst losses are the effect on human lives and health, the environment and material assets (what human values) (Aven & Flage, 2009). This definition does not distinguish between positive and negative consequences (Aven, 2012).

Uncertainty (U) is understood as the lack of knowledge about unknown quantities (i.e. about A and C). (Epistemic uncertainty)

2.2. Risk analysis

Through risk analysis the nature and the quantity of risk related to an activity is expressed. Usually a risk analysis is a methodology that uses analytical methods in a systematic approach to determine risk. This approach can be improved over time through learning from previous activities or analyses (Standards Norway, 2010). In other words; risk analysis is the structured use of available information to identify hazards and to describe risk i.e. present an informative risk picture to develop an understanding of the risk. The risk analysis shall identify the relevant initiating events (causes) and sources of risk, and develop the causal and consequence picture. Both positive and negative consequences shall be included, with their respectively likelihood (Aven, 2008). Factors that affect consequences and their likelihood should be identified (Standards Norway, 2009). The risk is thereby analyzed by comparing consequences and their likelihood, and other attributes of the risk. The main reasons for conducting a risk analysis is to support decision-making, provide basis for deciding whether the risk is acceptable or not, and to decide on the need for risk reducing measures. Risk analysis can be carried out at various phases in the life time of the system (Aven, 2008; Standards Norway, 2009).

One can divide risk analysis into three main categories; simplified risk analysis, standard risk analysis and model-based risk analysis (Aven, 2008). This thesis will focus on the lather approach. However, for the sake of clarity are all these three categories described in more detail in Table 1: Main categories of risk analysis methods Table 1.

Table 1: Main categories of risk analysis methods (Aven, 2008)

Main category	Type of analysis	Description
Simplified risk analysis	Qualitative	Simplified risk analysis is an informal procedure that establishes the risk picture using brainstorming sessions and group discussions. The risk might be presented on a coarse scale, e.g. low, moderate or large, making no use of formalized risk analysis methods.
Standard risk analysis	Qualitative or Quantitative	Standard risk analysis is a more formalized procedure in which recognized risk analysis methods are used, such as HAZOP and coarse risk analysis. Risk matrices are often used to present the result.
Model-based risk analysis	Primarily Quantitative	Model-based risk analysis makes use of techniques such as event tree analysis and fault tree analysis to calculate risk. (QRA)

2.3. Quantitative Risk Assessment (QRA)

QRA is used as an abbreviation for “Quantified Risk Assessment” or “Quantitative Risk Analysis”. The context usually has to be considered in order to determine which of these two terms is applicable. QRA can also be used as an abbreviation for “Quantitative risk assessment”. The difference between “Quantitative risk analysis” and “Quantitative risk assessment” is that the latter includes evaluation of risk, in addition to the analysis of risk (Vinnem, 2007).

Today QRA is a tool that is actively used throughout the planning and design period, and is closely integrated with the design process and is in many respects considered as routine (Falck, et al., 2000). The focus is mainly on technical measures and solutions, and takes into account; manning in the different areas, activity level, and requirements set to technical safety barriers, and requirements to emergency preparedness (Vinnem, et al., 2003).

A QRA systemizes the present state of knowledge including the uncertainties about the processes being analyzed, and is a key element in a risk management process. It identifies possible hazards/threats, analyses their causes and consequences, and describes risk by use of probabilities. A QRA provides a basis for characterizing the likely impacts of the activity studied, for evaluating whether risk is tolerable or acceptable and for choosing the most effective and efficient risk policy. It allows for the calculation of expected values so that different risks can be directly compared (Aven, 2011). Authorities are basing their regulations and operators are basing their design on the use of QRA as a tool to determine which safety barriers are needed, as well as what should be the dimensioning loads and requirements (Skogdal & Vinnem, 2011).

In a QRA, risk is typically described using probabilities and expected values, and compared with risk acceptance criteria. Commonly used quantitative risk indices in the offshore QRA include individual risk (IR), potential loss of life (PLL), fatal accident rate (FAR) and quantitative criteria for safety functions (Escape routes, evacuation etc.) (Vinnem, 2007). IR and PLL are defined as the probability of death of a randomly selected person and the expected number of fatalities, respectively, during a specified period of time. Whilst FAR is defined as the expected number of fatalities per 10^8 exposed hours, where 10^8 hours correspond to the time of 1400 persons present at their place of work through a full life span (Aven & Flage, 2009; Aven, 2008). The quantitative risk index that is most frequency used in offshore QRA is the FAR value; FAR can be divided into three values, these are; average individual risk for personnel group, area FAR, and total average risk for personnel.

QRA is a top-down approach and has, according to Apostolakis (2004), been found useful;

- QRA considers a number of scenarios that involve multiple failures,
- Provides a common understanding of the problem
- Increases the probability that complex interactions between events/systems/operators will be identified.
- Focuses on uncertainty quantification and creates a better picture of what the community of experts knows or does not know.

Usually other engineering studies will be carried out in parallel with the QRA. These studies are often based upon the design scenarios developed in the QRA. Furthermore, the output from the other studies is often used as input to the design process and in some areas used to improve the QRA (Falck, et al., 2000). This is illustrated in the figure below.

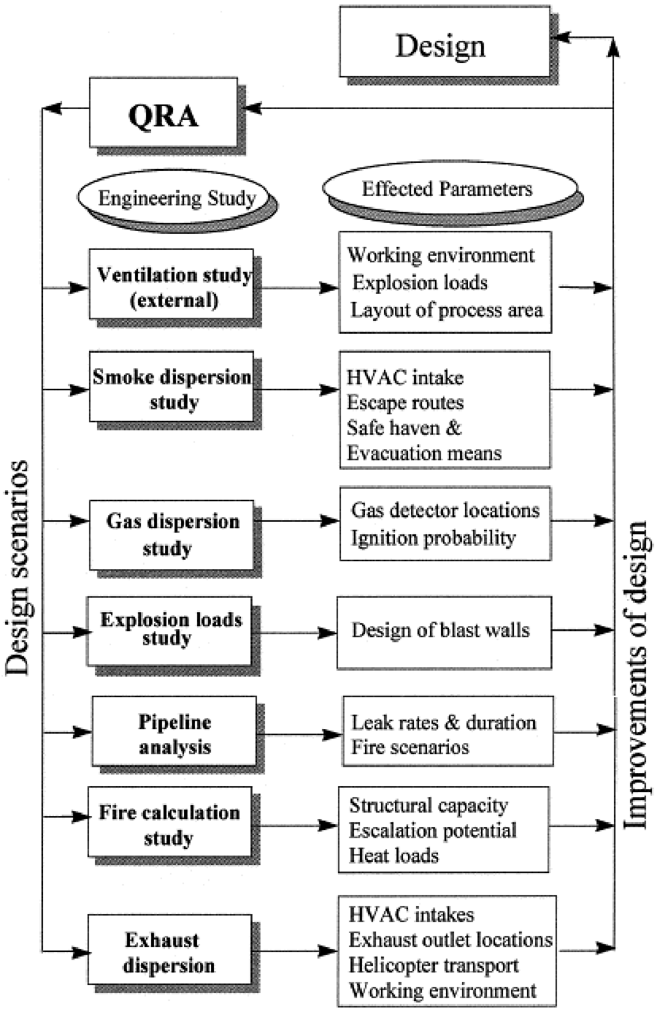

Figure 1: Correlation between QRA and risk related engineering studies (Falck, et al., 2000).

The Total Risk Analysis (TRA) is a term implying essentially a detailed fatality risk analysis (Vinnem, 2007). The TRA is performed when the entire frame of the design has been made, and after submission of Plan for Development and Operation (PDO). The purpose of the TRA is to verify the design and check compliance with overall risk acceptance criteria (Arif, 2012; Standards Norway, 1998).

The Concept Risk Analysis (CRA) is often performed after the decision has been made, and is performed before submission of PDO. A CRA often addresses a certain concept in a risk analysis; this can for instance be in a modification phase or a replacement phase on a platform. The purpose is to compare the alternatives and perform an assessment of compliance with acceptance and design criteria; this is done by identifying hazards, their causes and their consequences in a given modification (Arif, 2012; Standards Norway, 1998).

There are several countries that have legislation that use QRA studies in the design and operation of offshore installations; United Kingdom, Norway, Canada and Australia. This thesis will focus on the Norwegian legislations.

NORSOK Z-013 provides a process of how to perform a risk assessment. It states that systems subjected to the assessment shall always include (Standards Norway, 2010):

1) identify hazardous situations and potential accidental events,
2) identify initiating events and describe their potential causes,
3) analyze accidental sequences and their possible consequences,
4) 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.

These steps are illustrated in Figure 2, and the steps and requirements stated in NORSOK Z-013 will be briefly explained in Appendix A: Quantitative Risk Analysis Process. However, this is a general model, and the content within each element can vary significantly from analysts to analysts.

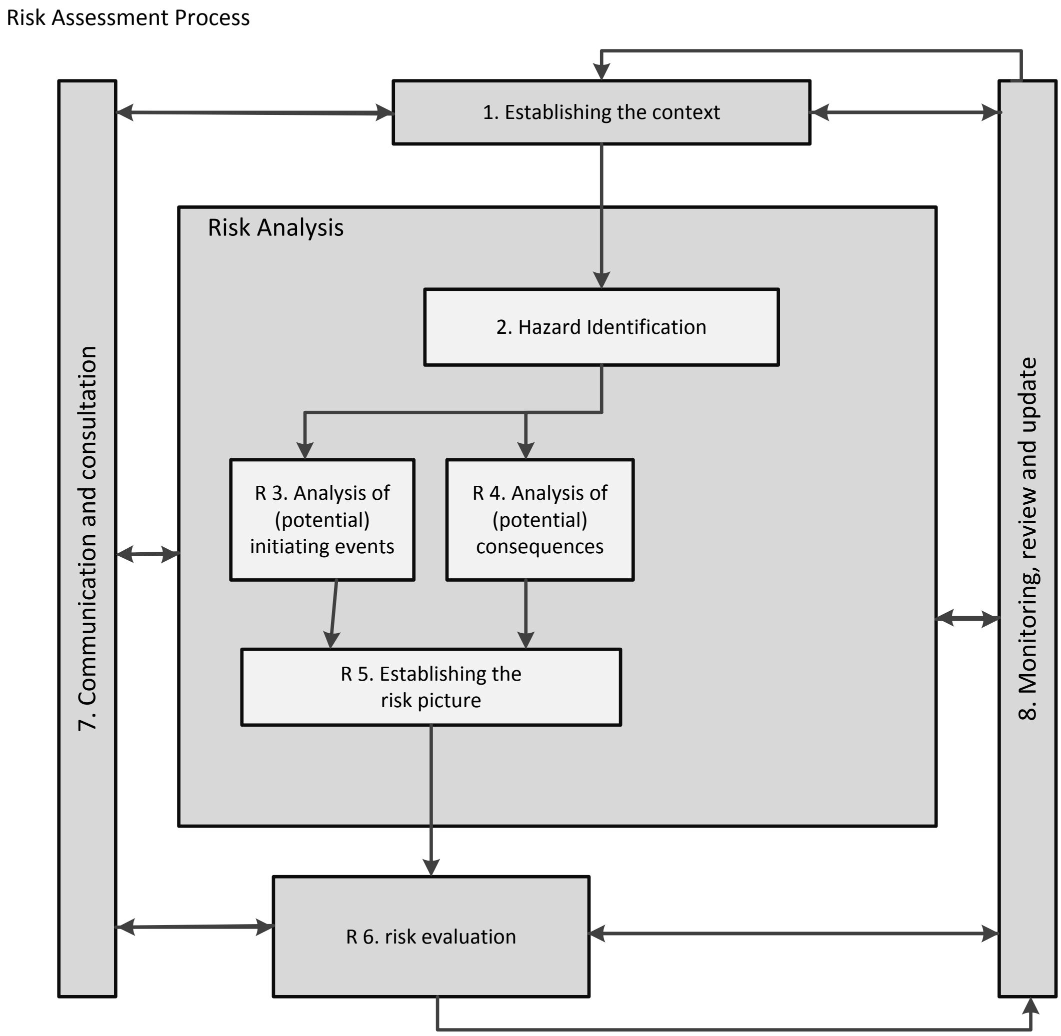

Figure 2: The process of performing a risk assessment (Standards Norway, 2010)

2.3.1. Challenges of QRA

Abrahamsson (2002) says that one of the main challenges of QRA is a proper treatment of the uncertainties in risk assessments; many risk analyses ignore the uncertainties beyond the best estimates, even though the risk analyses are to describe the uncertainties. This statement is supported by many other researches, for instance Reid (1992) whom says that the risk estimates are subjective, and there is a common tendency of underestimation of the uncertainties (quoted in (Aven & Zio, 2011). However, one has to acknowledge that there are different types of risk assessments which treat uncertainties to varying degree (Abrahamsson, 2002).

Most of the approaches developed to treat the uncertainty in QRA seem to be based on the thinking that uncertainty relates to the calculated probabilities and expected values. This causes difficulties when it comes to communicating what the analysis results mean, and could easily lead to weakened conclusions if large uncertainties are involved (Aven & Flage, 2009). As mentioned earlier, is probabilities conditioned on a number of assumptions and suppositions. They depend on the background knowledge of the system in mind. Uncertainties are often hidden in background knowledge, and restricting attention to the assigned probabilities could camouflage factors that could produce surprising outcomes. By jumping directly into probabilities, important uncertainty aspects are easily truncated, meaning that potential surprises could be left unconsidered (Aven, 2011).

According to Vinnem (2007) is one of the challenges/limitations of QRA the ability to analyze installation specific aspects. It is sometimes said that a QRA of an offshore installation is representative of an average installation operated in an average way, but with an overall shape and module layout of the installation in question. This aspect underlines the importance of the ability to represent specific details in the analytical models, to an extent that differences can be reflected.

As mentioned earlier is QRA dependent a sufficiently broad basis of relevant data for the quantification of accident frequency or accident causes (Vinnem, 2007). These data are not always available or representative, Vinnem (2007) says that when dealing with rare accidents will an average value have to be established over a long period, which may lead to an average percent of fatalities per year that never can be observed.

Hazard identification is often performed in an unsystematic manner or with insufficient attention to operational aspects and/or combination of failures or errors. The consequence of this is a lack of assurance that hazard identification is compete (Vinnem, 2007).

2.4. Emergency Preparedness

This element is not directly used in this thesis; however, it is mentioned in order to illustrate one of the reasons to why QRA is an important aspect in the offshore industry. The Emergency preparedness assessment is explained in Appendix B: Emergency preparedness Assessment Process.

Risk analysis is a tool for planning the emergency preparedness, and the emergency preparedness analysis shall be carried out in close interaction with the QRA. The information that should be carried forward from the QRA is relevant information about the major accidents identified, assumptions and premises made, and recommendations from the QRA (Standards Norway, 2010).

Emergency Preparedness is defined as technical, operational and organizational measures, including necessary equipment that are planned to be used under the management of the emergency organization in case hazardous or accidental situations occur, in order to protect human and environmental resources and assets (Standards Norway, 2010). The purpose of providing an ER system is to prevent accidents and harmful effect to people and assets. In order to protect against harmful effects one must clarify which situations are threatening with a damaging potential (Njå, 1998).

According to Njå (1998) is emergency preparedness inherent in all levels, including individual attitudes and overall competence, and covers all consequence reducing measures. He further states that the emergency preparedness support structure consists of three fundamental elements linked together, these elements are; situation, Personnel and equipment. The relation between these elements is illustrated in Figure 3.

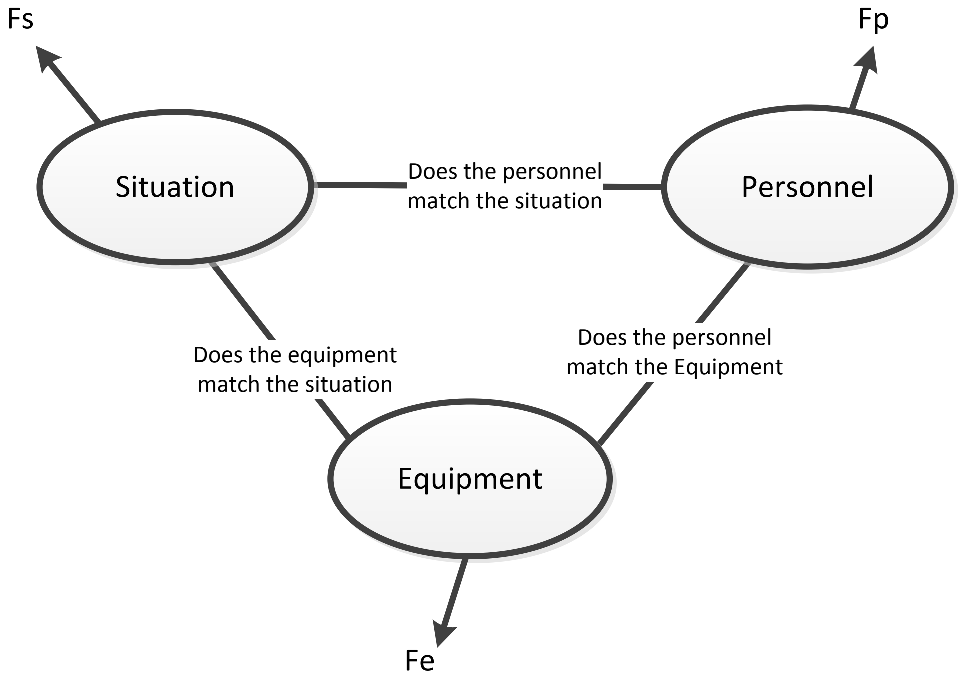

Figure 3: Interaction between elements in ER planning (Njå, 1998).

The ability of the emergency response system is dependent on these three elements, and their actual occurrence at the time of the real situation. A good emergency response system could be considered as a proper interaction between the three elements, and two of the elements must fail before serious damages occur (Njå, 1998).

As **Feil! Fant ikke referansekilden.** illustrates is the elements subject for forces that is efined as deviations;
Situation (F_S) is the deviation between the hypothetical situations applied for design of the Emergency response system and the occurred situation. *Personnel* (F_P) represent the deviation between assumptions made in the analysis process with respect to human resources and their actual presences and behavior at the time of incident occurrence. *Equipment* (F_E) represents the deviation between assumptions made in the analysis process with respect to applied equipment and its actual response at the time of incident occurrence (Njå, 1998).

2.5. Barriers

Safety barriers have been used to protect humans and property from enemies and nature hazards since the origin of human beings. The concept is often related to an accident model called the energy model, as illustrated in Figure 4 (Sklet, 2006). A traditional approach to managing the risk is by providing layers of protection between hazardous agent and the people, environment, or property. The layers of protection are intended to reduce the risk by reducing either the likelihood of potential accidents, or by reducing the magnitude of the impact. The risk can be reduced to very low levels by providing a sufficient number of layers of protection, and by making each layer highly reliable (Khan & Amyotte, 2003).

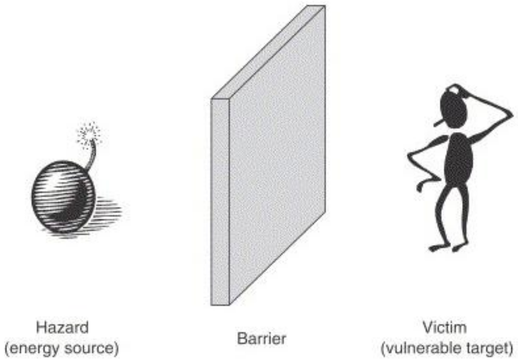

Figure 4: The energy model (based on Haddon, 1980) (Sklet, 2006)

Barriers shall be established in order to (PSA Norway, 2010b):

- reduce the probability of failures and hazard and accident situations developing,
- limit possible harm and disadvantages.

Barriers can be classified according to several dimensions, Sklet (2006) distinguish between *safety barriers*, *barrier elements*, *barrier functions* and *barrier systems*.

"Safety barriers are physical and/or non-physical means planned to prevent, control, or mitigate undesired events or accidents" (Sklet, 2006).

"A barrier function is a function planned to prevent, control or mitigate undesired events or *accidents"* (Sklet, 2006).

"A barrier system is a system that has been designed and implemented to perform one or more barrier functions." (Sklet, 2006).

The means may range from a single technical unit or human action, to a complex socio-technical system (Sklet, 2006). Physical barriers is referred to as barriers that often are implemented in the design, this may be fire-walls, explosion walls, dimensions of escape routes and so on. Whilst non-physical barriers are referred to as operational barriers such as procedures, risk culture and risk assessment, in other words; one may say this is barriers developed in the organization.

Barrier functions describe the purpose of safety barriers or what the safety barriers shall do in order to prevent, control or mitigate undesired events or accidents (Sklet, 2006). This is often illustrated by use of for instance fault tree analysis in the QRA.

A barrier system describes how a barrier function is realized or executed, and a barrier system may have several barrier functions. In some cases may there be several barrier systems that carry out one barrier function if a barrier function is performed successfully, it should have a direct and significant effect on the occurrence and/or consequences of an undesired event or accident (Sklet, 2006).

The figure below represents how Sklet (2006) recommends classifying the term barrier systems; this thesis will focus upon passive barriers (physical barriers).

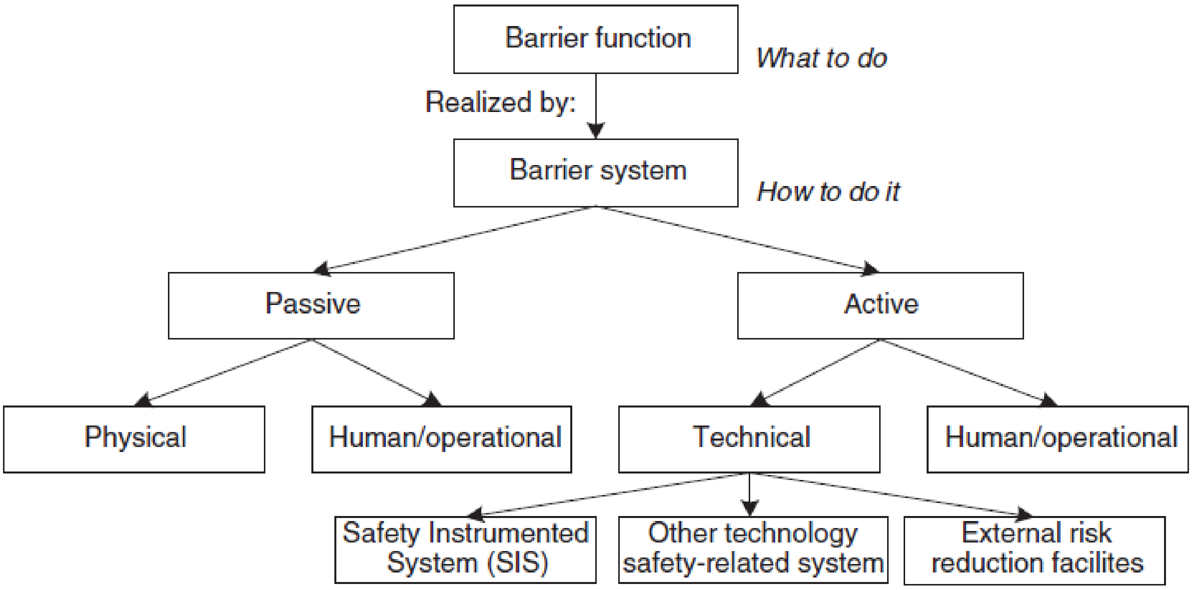

Figure 5: Classification of safety barriers (Sklet, 2006)

Another way to distinguish the term barrier is; *Inherent/integrated* and *add-on* barriers;

Inherent barriers can be defined in many different ways, two common definitions is mention below.

> *"An inherent barrier is reducing or eliminating hazards by using materials and process conditions which are less hazardous"* (Khan & Amyotte, 2003).
>
> *Or;*
>
> *"An inherent barrier is a barrier that is created by changing a parameter of a design"* (Sklet, 2006).

An inherent barrier is a barrier that is created by changing a parameter of a design, for instance, the design of escape routes or using a thicker vessel wall to withstand internal pressure (Sklet, 2006). An offshore development can never be completely safe, but the degree of inherent safety can be increased (Khan, et al., 2002). Inherent safety is a proactive approach for risk management, and can be incorporated at any stage of design and operation (Khan & Amyotte, 2002). The inherent safety can be increased by selecting the optimum design in terms of the installation configuration and the layout, and thereby reduces the risk to a level that is as low as reasonably practicable (ALARP) (Khan, et al., 2002). The ALARP principle will be further explained in the next section.

The layout plays an important role in defining the safety of the facility (Tugnoli, et al., 2008). However, this requires identification of risk contributors and their assessment, using quantitative risk assessment (QRA) techniques early in the project life cycle (Khan, et al., 2002). The fundamental objective in achieving inherent safety is to eliminate hazards completely. Elimination of hazards on an offshore facility is, however, difficult because most of the hazards are directly related to the function of the facility. The expression "inherent safety" is therefore referred to as taking advantage of the intrinsically safe features of offshore facilities (Khan & Amyotte, 2002).

Add-on barriers are, according to Sklet (2006), systems or components that are added just because of safety consideration. This term can be divided into passive and active barriers. Where a passive barrier is a barrier that is not dependent upon operational control, this may be for instance explosion walls. Whilst an active barrier needs to be activated by either human actions or by technical control systems, examples may be deluge systems (Sklet, 2006).

2.6. Risk Acceptance Criteria (RAC) and ALARP principle

According to NORSOK Z-013 is Risk Acceptance Criteria (RAC) defined as the criteria that are used to express a risk level that is considered as the upper limit for the activity in question to be tolerable. The RAC shall be established by the operator, and should be determined before the risk analysis process starts. Quantitative safety risk acceptance criteria should as a minimum cover risk related to people (loss of lives), environment and impairment criteria for dimensioning of vital buildings/equipment. This includes criteria for loss of main safety functions. The criterion often used in regulations regarding loss of main safety functions such as escape routes is a frequency of $1x10^{-4}$. Whilst the average individual risk shall often meet the criterion of FAR<10, this applies to an average for any 12 month period in operational phase (Standards Norway, 2010).

The main purpose of RAC is to keep the risk related to certain activities at a level that is considered acceptable and should be as low as possible. RAC are used in relation to risk analysis, and is the starting point for further risk reduction; the risk is **tolerable** if the calculated risk is lower than a pre-determined value, otherwise must risk reducing measures be implemented (Standards Norway, 2010).

However, the risk shall always be reduced to a level that is As Low As Reasonably Practicable. This term is referred to as the ALARP principle. The ALARP principle means that the benefits of measures should be assessed in relation to the disadvantages or costs of the measures. The ALARP principle is based on “reversed burden of proof”, which means that an identified measure should be implemented unless it can be documented that there is an unreasonable disparity between costs/disadvantages and benefits (Aven, 2008). This is illustrated in Figure 6, which also indicates that the ALARP area is the entire part under the acceptance limit for risk.

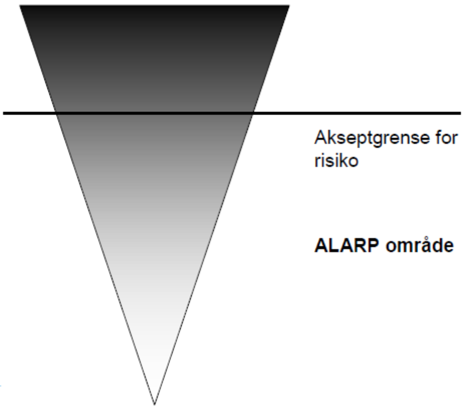

Figure 6: ALARP principle (Norwegian legislations) (Vinnem, et al., 2006).

2.7. Escape, evacuation and rescue (EER)

Escape is *the act of personnel moving away from a hazardous event to a place where its effects are reduced or removed* (IHS, 1999)

Escape route is *a route from an area of an installation leading to a muster area, temporary refuge (TR), embarkation area or means of escape to the sea* (IHS, 1999).
Or;
Escape routes *is a route from an intermittently manned or permanently manned area of a facility leading to safe area(s)* (Standards Norway, 2010).

From these definitions one can say that the purpose of the escape routes is to ensure that personnel may leave an area in case of a hazardous incident by at least one safe route and reach the designated mustering area from any position on the installation (Standards Norway, 2008; IHS, 1999). Escape routes need to fulfill their function until all personnel have reached a safe location on the installation. The routes may be impaired by:

- Heat
- Smoke
- Fire/explosion (causing structural damage)
- Obstructions (due to failure of procedural controls)

The number and capability of people present will influence the assessment of the escape routes. When determining whether your premises have adequate escape routes, you need to consider a number of factors, including (Business Advice, u.d.):

- the type and number of people using the premises;
- escape time;
- the number and complexity of escape routes and exits;
- whether lifts can or need to be used;

Evacuation *is the planned method of leaving the installation in an emergency* (IHS, 1999).

Evacuation route *is the escape route which leads from the temporary refuge to the place(s) used for primary or secondary evacuation from the installation* (IHS, 1999).

The purpose of the evacuation system is to ensure means of safe abandonment of the installation for the maximum personnel on board, following a hazardous incident and a decision to abandon the installation (Standards Norway, 2008).

***Rescue** is the process by which those who have entered the sea directly or in liferafts are retrieved to a place where medical assistance is available* (IHS, 1999).

The purpose of rescue and safety equipment is to provide personnel with suitable and sufficient protective equipment to effect rescue of personnel, enable them to reach escape/evacuation points and, if necessary, to maximize the chance of a successful recovery from the sea. The rescue and safety equipment have no interfaces with other safety systems/functions (Standards Norway, 2008).

Evacuation, Escape and Rescue (EER) is a general term used to describe the range of possible actions including escape, muster, refuge, evacuation, escape to the sea and rescue/recovery.

The objectives of EER are to (IHS, 1999);

- maintain the safety of all personnel when they move to another location to avoid the effects of a hazardous event
- provide a refuge on the installation for as long as required for a controlled evacuation of the installation;
- facilitate rescue of injured personnel;
- ensure safe abandonment of the installation.

Evacuation, Escape and Rescue Strategy (EERS) is defined as the results of the process that uses information from an evaluation of events, which may require EER to determine the measures required and the role of these measures (IHS, 1999). An EERS shall include a planned method of how to evacuate the installation in an emergency situation, and it should be in prioritized order. In addition shall safety and rescue equipment be mentioned and their locations.

2.7.1. Legislations

Escape routes shall be part of the daily used transport- and passageways, however, lifts shall not be considered as a part of escape routes. Escape routes shall in principle be provided near the periphery of the installation on each level. If escape routes leads to a higher or lower level should it be provided with stairways, which are designed so that it is possible to transport injured persons on stretchers. The numbers of these stairways shall be assessed based on the platform size, configuration of areas and equipment layout. In addition, all doors shall be constructed so that one person can easily open them from either side. They shall open in the direction of escape, without blocking the outside escape route (Standards Norway, 2008).

Figure 7: pictures of escape routes (MTE, u.d.; Safeguard tecnhology, u.d.)

From a permanently or intermittently manned area shall there be at least two exits to escape routes, leading in different escape directions. At least one of the escape routes shall be maintained until evacuation to the facility’s safe areas and the rescue of personnel has been completed. This applies to the escape possibilities from manned parts of each area, to the defined safe area(s). The requirement also applies to the entire escape route; from the central position in the main area, to the safe area (Standards Norway, 2008).

The dimension of escape routes should be adequate for the number of people who may be required to use them, and required width of escape routes shall emphasize easy transport of injured personnel on stretcher. According to NORSOK S-001 shall the dimension of escape routes be minimum 1m width (0.9 m for doors) and 2.3m in height (2.05m for doors). Escape routes intended for use by more than 50 persons shall be extended to 1.5m (1.2m for doors) in width. These dimensions are summarized in Table 2.

Whilst ISO 13702 states that the escape routes should be greater than 1 m wide, but for routes which are unlikely to be used frequently a reduction in this width may be acceptable (IHS, 1999).

Table 2: Minimum dimensions for escape routes (based on NORSOK S-001)

Escape Route Category	Escape route		Doors/openings in escape route	
	Width	Height	Width	Height
Main Escape Route (more than 50 persons)	1.5 m	2.3 m	1.2 m	2.2 m
Main Escape Route (less than 50 persons)	1.2 m	2.3 m	1.2 m	2.05 m
Local Escape Way leading to Main Escape Route	1 m	2.3 m	0.9 m	2.05

There shall not be any dead-end corridors that exceed 5 meters in length. The concept of a dead-end corridor is illustrated In Figure 8.

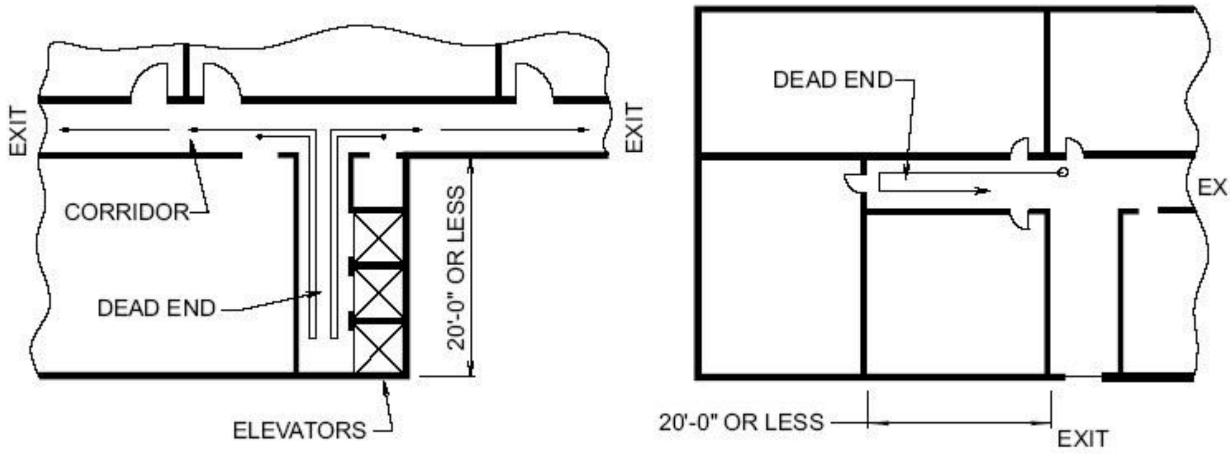

Figure 8: dead-end corridor (ICC, 2009)

ISO 13702 says that main evacuation routes not should be located in the path of explosion vents. This is due to the possible damage by blast effects and flying debris. Temporary refuge, accommodation, evacuation means, escape routes and rescue facilities shall be located where they are least affected from fires and explosions (Standards Norway, 2008).

Escape routes from all manned areas should be well marked (including signs) and lit so that they are readily identifiable by all personnel in an emergency. Marking shall show the preferred direction of escape, and shall be provided as necessary to allow personnel to identify escape routes, including indication of the direction to muster areas, embarkation areas and means of escape to the sea (Standards Norway, 2008; IHS, 1999).

ISO 13702 states that wherever practicable should escape routes be designed to remain passable by position rather than by special protection. To achieve this, external escape routes should wherever practicable be physically separated from explosion vent panels, sacrificial walls and open hazardous modules. Where this is not possible, alternative routes should be provided which are unlikely to be affected in the same incident.

The purpose of the emergency lighting system is to provide sufficient lighting for evacuation and escape in an emergency situation. Emergency lighting shall be provided in all accommodation spaces, control rooms, work locations, along all escape routes, the helicopter deck, emergency stations, lifeboat stations and lifeboat drop zones. The escape routes and evacuation system performance is dependent upon emergency power and lighting to ensure lighting for escape and evacuation if main electrical power supply fails (Standards Norway, 2008).

The installation shall be divided into main areas (accommodation, utility, drilling, wellhead, process, and hydrocarbon storage). The main areas shall be located and designed to minimize the risk to people, environment and assets. Main areas shall normally be separated by use of physical barriers as fire and blast divisions to prevent the escalation of an accident from one main area to another (Standards Norway, 2008).

2.7.2. Loss of escape routes

An assessment of loss of main safety functions shall be conducted; in this thesis will only escape routes be considered. Figure 9 clarify and exemplify how to assess loss of escape routes. In this example the facility has four main areas: Main area A (MA-A), main area B (MA-B), main area C (MA-C) and main area D (MA-D). Each main area is separated by the use of fire and explosion walls, which are illustrated with dotted blue lines. The green arrows indicate escape routes from one main area to main area MA-A, which are the safe area in this example (Standards Norway, 2010).

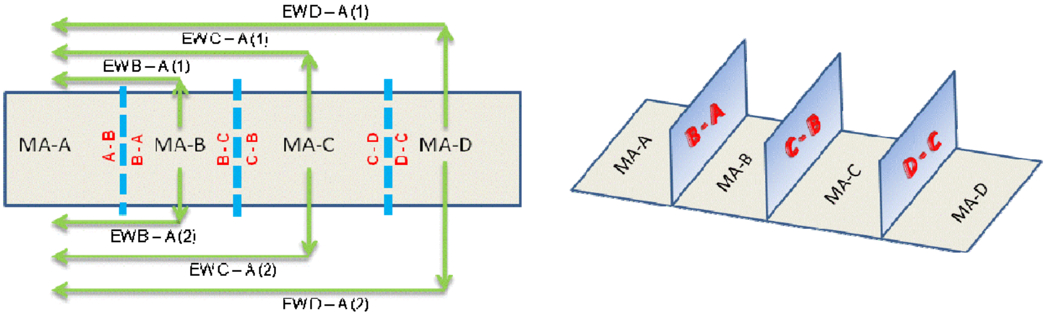

Figure 9: Simplified facility layout (Standards Norway, 2010).

Loss of escape possibilities from the main area that is initially exposed to the accidental event shall not be included in the assessment of loss of this main safety function. Nor shall the assessment include loss of escape possibilities from intermittently or not permanently manned areas (Standards Norway, 2010).

An assessment of loss of the entire escape routes from main area MA-D to MA-A shall include these steps (Standards Norway, 2010);

1. Identify all accidental events that do not initially occur in or expose main area MA-D, and which may expose both escape routes from this area to the safe area in MA-A.
2. Identify relevant environmental and accidental loads.
3. Compare the environmental and accidental loads with the design of the escape routes.
4. Identify scenarios which may cause the impairment of both escape routes.
5. Identify the probability for impairing both escape routes (based on information above)
6. Compare the results from step 5 with the established risk acceptance criteria (usually $1x10^{-4}$).

These steps shall be repeated for the escape routes from all other main areas, in this example from MA-B and MA-C.

2.8. Human behavior

In order to understand how and why humans behave as they do during an emergency situation, will this thesis first briefly explain how humans *process* information under normal conditions, and how humans *process* information under stressful conditions.

2.8.1. Information processing under normal conditions

We have evolved so that all the sensations such as vision, hearing, taste, smell, hot, cold, vibration, pain and posture are constantly being fed into a sensory register in our brain. Here the information is encoded and put into a central processing unit (*short-term* or *working memory*). There is essentially only one line to send the information to the central processing unit. Due to this limitation, the human can only process one complex task at a time. The figure below is one way to illustrate how human process information (Brooks, u.d.).

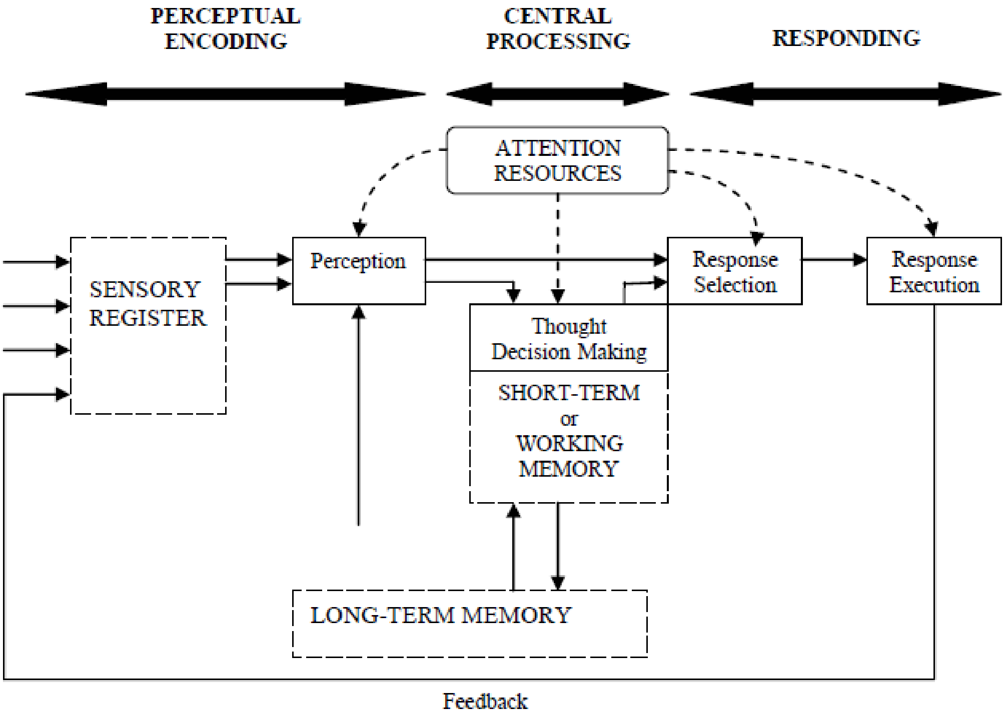

Figure 10: A model of Human information processing (Brooks, u.d.)

2.8.2. Information processing under stressful conditions

As illustrated in Figure 11 is the control of complex tasks done by the Supervisory Attentional System (SAS) in the brain. The SAS is very vulnerable to overload if events unfurl too quickly and it can be easily disabled. It is a very poor responder; it takes over 100 times as long to process a problem compared to the normal system. Therefore, response times take about 8 – 10 seconds, which may not be fast enough when you are dealing with an emergency situation (Brooks, u.d.).

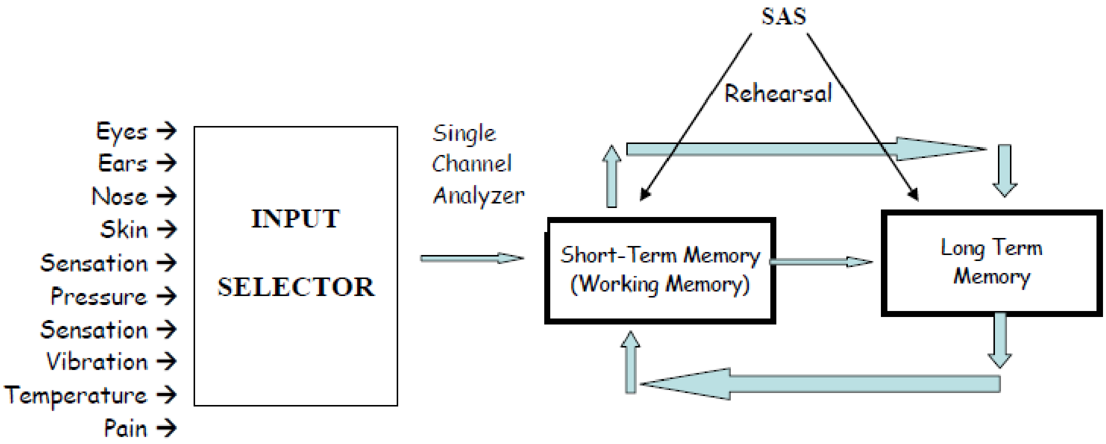

Figure 11: A Simple Diagram to Show How Human Information is Processed (Brooks, u.d.)

2.8.3. Human behavior under stressful conditions

"Some people were beyond reach [couldn't communicate with them] and did not react when other passengers tried to guide them, not even when they used force or shouted at them, some were just sitting in corners, incapable of doing anything." (Leach, 2005, quoted in (Brooks, u.d.)).

Irrespective of the type of catastrophe or extreme, humans appear to follow the same pattern of responses. Leach (2005) uses an easy to follow dynamic model of an accident and describes the wide spectrum of behavior during each developing stage of the accident (Brooks, u.d.).

This model consists of five phases (Brooks, u.d.);

1. Pre-impact phase- threat and warning stage
2. Impact phase
3. Recoil phase
4. Rescue phase
5. Post-trauma phase

Only the two first phases will be further explained in this thesis:

Pre-impact phase; even though there is a known threat, the usual behavior is inactivity, self-denial, a sense of immunity "it will never happen to me". These are all very normal responses to be expected. When the warning occurs the threat appears real. Behavior ranges from hopeless apathy, over-activity, self-denial, and ignoring warnings (Brooks, u.d.).

Impact phase; Irrespective of race, creed, sex, and level of training, a person will perform under one of three categories (Brooks, u.d.);

- 10 – 15% will survive in spite of everything; assess the situation and gather their thoughts quickly. They will succeed in formulating good decisions, and execute their plan of action well.
- 75% will be bewildered but with training may overcome the obstacles; bewildered and stunned, but with good training can follow the correct procedures to make a successful escape from whatever hazard confronts them. Their actions are mostly automatic in nature, and they will function more slowly as a result of the shock and amazement of the present situation.
- 10 – 15% will be totally ineffective in doing anything to save their own lives; will exhibit behaviors that impair their ability in making a successful escape, such as paralyzing anxiety, confusion, and screaming

3. Presentation of cases

This section will present two cases that will be used in this thesis; these two cases are slightly different, one is a modification case, whilst the other case is a new platform. The cases are the Yme MOPUstor platform and modification of the Troll A platform. These cases were provided by Aker Solutions MMO, and represents how a typical risk analysis is performed.

The presentation will emphasize the risk analysis conducted for each of the platforms, with the main focus on the escape routes and area classification. A brief presentation of the different fields will be given, as well as design specification with respect on main areas and escape routes. However, due to numerical information in both Yme and Troll A being restricted, only illustrative numbers will be presented.

3.1. Case 1: Yme MOPUstor (Yme)

MOPUstor is a mobile offshore production unit featuring a subsea storage tank, and Yme MOPUstor is an integrated wellhead, production, storage and offloading platform. Yme is located in the Egersund basin, approximately 110 km from the Norwegian coastline on 95 meters water depth (Safetec, 2012). Yme is one of the smallest fields developed in Norway with independent production facilities. The field was originally discovered by Statoil in 1986, but was abandoned in 2001. In 2010 Talisman Energy Norge AS started a redevelopment program, and is now the operator of the Yme platform (offshore-technology.com, u.d.).

The Yme field is illustrated, with platform and the main components, in Figure 12

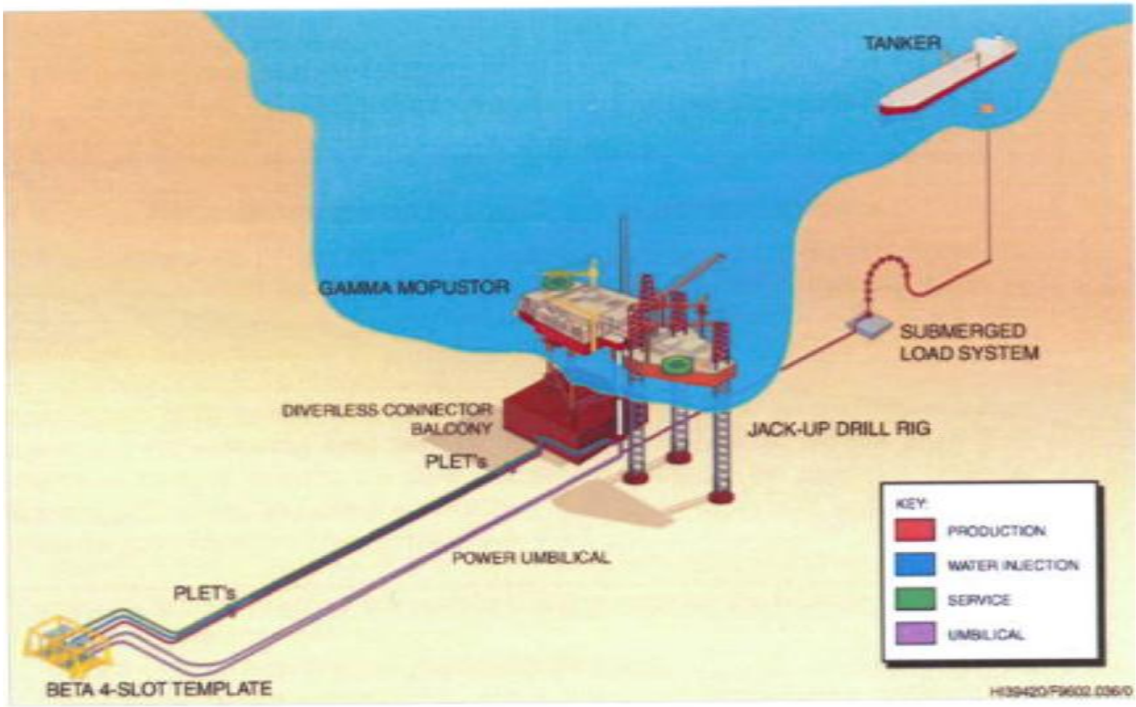

Figure 12: Yme field layout (Safetec, 2012)

Yme will receive production from two main reservoirs which are 12 km apart, Yme is located above one of the reservoirs. The oil is stabilized and stored in the MOPUstor subsea storage tanks for settling prior to metering and further export. The area does not have any export for gas, so the gas can for instance be injected into the reservoirs, or alternatively ne used as fuel onboard the MOPUstor (Safetec, 2012).

However, worth pointing out is that the owners (Single Buoy Moorings) of Yme MOPUstor have decided in agreement with Talisman to scrap the platform, and there is a settlement on cost allocation (DN, 2013).

3.1.1. Platform design

This section will present how the platform is designed with respect to main areas, firewalls and escape routes. Everything in this chapter is taken from the main report with appendices provided by Safetec; main report for Yme MOPUstor TRA and DAL (Safetec, 2012). There will therefore not be any references.

3.1.1.1. Main areas and sub-areas

Yme MOPUstor is divided into five main areas, illustrated in Figure 13;

- **A1**, Living quarter;

  This area consist of eight levels, but none sub-areas; decks A, B, C, D, E, as well as top deck, roof and helideck levels. The living quarter will accommodate up to 55 personnel.

- **A2**, Utility;

  The utility area has three levels, and this area consists of; weather deck, utility and water injection equipment.

- **A3**, Wellhead;

  Wellhead area is divided into three sub-areas; **A3.1** Cellar deck, **A3.2** Wellhead deck and **A3.3** hatch deck.

- **A4**, Process;

  This main area includes most of the hydrocarbon processing equipment, and consists of three decks. Each of these decks represents a sub-area; **A4.1** is the 1st deck, **A4.2** 2nd deck and **A4.3** Weather deck.

- **A5,** Hull;

  This main area consists of among others ballast tanks and methanol tank

  .

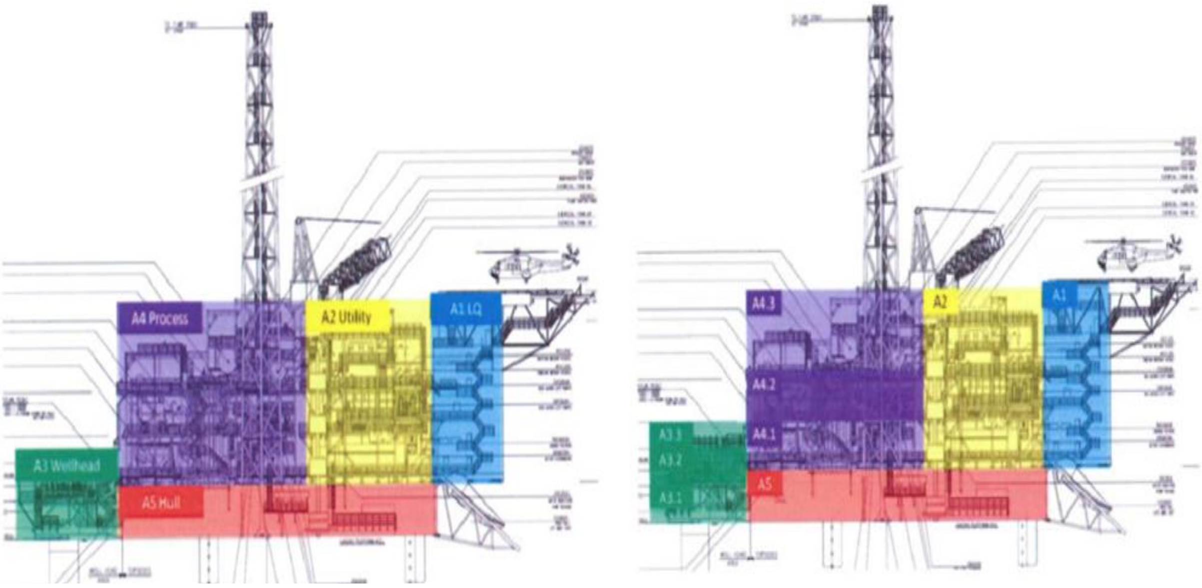

Figure 13: Yme MOPUstor, main areas and sub-areas (Safetec, 2012)

The process area is separated from the other areas by firewalls; the other main areas do not have any firewalls.

3.1.1.2. Escape routes

The escape routes on the 1st deck and in the main area Hull is illustrated in red in Figure 14 and Figure 15. Illustration of escape routes on the 2nd deck and the weather deck is not included in this thesis.

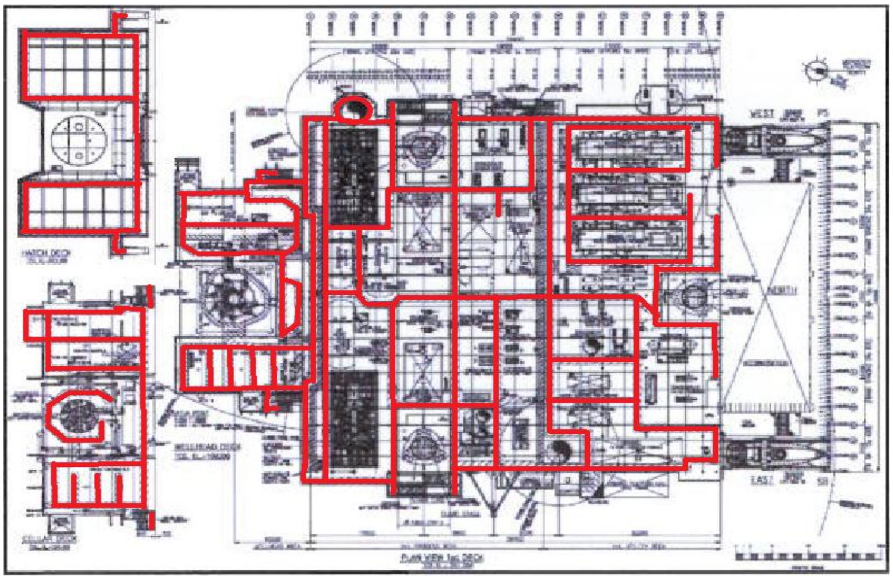

Figure 14: Escape routes on 1st deck (Safetec, 2012)

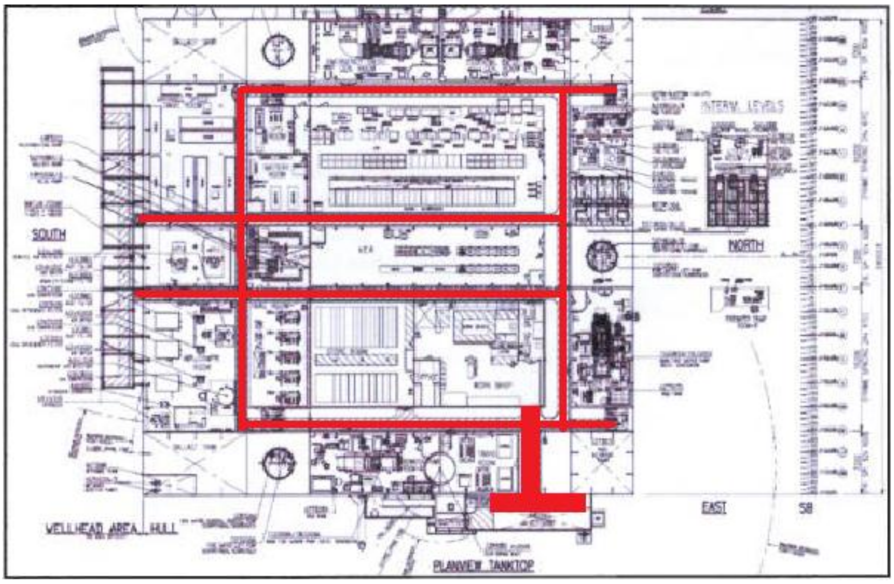

Figure 15: Escape routes in Hull (Safetec, 2012)

3.1.2. TRA process and results

This section is based on the main report with appendices provided by Safetec; main report for Yme MOPUstor TRA and DAL. However, due to confidentiality all values and numbers given will be illustrative and not the true values given in the report (expect for the RAC given in legislations).

This section will include an introduction on how the TRA was conducted and the main results. The TRA reflects, in this case, the technical and operational status for the platform when the operation started. The purpose of this analysis was to assess risk to personnel and to calculate impairment probabilities for the main safety functions; and in that way present a description of risk related to the operation. The analysis intended to identify critical challenges that could be changed by design or operation, and to provide an input for the ALARP process.

The risk analysis was conducted by use of other engineering studies; mainly fire and explosion analysis. Both the fire and the explosion analysis will be further explained below. The risk analysis' primarily focus was on major[1] accidents. However; occupational[2] accidents are also considered, and helicopter transport is included in the personnel risk calculations.

The standardized process for a QRA study was used (see Figure 2). A description of the platform and the Yme field was briefly mentioned before the analysis was conducted. This includes illustration of the main areas, a brief history and technical information.

After the short outline of the platform several assumptions and limitations were identified. These were separated between design, operation and analytical assumptions. The purpose of the assumptions was to create a robust foundation for the evaluation of the expected risk level on the installation. The operational input was based on experience from other installations, whiles the assumptions and premises wee based upon experience from other platforms, historical data and so on, which may hide uncertainties.

In order to come up with the main results the main events were studied separately with an independent analysis that followed the same standardized process for a QRA; Process events, Blowouts and well events, and riser and pipeline events. These events had their own appendix, and the analysis considered the main process related fire and explosion hazards due to release of hydrocarbons. The frequency of impairment of main safety functions,

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[1] Accidents with potential of multiple fatalities.

[2] Accidents that mainly affect one individual situated in immediate vicinity on the scene of an accident.

frequencies of leakage and the personnel risk was calculated, in the form as FAR and frequency.

A fire analysis, which took into account temperature, radiation, visibility with more, was conducted. In this analysis the impairment of escape routes was evaluated. It also evaluated how a fire in one sub-area/main area would impair the escape routes in another area. This analysis was taken into account in the total RAC for both FAR and impairment of main safety functions.

The criteria used for loss/impairment of escape routes when it comes to fire:

- Radiation above 8 kW/m2
- Visibility less than 4 meters
- Temperature of 100 degrees Celsius or above

Immediate fatality was assumed to be at a radiation above 25 kW/m^2, and RAC for collapse of the jack-up legs are set to be at a temperature of 400 degrees Celsius.

The results were divided into Personnel risk and impairment of main safety functions. Personnel risk is represented by use of FAR values where the acceptance criteria are set to FAR < 10. The FAR value is divided into total average for personnel, average individual for personnel groups, and area FAR, and is based upon estimated exposure for personnel and escape routes in each subarea. The TRA indicates that the FAR value is within the RAC (FAR < 10) with a good margin.

Six different safety functions were evaluated; including escape ways, evacuation, and prevent escalation. The acceptance criterion for escape from all main areas is set to be a frequency of 1.0E-04 per year. The simulations indicate that the annual frequencies of impairment of escape ways related to fires and explosions are within the acceptance criterion which is set to be 1.0E-04, both for main areas and sub-areas. These simulations were done without the use of deluge systems. The impairment of barrier, the main safety function “prevent escalation”, is below the RAC which are set to be 1.0E-04 in all areas except from the Process area. The reason why the TRA find that the process area will exceed the RAC is a result of a combination of high leak frequencies, large accumulated gas clouds and high explosion overpressure.

3.2. Case 2: Troll A

The Troll A platform is an offshore natural gas platform in the Troll gas field off the west coast of Norway. The field was discovered in 1979, and comprises two main structures; Troll East and Troll West. The Troll A platform is located 80km north-west of Bergen, on a sea depth of 302.9 meters. The Troll A platform combines production, processing, Living quarter, import and export of gas. In addition to gas from its own wells, the Troll A platform receives gas from both Troll B and C, and the gas gets exported to the mainland (Kaushik, 2013).

This case study addresses a risk analysis done due to modification of the Troll A platform. The main process was originally with gas/liquid separation, as the reservoir pressure was high enough to export the gas/liquid without a gas compression. However, as the pressure in the reservoir reduces in pace with the production making modifications to maintain the export rate is required (Scandpower, 2011).

These modifications are illustrated in Figure 16, where the modification is two new compressors.

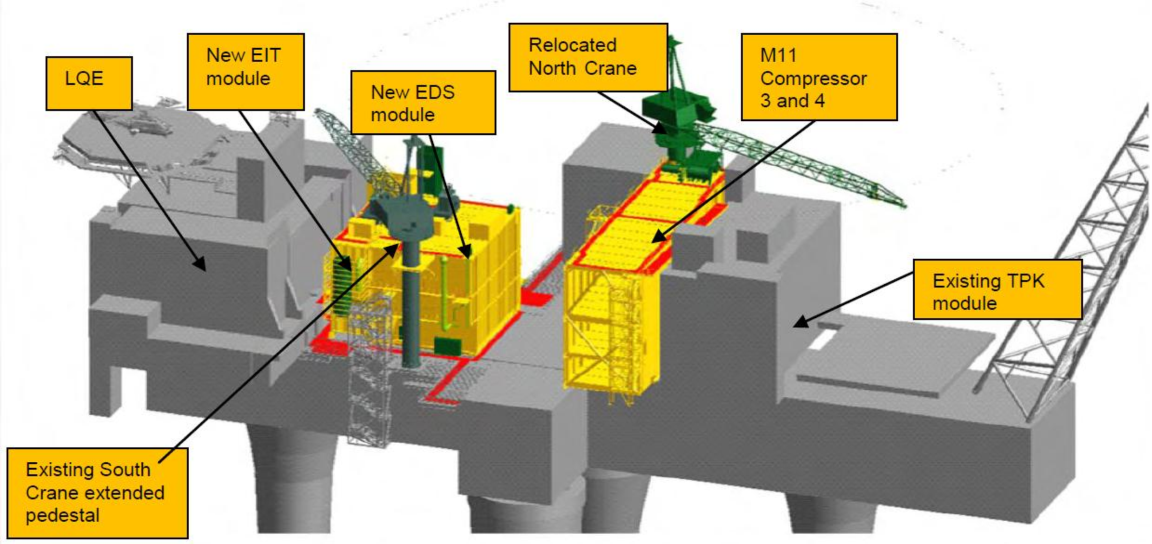

Figure 16: modification of Troll A (Scandpower, 2011)

3.2.1. Platform design

This section will present how the platform is designed with respect to main areas, escape routes, firewalls and lifeboats. Everything in this chapter is taken from the report "*concept risk analysis for Troll A Pre-compression 3&4 FEED study*", provided by Scandpower (Scandpower, 2011). There will therefore not be any references.

3.2.1.1. Main areas

The Troll A platform is divided into three main levels; main deck, mezzanine deck and weather deck. The platform is in addition divided into 7 main areas. These are illustrated in Figure 17 by the use of different colors.

The main areas are;

- Living quarter
- Ancillary equipment area, West
- Wellhead area
- Process area, separation
- Recompression
- Risers and pigging
- Riser shaft
- Ancillary equipment area, East

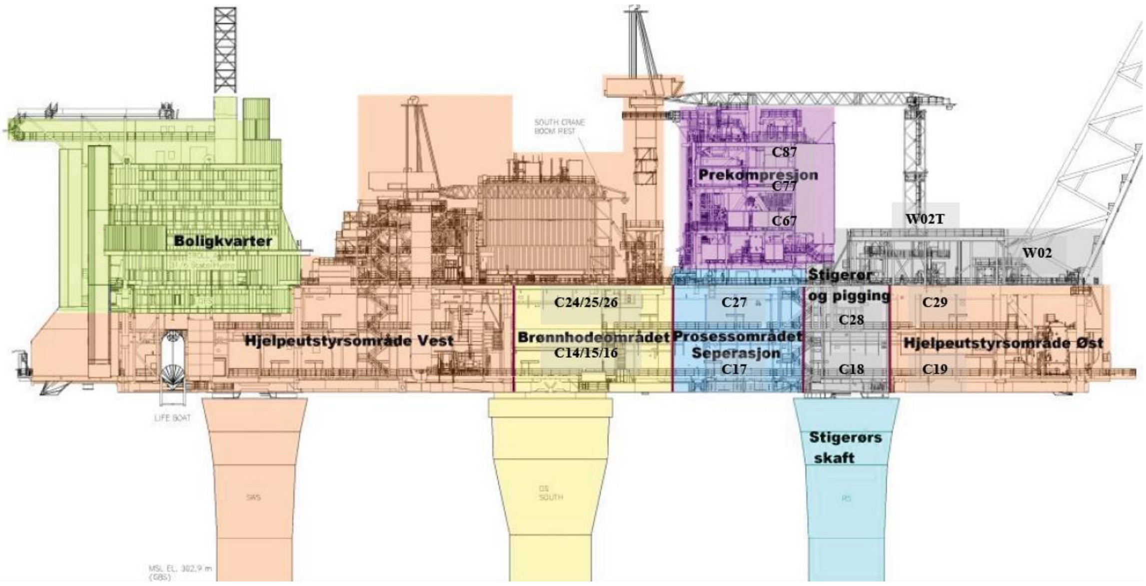

Figure 17: Troll A, main areas (Det Norske Veritas, 2010)

The red lines on the figure above illustrate firewalls between the main areas.

3.2.1.2. Escape routes and lifeboats

The main escape routes on the Troll A platform is directed west. This is because the lifeboats are located in the western part of the platform. On the main deck and the mezzanine deck the escape routes are straight lines at one plan. In the main deck there are intern escape routes between the process and the riser area, as well as intern escape routes between the riser and Ancillary equipment area east. On the weather plan, on the other hand, one can escape to the west and down to the muster area on the west side of the platform.

Please see the three figures below for an illustration of the escape routes on all three levels; main deck, mezzanine deck and weather deck. The red lines indicate firewalls.

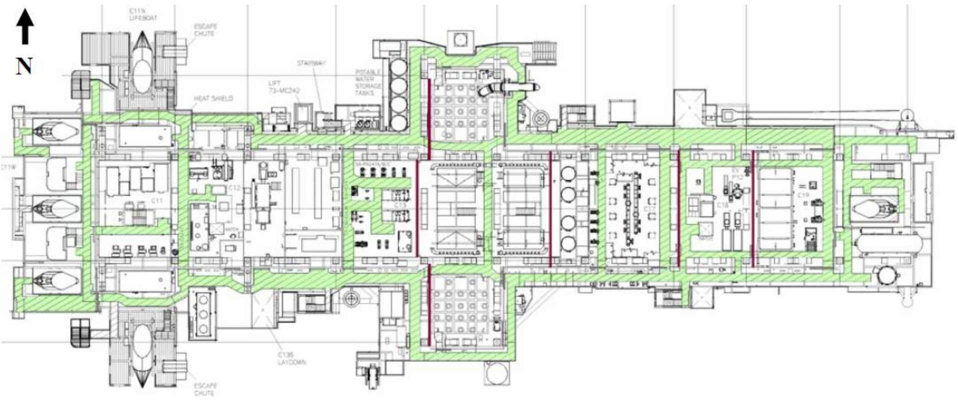

Figure 18: Escape routes Troll A, main deck (Det Norske Veritas, 2010).

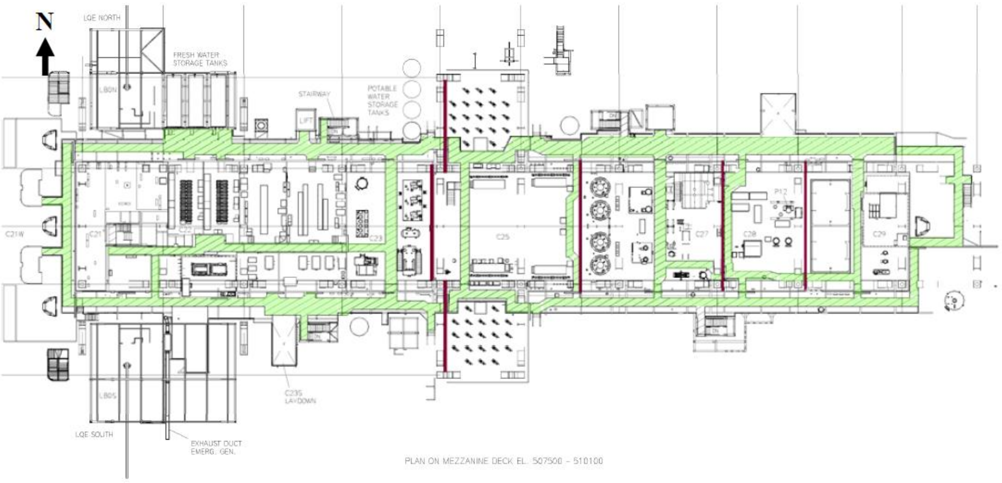

Figure 19: Escape routes troll A, mezzanine deck (Det Norske Veritas, 2010).

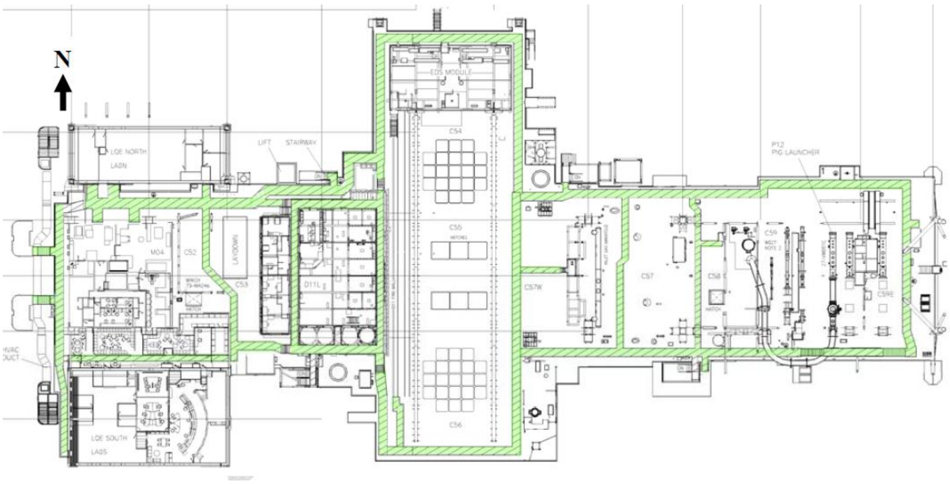

Figure 20: Escape routes Troll A, weather deck (Det Norske Veritas, 2010).

The *primarily means of evacuation* are set to be by helicopter, when it is enough time and the condition allows it. In addition to helicopter the platform is equipped with the following means of evacuations;

- West side
    - Five lifeboats, three is free fall lifeboats and two slewing davit lifeboats. (fit 350 personnel) – *secondary evacuation*
    - Two evacuations stockings, with corresponding rafts - *tertiary evacuation*.
- East side
    - One lifeboat, free fall lifeboat (fit 70 personnel) – *secondary evacuation*
    - One evacuation stocking, with corresponding rafts – *tertiary evacuation*

The location of these evacuation means are illustrated in Figure 21.

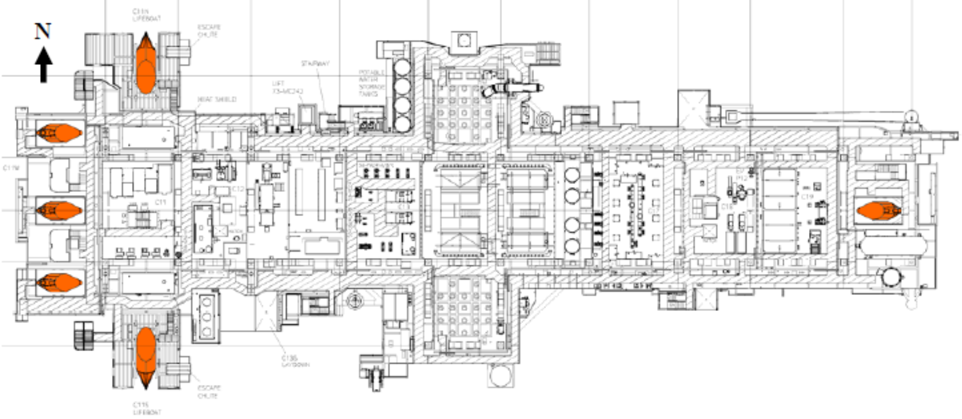

Figure 21: lifeboats Troll A (Det Norske Veritas, 2010).

3.2.2. CRA process and results

This section is based on the report "*concept risk analysis for Troll A Pre-compression 3&4 FEED study*", provided by Scandpower (Scandpower, 2011). Due to confidentiality, the values given by calculations in the report will not be mentioned in this thesis.

The analysis is conducted to identify significant risk aspects that will influence the total risk picture of Troll A platform, after the modification is implemented (an undesired event in the new module). The analysis is with respect to both the future operational phase and the installation phase, when it comes to risk to personnel and risk of impairment of main safety functions (presented by the use of FAR and PLL values). The risk analysis was then further used to update the TRA for Troll A.

The CRA methodology used in this case is not quite the same as the standardized QRA model mentioned earlier in this thesis. The model is therefore illustrated in Figure 22.

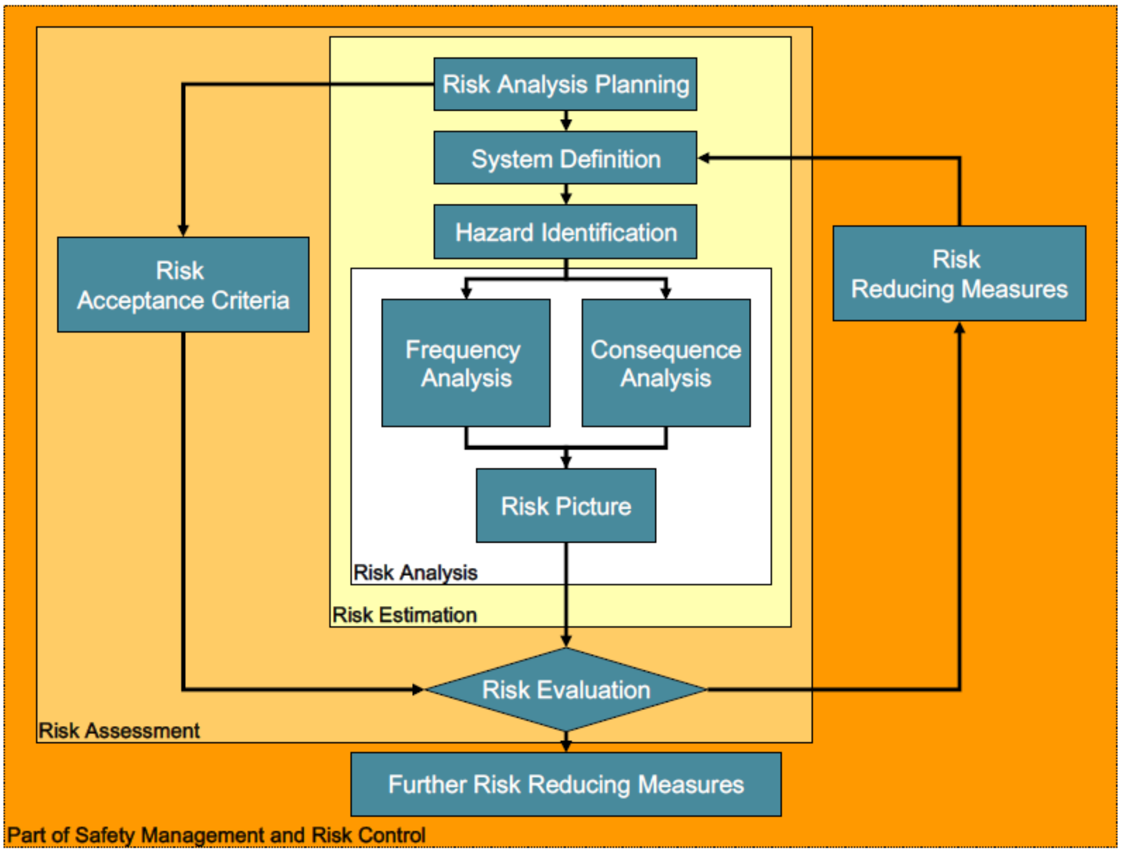

Figure 22: QRA process used in Troll A (Scandpower, 2011)

Available documentation of the platform was first collected and evaluated in order to understand the system. Then the Pre-compression modification was defined and described, and the RAC used in the study was identified and described. The RAC for overall FAR for all personnel was set to be FAR<10, and for the personnel group the RAC was set to be FAR<25. The frequency tolerance criteria for loss of main safety functions were set to be the same as the international standards suggest; frequency less than 1.0E-04.

The hazards used in the assessment are based upon the hazard identification that was carried out for the operational phase, during the design of the whole platform.

The next step was to calculate/estimate the frequency of each hazard identified. This was done by use of event trees, statistical data and engineering experience. First was the leak frequency, initial leak rates and leak duration (and thereby fire duration) for the process segment calculated in specific scenarios. These were used in an event tree analysis to calculate the leak frequencies that may occur due to ignition, strong explosions, blowout failure, fire water failure and escalation to equipment within an area. Examples on events in this case was; Un-ignited leaks, local fire and strong explosions.

The next phase was to evaluate the consequences of the fire and explosion scenarios, this was mainly based upon the fire simulations. The consequences are represented as potential loss of life (PLL) and the impairment of loss of main safety functions. The PLL was calculated by multiplying the probability of fatalities in the area with the average manning in the area.

The criteria used for loss/impairment of escape routes when it comes to fire:

- Radiation above 6.3 kW/m2
- Visibility less than 5 meters

The CRA for the modification of the Troll A platform indicates that all the risk tolerance criteria are fulfilled after the proposed modification design. According to the calculation is it assumed that the FAR value will increase after the modification, however, the FAR value will still be less than the criterion of 10. The frequency for loss of main safety functions after the modification of Troll A will not exceed the criterion of 1.0E-04. However, the analysis related to the loss of the main safety functions summarizes that the frequency of impairment of main safety functions due to fire and explosions are relatively high, even though it does not exceed the criterion. ALARP measures should be taken to protect the loss of the main safety functions like escape ways.

The CRA states that even though the tolerance criterias are met, there is a potential for further risk reduction related to the pre-compression project (ref. the ALARP principle). The CRA provided suggestions for potential risk reducing measures, which respective partners followed up.

One of the risk reducing measures considered was related to escape routes and main area. More specifically, not installing any firewalls between the new compressor and the existing TPK[3] module. The new FAR and PLL is calculated and it indicates that the values will increase. The frequency for loss of escape ways will also increase. This solutions was therefore not recommended, as it would not be a risk reduction measure.

---

[3] Existing pre-compression module

4. Discussion

The escape routes are normally evaluated through design review and other assessments. However; the evaluation should be traceable and/or included in the system description in the risk analysis. There are no specific requirements to how the design of escape routes should be evaluated and considered in a risk analysis.

This section will contain further analysis as well as discussion regarding the case studies presented in the previous chapter. In order to make the discussion clearer, the chapter has been divided into two sub-chapters: *success factors*, and *technical aspects*.

In the first sub-chapter, the five success factors introduced earlier will be discussed. This will include how these factors were taken into account in the two risk analysis introduced in this thesis, with main focus on escape routes.

The second sub-chapter will discuss the requirements regarding escape routes in order to make robust solutions. In addition this section will discuss the relation between escape routes and other elements, such as cost and main areas.

4.1. Success factors

In order to be able to answer the objective in this thesis several success factors that should be included in a risk analysis are identified. A success factor may be defined as important elements that need to be in order to accomplish one or more desirable goals (business dictionary, u.d.). In this context the success factors are seen as in order to perform a useful risk analysis in order to evaluate the escape route design sufficiently.

The success factors are divided between the main elements of a risk analysis process introduced by Aven (2008). These success factors were identified by the use of brainstorming, with background information through presentation of the cases and review of the theory relevant for this thesis. Figure 23 illustrate all the success factors identified in each step of the risk analysis.

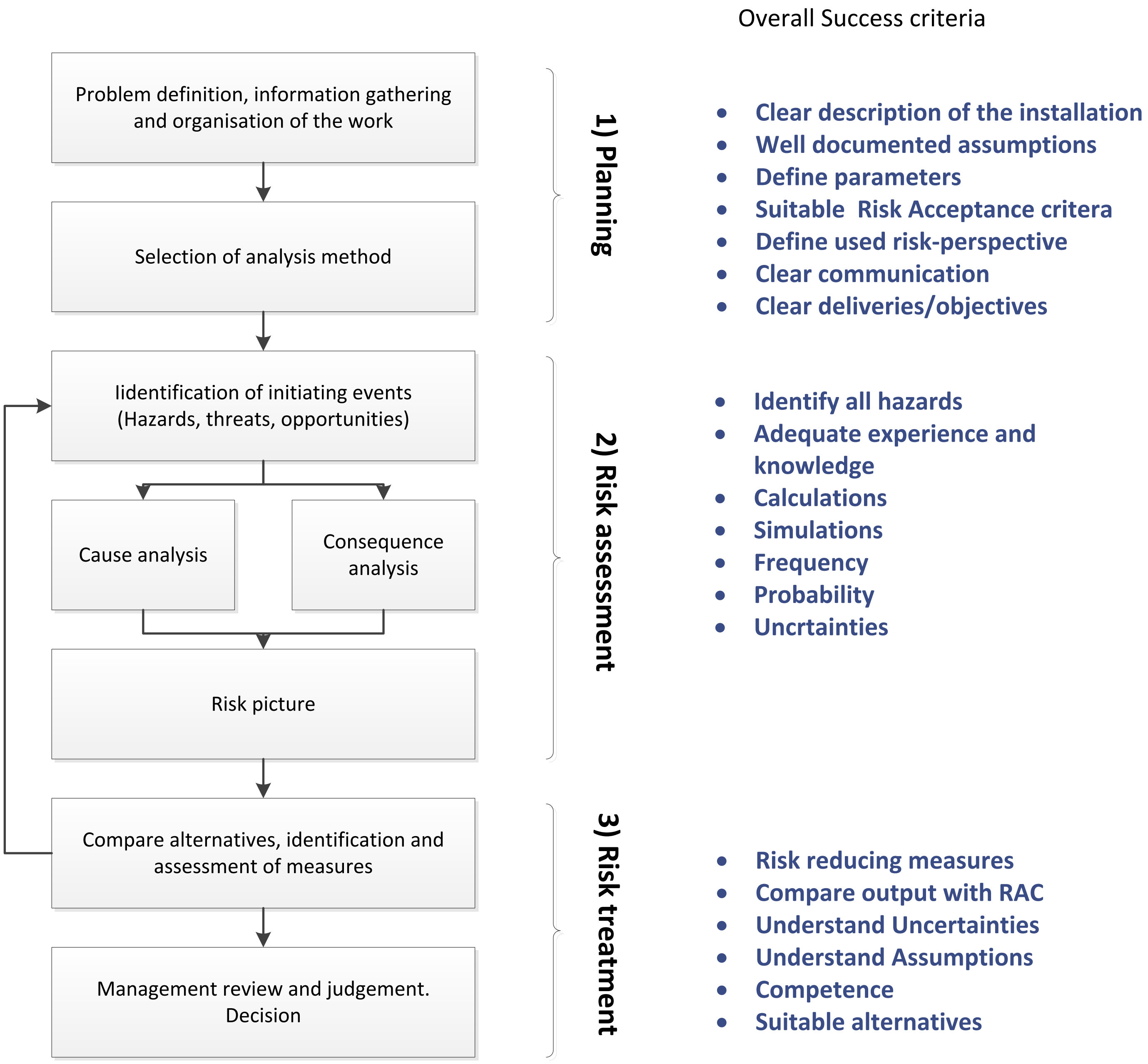

Figure 23: success factors in risk analysis (figure adopted from Aven (2011a))

In this thesis only five of the success factors will be discussed. Based on the personal opinion of the writer, the five success factors are illustrated in Figure 24 are as the most important in terms of evaluating escape routes through a risk analysis. In this thesis, the five success factors carry equivalent risk. Although this approach might not be fully accurate or realistic, it is done in order to simplify the discussion. In real life, these factors would be assigned different levels of risk depending on the analyst (as a result of background knowledge and different risk perspectives)."

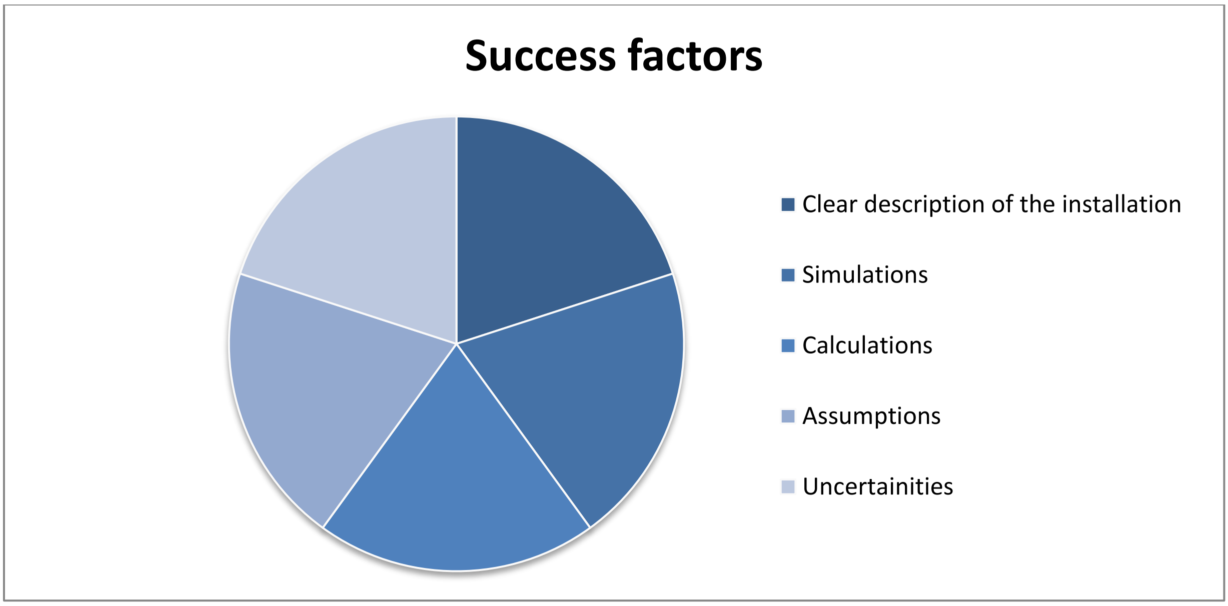

Figure 24: success factors discussed

The next sections will discuss these five success factors, with the main focus on the objective of this thesis. In each success factor, some sub-factors, that is seen as important for the purpose of this thesis have been identified. Some of the success factors could be discussed simultaneously, but in order to simplify and make the discussion clearer they are discussed separately.

4.1.1. Clear description of the installation

A clear description of the installation is important in order to understand how the installation is designed, and to provide a basis for simulations and calculations. If the analysis lacks installation description, important aspects can potentially be overlooked and/or interpreted insufficiently. The box below introduces three criterias that are seen as important in the description of the installation in a risk analysis, related to the evaluation of the escape routes.

The QRA should be provided with detailed figures of;

- *how and where escape routes are designed*
- *how the installation is divided into main areas*
- *what escape route design has been used*

Escape routes should ensure that personnel can leave certain area in case of a hazardous incident by at least one safe route. The escape routes should also enable personnel to reach the designated mustering area from any position on the installation (Standards Norway, 2008; IHS, 1999). To divide an installation in main areas is a method in order to split the installation into different zones, which have different frequencies for the presence of potentially explosive atmosphere (Standards Norway, 2010).

Yme MOPUstor:

In the performed risk analysis for Yme, the escape routes are presented by use of drawings. However; the drawings of the escape routes are somehow unclear. It is important to mention that the escape routes are clearly presented by use of red lines in this thesis; these red lines were not existent in the main report. Evacuation means, with description and location are not illustrated or mentioned in the available documentation of the risk analysis for Yme.

The main areas are described including the use of fire walls, and the main areas are also divided into sub-areas. The description includes a briefly introduction to what each main area and sub-area contains. This is done in order to simplify the analysis; these descriptions should be clearly explained and illustrated in the QRA.

In the risk analysis for Yme MOPUstor is it stated in one of the appendices that it is assumed that the installation is in compliance with design requirements. However, design specifications are not included in the main report and appendices supplied for this thesis- it is uncertain for the writer if this exists or are easy to find. This means that which kind of escape routes used is not mentioned, or described in the reports available for this thesis.

Troll A

The final CRA provided for this thesis lacked of illustrations of escape routes, main areas and which kind of escape routes used. There was an overview of the platform, and an illustration of the modification.

However, a clear description of the escape routes before the modification was included in an appendix provided as basis for the risk analysis. Evacuation means, with description and location was illustrated and briefly explained in the same appendix document as the escape routes.

The main areas are described including the use of fire walls in the same appendix as the escape routes. However, the illustration might be somewhat unclear; it is unclear where the sub-areas are, or if the platform is divided in sub-areas. The description does not include a brief introduction to what each main area and sub-area contains.

The design specifications are not included in the main report or in the appendices supplied for this thesis. This means that which kind of escape routes used is not mentioned, or described in the reports available for this thesis.

4.1.1.1. Comparison

Both Yme and Troll A has ***illustrations of the escape routes***. However, the escape routes on Yme are not clearly marked, and it can be difficult to see where all the escape routes are. This may lead to misunderstanding, and might result in that the escape routes are improperly understood by other assessors. This may have effect on those who use the drawing for platform modifications, and for those who perform future studies. Future analysis will probably be of poorer quality as long as the substrate is poor. In Troll A the escape routes are marked in a sufficient matter and the illustrations is not leading to any misinterpretations. Illustrations of escape routes may be essential in simulations of performance; unclear presentation may lead to wrong evaluation of the escape routes in a later phase.

Both in Yme and Troll A were the ***main areas described and illustrated*** by use of pictures and different colors. However, the description was more detailed in the main report for Yme, compared with Troll A; the division between main areas was marked in a better matter. In both Yme and Troll A was almost every main area divided into sub-areas; makes it easier to perform simulations, calculations and the overall analysis. This is due to that one can focus on smaller parts of the main areas, and make it easier to evaluate the results. In addition the results may be more accurate if one can focus on smaller parts of the installation at a time. However, in Troll A was the division of sub-areas somewhat; uncertain were the boundaries are. Firewalls were illustrated in the reports for both Yme and troll A, by use of clear markings in red. Main areas shall be separated either by distance, by use of physical barriers or by a combination of these to prevent external escalation of an accident. The philosophy is to minimize the risk to people, environment and assets; and by the use of main areas one reduces the probability for expansions of gas-leaks and fires (Standards Norway, 2010). The two cases lacks of a complete safety strategy (Evacuation, Escape and Rescue Strategy).

There are no clear descriptions of ***what design of escape routes*** that are used, in neither of the two cases. This includes a division of for instance the use of fully enclosed tunnels, and protected open walkways. It may be an advantage to state which kind of escape routes are designed, and where. This is because it may for instance be used in different simulations, and if there are needs for any modifications in the future and the old simulation-file with respectively model of the installation is not available is it essential to have this information documented. In addition should it be stated what kind of add-on barriers the different escape routes are supplied with. The different design and add-on barriers will affect the simulations and calculations. A complete EERS would have given a better basis for these issues.

4.1.2. Simulations

Simulations are important in the evaluation of the performance/effectiveness of the escape routes. By the use of the simulation results one get an indication on how well the escape routes may function in order to reach requirements, and that personnel manage to escape to safe haven. The box below introduces three criteria's that is seen as important in simulations included in a risk analysis, related to the evaluation of the escape routes.

The QRA should be provided with different simulations;

- *Fire and explosion simulations*
- *Evacuation simulations*
- *Simulations with respect on human behavior*

Yme MOPUstor

The performed simulations are divided into fire and explosion simulations and these simulations are performed for each main area identified on the platform. The simulations are done without any add-on barriers, such as deluge systems.

There are no simulations of evacuation included in the main report or in the appendices available for this thesis. Consideration of human behavior is not included as well.

Troll A

It is performed both explosion and fire simulations, these are only performed in the new module, and the existing TPK modules. It is not described how these simulations are performed, other than the fire simulations are performed for selected scenarios (critical scenarios). This means that it is unclear if these simulations are done with or without add-on barriers.

There is no evacuation simulations included in the main report and appendices available for this thesis. Consideration of human behavior is not included as well.

4.1.2.1. Comparison

As part of system development many industries make substantial use of simulations in order to understand the system performance. However, it is important to ensure that the information provided the simulations are useful and correct. This is because the results could be ineffective or unreliable if the use of the simulations is insufficient (Cohen, et al., 1998).

Figure 25 is included in order to illustrate why it is important to use simulations. The figure shows the major reasons for the usage of performance-based simulation tools seen in eyes of 584 firms (134 engineering consulting firms, 440 architectural firms, and 10 government statutory bodies). The survey was performed between early December 1998 and early January 1999 (Hien, et al., 2000).

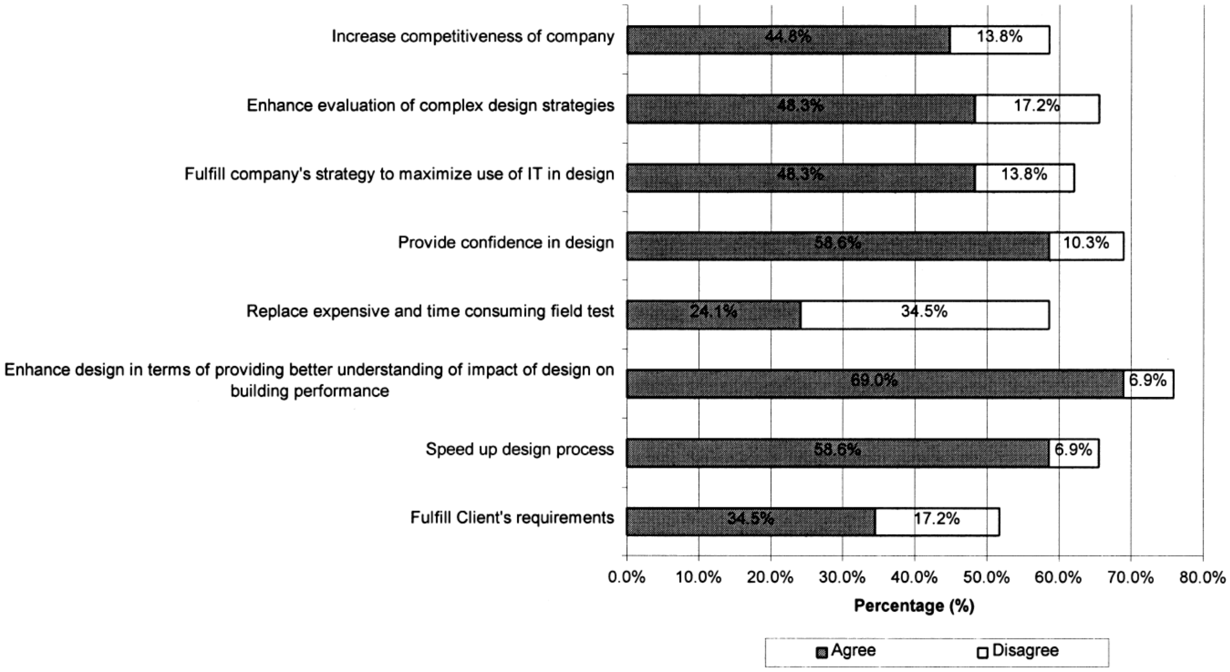

Figure 25: Reasons for usage of simulation tools (Hien, et al., 2000).

As one can see; 69% of the firms surveyed did utilize the tools to enhance the design in terms of providing a better understanding of the impact of the design on building performance. 58.6% felt that the tools speed up the design process as well as providing confidence in the design. Only about 35% indicate that the usage is to fulfill the client's requirements (Hien, et al., 2000).

Fire simulations are important in order to be able to indicate expected visibility and radiation in the escape routes in case of fire. By conducting such simulations one may predict how long personnel can escape by use of the escape routes. The radiation levels and smoke should be studied in order to develop a good estimation of the risk picture. In the Yme MOPUstor is the simulations done without any use of add-on barriers. If the simulations used deluge systems could the visibility and the radiation in the area be different; the main purpose of deluge system is to keep equipment and structure at low temperatures. However, in Troll A is it unclear if it is used add-on barriers, this could result in misleading results and greater uncertainties in the decisions. For instance should the results from simulations be interpreted differently with use of deluge systems then without such add-on barriers.

By the use of ***evacuation simulations*** may it be possible to indicate what the duration is from an undesired event is discovered and to all personnel are evacuated to safe haven. It may be possible to indicate if there is any need for changes in the escape routes design. Simulations can indicate where it is expected that congestions may occur in case of evacuation, and by proactive means try to prevent this from happening. Evacuation simulations may be necessary in order to make well-supported decisions on the robustness of the escape routes (Pel, et al., 2011). It seems like none of the risk analysis studied in this thesis has provided any information regarding simulations on evacuation of personnel, in order to evaluate the escape routes. This may lead to unknown congestion and wrong interpretation of the escape routes effectiveness.

Another aspect is how the employees will react to an emergency situation; there is no indication to that this is taken into account in neither of the risk analysis. As mentioned earlier in this thesis will people react different to the same situation i.e. the reaction is among others based upon background, training and experience. The ***human behavior*** will affect the risk to all personnel; for instance may walking speeds be different in an emergency situation than during for instance evacuation drills. It is difficult to take into account the human behavior, due to that it is a lot of uncertainty involved. It is uncertainty related to how many that will gather their thoughts quickly, become paralyzed, or act automatically etc.

Nevertheless, by performing simulations is it possible to evaluate the escape routes in a better matter, and it should not only be conducted simulations related to fire and gas explosion. By not performing simulations regarding evacuation or consider human behavior may important aspects be overlooked.

4.1.3. Calculations

In order to be able to compare the expected personnel risk with the acceptance criteria stated by legislations is it necessary to perform calculations of frequencies and probabilities. The box below introduces three criteria's that is seen as important in the calculation included in a risk analysis, related to the evaluation of the escape routes.

The risk calculations should be/include;

- *Fatalities risk (FAR, PLL)*
- *Impairment of main safety functions*
- *Used values should be traceable*

Yme MOPUstor

The risk analysis has a focus on FAR values, and loss of main safety functions. The calculations are conducted for three different events, these sections are as mentioned earlier; process, riser and pipeline, and blowouts and wells. In each event is a frequency of gas-leaks and leak-rate calculated; these are used to calculate annual frequencies for an ignited leak. By calculating this is the risk of impairment of safety functions and risk for personnel estimated, by the use of event trees.

Troll A

The risk analysis is provided with PLL and FAR values, and loss of main safety functions in both explosion and fire scenarios. These are divided between; process accidents in new module, riser and pipelines accidents, and blowouts and well leakages. It is also conducted calculation of leak-rate and leak frequencies, where the model is based on generic data with observed incidents from 1992-2008.

4.1.3.1. Comparison

The two risk analysis introduced in this thesis has included calculations regarding ***FAR***. In Yme MOPUstor are the FAR values divided in three; Total average, average individual, and area FAR; these are based on the sub-area division. By performing calculations on each sub-area simplifies the assessment substantially, and it makes it easier to evaluate each area that is classified. In Troll A is the PLL values calculated for both fire and explosion, before they are added together, and thereby is the FAR values for the different areas found. These values are then compared with the values calculated before the modification. ***Loss of main safety functions*** is included in both cases. In Troll A is it only calculated related to process accidents in the new module, whilst on Yme is it calculated for every main area (and sub-area).

The importance of calculating both FAR and impairment of safety functions is to compare the values with the identified RACs, and follow the ALARP principle. If the values are somewhat above the acceptance limit, there will be a dedicated search for risk reducing measures (Aven & Vinnem, 2007). However, in the Norwegian legislations is there no lower limit for where to end the risk reducing measures. This means that risk reducing measures should be identified and implemented as long as the cost involved is not reasonably high compared to the risk reduction. However, it is unclear where the line between safety and cost goes; when are the cost grossly proportional compared with the benefit gained?

Figure 22 shows an iterative loop, which indicates the importance of risk evaluation (i.e. the consideration of results from the risk analysis in relation to risk acceptance criteria). If the risk results are unacceptable, then a new loop is created through implementation of risk reducing measures, and an updating of the risk analysis to reflect these changes (Vinnem, 2007). This indicates that if one does not perform calculations regarding FAR or impairment of safety functions one cannot reach the best solutions with terms of achieving the lowest possible risk.

The values used in the calculations should be ***traceable***; due to that all calculations must always be seen in relation to the background knowledge. The results are dependent on the values and methods used in the calculations, and the result may vary from assessor to assessor. In Yme is the basis for the estimation of event frequency somewhat mentioned (ref. to another document), the basis for the calculation of impairment of escape routes is also mentioned. In the CRA for Troll A is it mentioned that some the values used are based on the values provided in the TRA.

4.1.4. Assumptions

In a Quantitative Risk Analysis is it needed to have some qualitative assumptions, this is because it is likely that all the data needed is not available. The assumptions are filling the gaps and make the analysis easier to conduct. The box below introduces two criteria's that is seen as important in the assumptions made in a risk analysis, related to the evaluation of the escape routes.

The assumptions should be;

- *Clearly defined, explicitly documented*
- *Traceable*

Yme MOPUstor

The assumptions are included in an own appendix, and mentioned without any description in the main report. It is stated that the assumptions are based on information from Talisman and Aker Solutions during the project. The assumptions in the appendix have a general description and a description on the effect on the risk level. However, which background knowledge it is based upon is somewhat unclear; it is only referred to different document (by the use of numbers). However, a responsible person is mentioned for each assumption. There are several assumptions made for design, one of them are regarding fire and blast barriers.

Troll A

The assumptions are listed and described in a table in the main report, but they could have been described more in detail. It is stated what the assumptions is based on, but it is not described if these background documents will be available for the reader. There are no assumptions linked directly to escape routes.

4.1.4.1. Comparison

In the two cases studied in this thesis the assumptions could be subjected to misinterpretation by other assessors. This is due to lack of description, especially in the report for Troll A. Yme has an own appendix with assumptions; this makes it easy to use as input in a later phase.

All assumptions shall be identified, made visible and communicated to the users of the analysis results, this could be done by clearly and explicitly document the assumptions (Standards Norway, 2010). This is important because the risk analysis is will not be valid unless the assumptions are correct and followed; by a small change in assumptions may the whole analysis be affected. Lack of clear documentation of the assumptions can lead to misinterpretation in modification phases due to that the new assessors do not have the same background knowledge as the original assessor, and thereby understand the assumptions and results differently. However, Troll A is just a CRA for the new modification and the main documentation of the assumptions is in the TRA (Which is not available for this thesis). The original assumption is applicable as long as the installation has not been subjected to any changes that could have affected the assumptions.

In both Yme and Troll A are there lacks of description of what background information that are used in order to identify the assumptions. However, in Yme is it referred to different documents, however it is uncertain for the reader which documents these are and how to find them. It is important that the assumptions are traceable; this is especially important in case of that the person who made these assumptions no longer is available when the installation is subject to modifications. Assumptions play an important role in the results, and if the assumption varies, might this result in that the results differ significantly. Every assumption subjected to changes, these changes may be background knowledge, new module etc.

It seems like the assumptions in these two cases are not adequately verified; there are no descriptions of how deviations from these assumptions could affect the analysis. Every assumptions can make a significant different in both simulations and calculations. It is therefore important to have a thoroughly explanation to how and why the assumptions are made, and which background knowledge the assumptions are based on. Assumptions is often based on historical observations, and it is assumed that the future performance is similar; these assumptions may turn out to wrong. The results will always reflect the choice of assumptions and data basis. Therefore is the background for the given assumptions important; different assumptions may lead to different evaluations and conclusions.

4.1.5. Uncertainties

Risk analysis will always be subject to uncertainties, and it is therefore import to address this aspect. The assigned probabilities and parameters are based on the background information and knowledge of the assessor, and these are subjected with inherent uncertainties. The box below introduces two criteria's that is seen as important when considering uncertainties in a risk analysis, related to the evaluation of the escape routes.

The uncertainties should be;

- *Clearly communicated and documented*
- *Understood*

Yme MOPUstor

The uncertainties in the parameters chosen in the simulations are not discussed. The uncertainties in the assumptions are not discussed as well, some places is it just stated that the assumption are considered to be uncertain and conservative. Uncertainties related to the calculations are not mentioned.

Troll A

The uncertainty related to assumptions, calculations and simulations is not mentioned in the report that is available for this thesis.

4.1.5.1. Comparison

According to NORSOK Z-013 should it be provided a discussion of *uncertainty*, which among others includes; description of used risk perspective, and the effect/level of uncertainty. In both cases used in this thesis was it lack of description of uncertainty. Because risk analysis focuses on decision making under uncertainty, one need a clearly understanding of what uncertainty is (Yoe, 2011). The results will always be subject to uncertainties; this may be due to among others assumptions and the relevance of data. Therefore is it important that the risk analysis communicate the uncertainties in a clear and adequate matter.

In these two cases are the uncertainties related to simulations inputs and parameters in calculations, in addition information used in order to develop the assumptions. As mentioned above is it important to have assumptions that are traceable, this is to reduce confusion and to avoid that assumptions could lead to more unknown uncertainties in later modification phases. It is important to evaluate the uncertainties related to the assumptions and parameters used in the analysis. In Yme is it only stated at few of the assumptions that they are considered to be uncertain and conservative. It should be a further explanation, which include why the assumptions are uncertain and which background information that are used. As mentioned earlier is it important to acknowledge that risk extends beyond probabilities; many assumptions are made, and these have to be reflected and understood in order to be able to understand the probabilities. Thereby use this in order to reach an adequate/best possible solution on for example escape routes. One example may be that calculations used in order to establish the FAR values are estimated by use of many different factors. This lead to relatively high uncertainties in the result, because the calculations are dependent on assumptions made regarding for example personnel involved at any time.

Another aspect that may affect the uncertainty is the background knowledge used in the risk assessment. These factors might influence how a person understand the simulations and calculations, for instance; lack of experience might affect the decision with respect to overlooking important aspects in design of safety (escape routes). One should evaluate if the background knowledge is strong or poor (will be explained under section 5.4).

Uncertainty can also be related to how personnel perceive risk, and how they react when it is time to evacuate. As mentioned earlier will humans be affected in different ways during an emergency situation, this is even though they have the same level of training; 10 – 15 % of the people (statistically) will be totally ineffective, and not react to the situation at all. This is an uncertainty that is not mentioned in the two cases used in this thesis. The importance of this aspect is explained under the discussion of simulations.

4.1.6. Reflection

It is important to understand that this discussion only is based on the two cases introduced in this thesis; the discussion could have been different if it was more than two cases, or two other cases.

The two cases introduced are of different risk analysis status; therefore will these two cases be different when it comes to the analysis performed and its extent. This includes the level of documentation.

Yme is a Total Risk Analysis (TRA) of a new platform, and the escape routes are therefore designed due to experiences from other platforms. However, simulations on fire and explosions have a major role in analyzing if the design satisfies the requirements and RAC. This thesis was provided with the main report and all appendices in the risk analysis. This report was included all documentation used in the risk analysis.

Troll A is a Concept Risk Analysis (CRA) which is used as input to the updated TRA. Troll A does not need all the stages of the analysis, since it is already performed a TRA for the platform. This results in different objectives and perspectives when it comes to escape routes. The main purpose of this analysis was to evaluate if the new installation/module will affect the risk level in any significant ways; where it was only conducted analysis on the new module. The risk level is compared up against the risk levels calculated during the TRA before the modification. This led to that all documentation was not available for this thesis; did not have any documentation except for the risk analysis performed for the modification project.

4.1.7. Summary

The table below is a brief summary of the findings from the discussion above.

Table 3: brief summary of discussion (success criteria)

Success criteria	
Clear description of the installation	• Illustration of the escape routes was sufficient in Troll A, but could have been clearer in Yme. • Main areas was described and illustrated in both cases, but clearer in Yme. • What used escape route design was not mentioned in neither of the cases.
Simulations	• Fire and explosion simulations included in both cases • Evacuation simulations not conducted in neither of the cases • Human behaviors not included in neither of the cases
Calculations	• FAR and PLL values introduced • Impairment of main safety functions mentioned • Traceability of values are somewhat satisfying in both Yme and Troll A
Assumptions	• Lack of description in both cases, especially in Troll A. • Assumptions insufficient traceable in both cases, especially in Troll A. Background information not included clearly.
Uncertainties	• Poorly description of the uncertainty that are present in the values used, in both Yme and Troll A. • No evaluation of uncertainties related to human behavior during an emergency situation.

4.2. Technical aspects

This section will discuss if the requirements regarding escape routes are adequate in order to reach a robust solution. In addition will the relation between escape routes and costs, be discussed and how to evaluate if one should prefer to reduce frequency of undesired events on behalf of escape routes by implement new main areas by use of firewalls.

4.2.1. Requirements

The requirements regarding the design of escape routes are found in NORSOK S-001 and in ISO 13702, and they are mentioned in the theory in this thesis (ref. section 2.7.1.). Some of the requirements regarding escape routes could be interpreted in many different ways, and should have more explanations and guidelines. These will be further discussed in this section.

- *There shall not be any **dead-end corridors** that exceed 5 meters in length* (Standards Norway, 2008).
    - The legislations do not have a clearly definition of where these 5 meters starts. This may lead to that the oil companies design and interprets them differently.
    - There are no explanations as to why the requirements are set to be 5 meters; would the risk increase significantly if it was set to be 6 meters?
    - However, the regulations recommendation of 5 meters seems reasonable on the basis of the philosophy that the route out from a closed area with only one entrance shall permit an efficient escape if necessary. The distance seems reasonable if one is to set a limit at a certain number of meters.
        1. Maintain an effective escape as possible
        2. Dead ends can easily lead to personnel escaping in the wrong direction if the distances are so great and complex
        3. If thick smoke occurs, may it be difficult to find the right direction if the distance is too long.
        4. It is important to ensure that the evacuation time is as short as possible and therefore must facilitate regulatory framework that ensures this.

- *There shall be at least* ***two exits to escape routes****, leading in different escape directions* (Standards Norway, 2008).
  - ➢ It is not stated how this shall be done, this may lead to that a lot of responsibility is placed in the designer. If the designer does not have adequate experience and background knowledge could this lead to adequate design of the escape routes.
  - ➢ A minimum requirement to the escape length is not mentioned. In theory, according to the requirements, can the escape route involve as many main areas as possible as long as the personnel reach the safe place before the escape routes collapses or become intolerable for personnel.
  - ➢ However, the regulations recommendation of two escape routes, leading in different directions seems reasonable on the basis of the philosophy that the escape shall be as effective as possible and that all personnel should be able to escape.
    1. Maintain higher possibility to escape
    2. Maintain an effective escape as possible
    3. There is a higher probability that there will be at least one escape route available, therefore will the possibilities for escaping the area be higher.

- *The* ***dimension of escape routes*** *shall be minimum 1m width, and 2.3m in height. Escape routes intended for use by more than 50 persons shall be extended to 1.5m in width* (Standards Norway, 2008).
  - ➢ These requirements are straightforward and cannot be misunderstood and interpreted differently from person to person.
  - ➢ The regulations recommendation seems reasonable on the basis of the philosophy that the escape shall be as effective as possible and that all personnel should be able to escape.
    1. Make it possible to emphasize easy transportation of injured personnel
    2. Maintain an effective escape as possible
  - ➢ ISO 13702 have some additional requirements, that is not stated in NORSOK S-001, it seems like NORSOK S-001 is stricter than the ISO 13702. In ISO 13702 is it states that for routes which are unlikely to be used frequently a reduction in this width may be acceptable (IHS, 1999).

Another aspect related to the legislations is that it is not any requirements or guidelines regarding how to **choose type** of escape ways. However, it is stated in ISO 13702 that the escape routes should be design to remain passable by position rather than special protection.

Khan & Amoyette (2002) provides an example regarding selection of escape route design. This example is related to how to design in order to minimize impairment on escape routes due to incidents associated with risers and gas compression and separation facilities.

They state that it is fundamental philosophies applied to the provision of escape routes:

(i) fully enclosed tunnels,
(ii) protected open walkways.

According to Khan & Amoyette (2002) has past studies indicated that both philosophies can be applied successfully. However, it is indicated that the protected walkways are more inherent safe; this is because there are no reliance on mechanical systems. A fully enclosed tunnel requires a pressurization system to achieve a similar performance level as that mentioned above for protected walkways. This reliance on an active system cannot be considered as inherently safe as a system reliant on only passive components. However, in certain scenarios a fully enclosed pressurized tunnel may be a more appropriate alternative. Therefore, as with all proposed risk reduction methodologies, there is a need for a case-by case evaluation (Khan & Amyotte, 2002).

4.2.2. Escape routes vs. main areas

In some cases may the question be to reduce the main areas in order to reduce probability of generation of large gas clouds and reduce the ignition sources. However, this may affect the main safety functions, especially the escape routes in a negative way.

One example is provided in Figure 26, where MA-C is divided in two main areas (illustrated by the color lilac). A main area shall be separated either by distance, by use of physical barriers or by combination of these; in this case represent the lilac line a firewall.

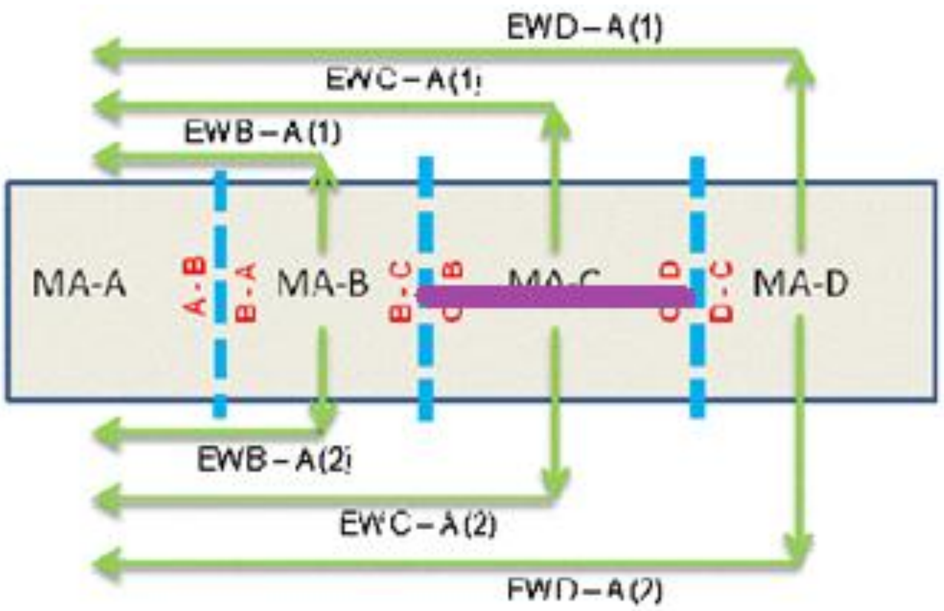

Figure 26: Example escape routes vs. main areas (figure adopted from NORSOK Z-013)

This new partition of the main area lead to that the leak frequency is split between two areas, and thereby reduce the probability for ignition of a gas-cloud and for a larger explosion. However, this amendment reduces the opportunity for an effective escape if an undesired event should occur. The impairment of the escape routes is increased, but the impairment does not exceed the criterion which is set to be 1x10-4.

Is it “right” to reduce the frequency at the expense of escape routes?

As stated in NORSOK Z-013, and highlighted by Jan Erik Vinnem through e-mail, is escape ways impairments calculated for each area, so this does not give any punishment from impairment. It could be possible to reach satisfying escape routes according to requirements, and make this change with the main areas.

If the platform in this “dilemma” has a stair tower on the eastside of the platform (right side), and a few horizontal fire divisions could it possible to create two independent escape routes which will satisfy the requirements. One of the escape routes will be the original escape route leading directly to the safe place (main area A). Whilst the new escape route may for instance be into MA-D, and thereby go up/down a stairway and under/over a horizontal fire division and thereby escape Westover to MA-A. This escape route is a longer escape way than the original escape way, and is not a robust solution (the escape takes longer time, more vulnerable to smoke/radiation). However; this solution satisfies the requirements which state that the main area shall have two escape routes, leading in different directions.

Even though the escape route will be longer, one should prioritize to divide the main area in two- unless if it is indicated that the potential explosion pressure might increase substantially. However, if the deck possessing a process area and if it is a deck over the studied main area, will the solution to divide the main area in two be a bad idea. This is due to that it would be expected poor natural ventilation, and poor ventilation results in high explosion pressure and higher possibility for an explosion to occur.

Another aspect to evaluate in this “dilemma” is the frequency reduction versus the cost of implement the new firewall, this is done by the use of the ALARP principle. The ALARP principle fundamental is to reduce all risks to a safety level that is as low as reasonable practicable. Unless it is illustrated that the cost is grossly proportionally to the benefits gained.

In order to evaluate if one should implement the new firewall is it several factors that needs to be taken into account. One have to conduct an assessment of the risks that needs to be avoided and an assessment the sacrifice involved in taking measures to avoid that risk. Thereby compare these two assessments. Even though the risk level is demonstrated to be low does not this mean that it is not reasonably practicable to reduce it further; the basis on which the comparison is made involves the test of ‘gross disproportion’. This could be done by the use of cost-benefit analysis (which is not included in this thesis).

Clearly, the balance between benefits in terms of reduced risk and the costs of control measures will play a part in achieving and justifying ALARP. For example, if a control measure has a benefit that greatly outweighs the cost, this control measure would almost always have to be implemented, or very good reasons provided for not doing so. In contrast, if the cost greatly outweighs the benefit, demonstrating that the control measure is not appropriate is straightforward, as other options will almost certainly exist that are able to achieve a similar level of risk reduction at lower cost. If benefits and costs are both high, or are both low, more careful consideration may be required before selecting or rejecting control measures (NOPSEMA, 2012).

It is not an easy decision to decide whether one should prioritize the escape routes or the division of main areas. It is many factors that need to be taken into account, which this example tries to explain. Therefore is it important to evaluating every aspect; and the prioritizing will therefore be different from facility to facility.

5. Recommendations/ improvement potentials

After analyzing the risk analysis reports in the two different cases, have the reader acquired an overall understanding on how a risk analysis is demonstrated in the oil industry with respect on escape routes. This chapter will introduce some improvements potentials, related to how escape routes should be evaluated in a risk analysis.

However, it is important to state that the improvement potentials that are introduced in this chapter only are valid for these two cases and it could have been different if other cases where used.

5.1. Human behavior

It seems like human behavior during emergency situations are negligible in the performed risk analysis for Yme MOPUstor and Troll A. This is an aspect that is important to understand in order to be able to design robust solutions for escape routes. An escape route can be adequate in a normal situation, but when an abnormal or emergency situation arise will many aspects influence how personnel will react, and thereby might the escape routes be less efficient than assumed. By understanding human behavior, and take this aspect in account in the risk analysis may it be possible to estimate the time to egress more accurate. In addition is it important to use human behavior in relation to design the emergency plan.

As mentioned earlier; human will react differently in an emergency situation then in a normal situation, it is also suggested that people do not respond in the same way in one circumstance, as they do in another. This may indicate that humans act according to how they adapt to both a situation, and the location (Kobes, et al., 2010). People will also react different to the same situation i.e. the reaction is based upon background, training, and experience and so on. It is indicated that personnel will react within three different groups (Brooks, u.d.);

- 10 – 15% will manage to formulate good decisions.
- 75% will act in an automatic nature, but more slowly as a result of the shock and amazement of the present situation.
- 10 – 15% will be totally ineffective; paralyzing anxiety, confusion, and screaming etc.

However, at present, our knowledge of occupants' performances when confronted with fire and other emergency situations are still very limited (Kobes, et al., 2010). This is due to difficulty in predicting how human will behave; there are a lot of uncertainties involved and every person will react differently (as mentioned above).

However; Figure 27 indicates how important human and organizational factors are in relation to EER performance. It is therefore need for further studies in order to be able to predict how personnel might react, and to involve human behavior in the evaluation of escape routes design.

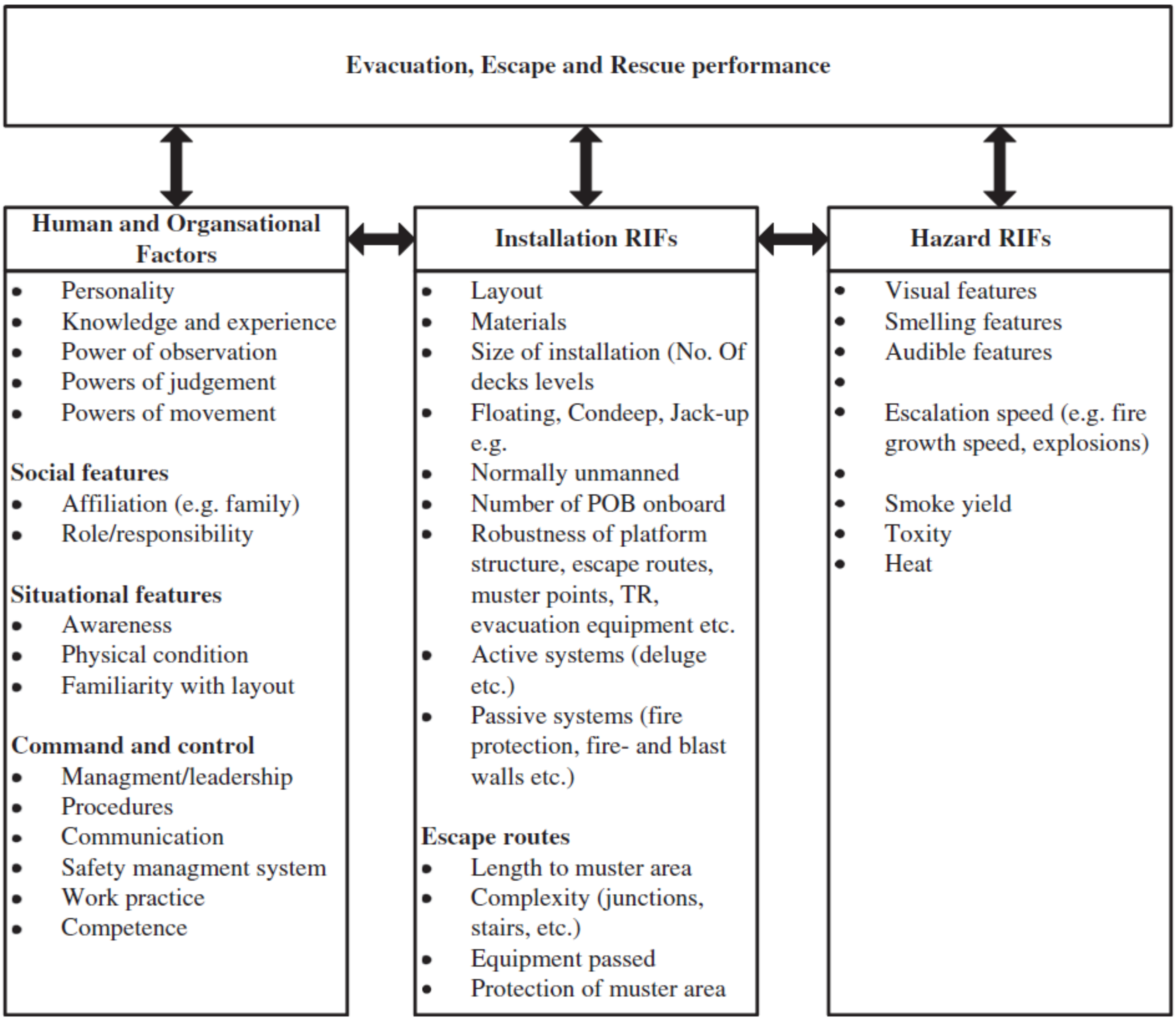

Figure 27: EER Performance, partly based on kobes et al. (2010) (Skogdalen, et al., 2012)

5.2. Evacuation simulations

Simulations of evacuation are somewhat related to the improvements potential that discuss more focus on human behavior. This kind of simulations are not performed in any of the two analysis evaluated in this thesis. This might be due to that there are no requirements regarding performing such simulations. However, one should evaluate these simulations in relation with the human behavior.

As mentioned earlier might simulations of evacuations indicate the durations from an undesired event is discovered and to all personnel are evacuated to a safe place. When one conducts such simulations is it possible to see if there are any places where the escape routes have a congestion effect (illustrated in Figure 28). This might indicate where it is need for any adjustments, or where the escape routes have potential for improvements.

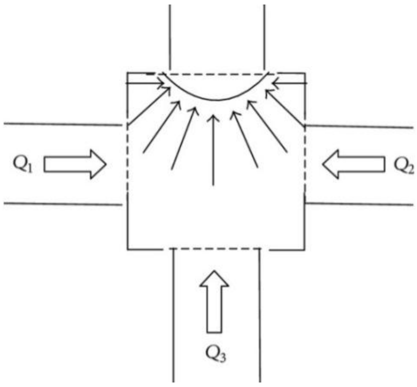

Figure 28: sketch of typical congestion (Huang, et al., 2013)

By simulating evacuation is it possible to design in order to limit the probability of fatalities. One example may be the fire in 1998 in a disco in Gothenburg, Sweden. Numerous bodies were found at and around the entrance to the available staircase (Gwynne, 2007). Evacuation simulations could have indicated that there was a need for more escape routes, or wider escape entrance, and that it would be congestion if one of the escape routes were blocked.

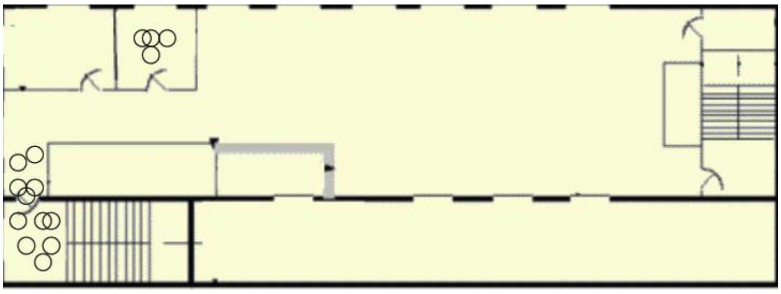

Figure 29: Evacuation simulation, Gothenburg Disco in Sweden (Gwynne, 2007)

5.3. Assumptions should be traceable

Assumptions are a necessary condition in order to achieve the results one need. All models are subject to a number of qualitative assumptions, in risk analysis are these assumptions often made in order to fill the “gap” from lack of “hard” data. The risk analysis is only valid as long as the assumptions are valid; a small change in the installation conditions may lead to that the risk analysis provides an insufficient picture of the real world. This is because the analysis always should be seen in light of the assumptions that are made.

As mentioned earlier is it important to have assumptions that are traceable. Different analysts could come up with different values, depending on assumptions and presuppositions. The made assumptions should have a clear description of the background knowledge used in order to identify the assumptions. This can be done by describe it directly in the risk analysis, or to refer to a document that are easy to access. Assumptions should also be subject to a sensitivity study in order to illustrate how changes in the assumption would affect the results, and the robustness of the assumption discussed. The assumptions may to a greater or lesser degree constitute uncertainty factors in the sense that the assumptions might not be valid. If assumptions turn out to be wrong, the result could be that the actual outcome of a predicted quantity is surprising relative to the assigned probabilities (Aven & Flage, 2009).

Vinnem (2010) provides an example of the importance of traceable and explained assumptions in a risk analysis; In a LNG plant was it assumed that a gas release from an LNG tanker, resulted by a collision with passing vessel, would be ignited immediately due to sparks generated by the collision. This assumption made it unnecessary to consider how the gas cloud would spread by the wind and heating of the liquefied gas (in order to find scenarios the public might be exposed to). However, no explanation was provided of how such ignition of a very heavy and cold gas could occur physically. The risk analysis was in this case used to ‘prove’ that it was not necessary to follow the US practice for safety zones. The analysis rested on the subjective assumptions about leak rates, leak durations and an optimistic assumption that all safety systems would always function as intended. Which lead to an implementation of a safety zone that was, by many, evaluated as severely insufficient. However, later did an updated QRA study confirm that the risk level for the public had increased substantially, by a factor of more than 50 for accidents with at least 100 fatalities (Vinnem, 2010, p. 666).

5.4. Background knowledge

It is important to recognize that the description of risk depends on the background knowledge of the analyst. All probabilities are conditioned on the background knowledge that we have at the time we quantify our uncertainty. The background knowledge covers among others assumptions and presuppositions, and knowledge about the phenomena involved (Aven, 2012). If the background knowledge changes, might the probability assigned also change; this indicates that the background knowledge is the basis for an assigned subjective probability. However, it is important to state that for a given background knowledge the probability is not uncertain (Aven & Flage, 2009).

Since the background knowledge includes assumptions and suppositions, and may therefore hide uncertainties is it essential to describe which background knowledge that the probabilities are based on. This is because probabilities must be seen in relation to the background knowledge in order to interpret it correctly.

Another aspect that is important to describe is if the background knowledge is considered strong or poor. Strong knowledge is referred to as small or a low degree of uncertainty, whilst poor knowledge means large or a high level of uncertainty (Aven, 2013). Aven (2013) mention two different approaches in how to evaluate the strength of the background knowledge. These will be briefly mentioned below (Aven, 2013, pp. 138-139).

Method 1:

This method is based on crude direct grading of the strength of knowledge.

The knowledge is weak if one or more of these conditions are true:

a) The assumptions made represent strong simplifications
b) Data are not available, or are unreliable
c) There is lack of agreement/consensus among experts
d) The phenomena involved are not well understood; models are non-existent or known/believed to give poor predictions

The knowledge is strong if all of these conditions are true

a) The assumptions are seen as very reasonable
b) Much reliable data are available

c) There is a broad agreement/consensus among experts
d) The phenomena involved are well understood; the models used are known to give predictions with the required accuracy

Method 2:
This method is based on an identification of all the main assumptions on which the probabilistic analysis is based. These assumptions are converted to a set of uncertainty factors. The idea is to perform a crude risk assessment of the deviations from the conditions/states defined by the assumptions. Thereby assign a risk score for each deviation, that represent its implication on the occurrence of the event A and their consequences C.

A quick and very rough way of carry out this crude risk assessment is to use the same criteria's (a-d) as in method 1. The strength of knowledge is weak if several of the criteria's is considered true; then the assumption deviation risk is set to be high. The strength of knowledge is considered high if the assumptions deviation risk is set to be low.

5.5. Broader focus on uncertainty

The decision support is based upon how the risk is interpreted by the assessor, and as of today is normally the (A,C,P)-perspective used in Quantitative Risk Analysis. As mentioned earlier may this perspective hide uncertainties and/or the assessors not express the uncertainties sufficiently. Uncertainties may be understood as lack of knowledge about unknown quantities (Aven & Flage, 2009).

There are uncertainties related to;

- Event (A), uncertainties related to if the event will occur, when it will occur and how it will occur.
- Consequences (C), uncertainties related to what the consequences will be.
- Probability (P), uncertainties hidden in among others assumptions, and background knowledge.

Probability is a subjective measure of uncertainty, conditional on available background information and knowledge P(A|K). The background knowledge could be based on hard data and/or expert judgment. This means that a probability always are conditional on the background knowledge, and given this background knowledge there is no uncertainty related to the assigned probability, as it is an expression of uncertainty. However, as mentioned above are the assigned probabilities conditional on specific background knowledge, and they could produce poor predictions. Surprises relative to the assigned probabilities may occur, and by just addressing probabilities such surprises may be overlooked (Aven, 2009). As mentioned earlier in this thesis is it a common tendency of underestimate the uncertainties in A QRA. This causes difficulties when it comes to communicating what the analysis results mean, and could easily lead to weakened conclusions if large uncertainties are involved.

It is therefore preferable to use an approach that has more focus on the use of uncertainties and express them adequately, instead of focus on the probability. Aven (2010) states that uncertainty is a more fundamental concept than probability and should be the pillar of risk; Probability is just a tool used to express the uncertainties and does not capture all aspects of concern, and the uncertainties beyond the probabilities should be taken into account (Aven, 2010; Aven, 2009).

As mentioned earlier does Aven (2008) defined risk [(A,C,U) perspective] as the two dimensional combination of

i) events A and their consequences C, and
ii) the associated uncertainty U about A and C, including uncertainty about underlying phenomena influencing A and C.

A risk description based on this definition would cover the following components (Aven, 2011):

Risk description = (A, C, U, P, K)

That is, risk is described by events A and consequences C, knowledge-based probabilities P, uncertainties U not captured by P, and K the background knowledge that U and P are based on. This description covers probability distribution of A and C, as well as prediction of A and C. The U may for example be a qualitative assessment of uncertainty factors, such as assumptions the probabilities are based on (Aven, 2011).

However, the use of the (A, C. P) perspective is easier to understand for those that need to review and conduct the risk analysis, compared with the (A, C, U) perspective. In the (A, C, P) perspective is the uncertainty embedded into the event and consequences. The probability reflects the uncertainties in the consequences and the likelihood of the event, but as mentioned earlier will there be inherent uncertainties that is not considered in an (A, C, P) perspective.

6. Conclusion

This thesis has evaluated how escape routes are taken into account in two different the risk analysis. This is done by the use of five success criteria's. The research indicated that there were some improvement potentials for how to evaluate escape routes in the risk analysis in order to reach a robust solution. However, it is important to remember that these improvement potentials was based on two cases, and might therefore not be applicable for other analysis. There are few requirements regarding how escape routes shall be evaluated in risk analysis in the legislations.

The figure below illustrates the five improvement potentials identified in this thesis.

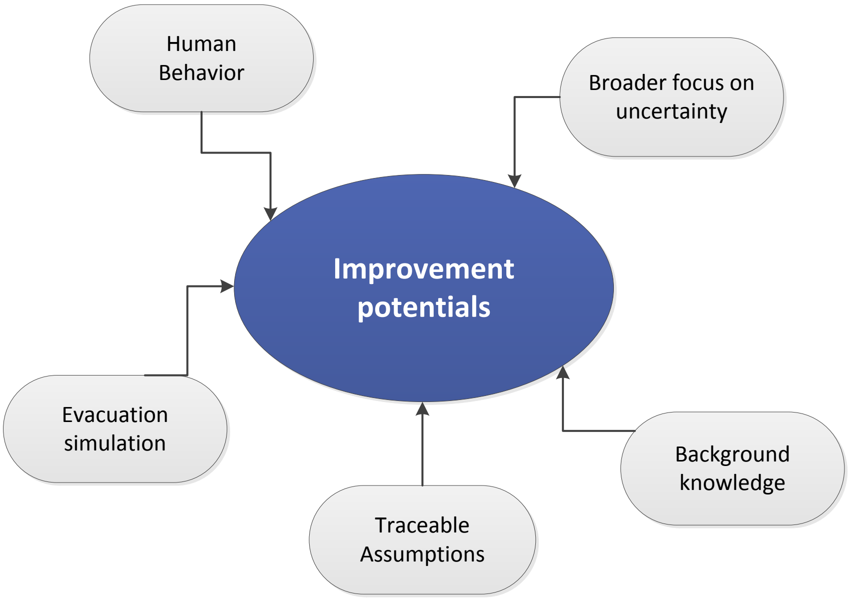

Figure 30: Improvement potentials

Some of the requirements regarding escape routes could be interpreted in many different ways, and should have more explanations and guidelines;

1. dead-end corridors
2. two exits to escape routes
3. how to choose the type of escape routes design (not mentioned in legislations)

6.1. Reflection

During the writing process have I identified that the thesis could have been organized differently.

I could have used the success criteria’s as a starting point of the thesis, instead of introducing them in the discussion. Then I could had linked the theory directly to the success criteria’s and used the cases in order to support and supplement the criteria’s. This way would the main focus on the thesis be on the mindset of the risk analysis rather than the framework.

In addition would it have been preferable to evaluate more than two cases, this would have resulted in a more extensive comparison. Should maybe had one QRA, one TRA and one CRA, in order to evaluate the “whole” spectrum.

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Appendix A: Quantitative Risk Analysis Process

Establishing the context

According to NORSOK Z-013 is the objective of this phase to define the basic parameters and to set the scope and criteria for the rest of the process. In this phase the objectives, scope and responsibility will be defined by the operators. Whilst methods, models and tools to be used will or might be defined by another company. A crucial part of this phase is to define the limitations of the study, in addition should risk acceptance criteria and system boundaries be defined.

Hazard identification

A hazardous event is an event that will bring, if it occurs, the system or installation into a condition with higher risk or fewer barriers against further escalation and significant damage.

Identification of hazards is critical, and should be comprehensive and thorough. This phase should include all hazards (everything that can go wrong), whether or not they are considered to be under control of the organization. In this phase shall also the sources of the hazards be identified, and an identification of risk reducing measures be conducted. It is also important to classify hazards that may be relevant for an emergency preparedness analysis (Standards Norway, 2010).

Quantitative analysis of initiating events

In this phase shall potential causes of initiating events be analyzed and identified, and the probability of the event shall be assessed. Factors for consideration may be for instance available safety barriers and design standards (Standards Norway, 2010).

Quantitative analysis of potential consequences

According to NORSOK Z-013 this phase shall assess possible outcomes that may contribute to the overall risk picture. One shall determine the influence of the performance of barriers, the magnitude of the physical effects and the extent of damage to personnel, environment and assets.

Establish risk picture

In this phase useful and understandable information of the risk assessment shall be communicated to the decision makers. The presentation shall be clear and balanced, and the methods and tools used shall be verified. It is important that the risk picture is understandable for all relevant personnel, and that all risk exposures are ranked, and that uncertainties are discussed. Sensitivity analysis shall be carried out, here shall the most important assumptions and aspects be identified. Fatality risk contributors shall be considered and calculated when possible, this may include; escape fatalities, evacuation and rescue fatalities. When required shall the probability of loss of main safety functions be established (Standards Norway, 2010).

Risk evaluation

In this phase shall a basis for decision-making be established, this includes an expression of risk as a cumulative frequency for all consequences. All possible risk reducing measures shall be identified, including; measures that provide inherently safer design, reduce the possibility of occurrence of accidental events and so on.

Appendix B: Emergency preparedness Assessment Process

Feil! Fant ikke referansekilden. shows the Emergency preparedness process in relation to input from the QRA;

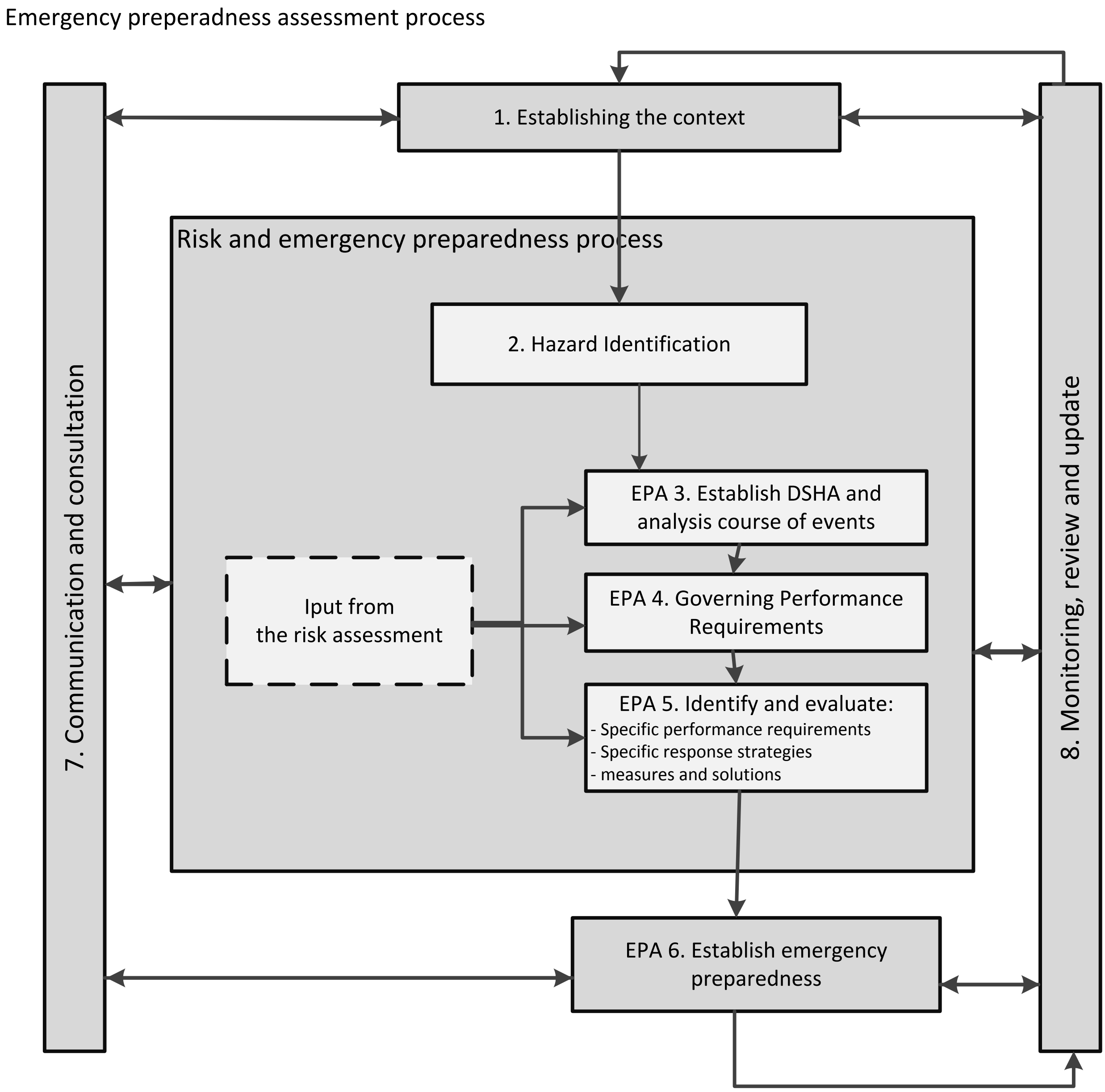

Figure 31: The process of performing an emergency preparedness assessment (Standards Norway, 2010)

Establishing the context:

This phase shall establish the basic parameters (objectives, scope, responsibilities, required competence etc.), and it is important to use input from the QRA. This includes assumptions made in the QRA, which may influence the EPA. This phase should also identify the overall emergency preparedness philosophy (Standards Norway, 2010).

Hazard identification:

This phase has the same requirements as under the QRA, however; only hazards relevant for the emergency preparedness analysis process should be used (Standards Norway, 2010).

EPA 3, establish DHSA

This phase shall establish DSHA and analyze course of events. According to NORSOK Z-013 shall this phase select and describe the DSHA's that reflect the analysis object(s) and operation in question. Each DSHA should get a description, and major accidents identified in the QRA; this includes dimensioned accidental events (Standards Norway, 2010).

EPA 4, governing performance requirements

This phase shall identify governing performance requirements for emergency Preparedness, where the company performance requirements shall be the starting point for the analysis. The list of the governing performance requirements shall be in accordance with the operator overall emergency preparedness philosophy, in addition to relevant requirements from authority regulations (Standards Norway, 2010).

EPA 5, Identify and evaluate

The objective in this step of the EPA is to identify and evaluate the need for specific requirements and emergency preparedness measures, and to establish emergency response strategies. This analysis shall give input to emergency preparedness solutions; this includes escape routes, equipment for rescue of personnel, means and evacuation and so on (Standards Norway, 2010).