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Abstract

The Norwegian risk management approach for offshore installations requires that risk analysis shall provide a basis for making decision on the design accidental load that shall be used in the design to avoid major accident risk. One of the major risks on offshore installations is explosion risk. An explosion involves interaction of many variable uncertain parameters. Explosion risk assessment is a complex process which involves a range of analyses with uncertainties. As a part of risk analysis, dimensioning accidental load for explosion is determined using a probabilistic explosion assessment as described by NORSOK Z-013 and comparing the results with applicable risk acceptance criteria. Dimensioning accidental loads determined as above provides decision support in establishing design accidental loads that are considered to be valid throughout the installations lifetime.

Design accidental loads are established in the early phase of the project. A decision needs to be taken at the initial phase of the project where sufficient information to determine the real picture is not available. Currently no clear guidance exists in the industry on how the design accidental loads are selected based on DAL determined by the risk analysis.

Different views exists across the industry whether to consider modifications into account in establishing design accidental load. The influence of minor modifications on DAL during the operational phase is discussed. Minor modification projects, not individually considered to have significant impact on the total risk level, but together and over time result in significant increase in risk level.

Petroleum safety authority’s updated definition for risk as “the consequences of the activities, with associated uncertainty” demands increased focus in the way the uncertainty is presently handled in the risk analysis. Current offshore risk assessment process uses (A, C, P) perspective and describes risk using probabilities and expected values for the decision making and no account for the uncertainties hidden in the analyst's background knowledge is given. This may bring surprises when the knowledge used in the analysis is weak.

The decisions following this approach and comparing with risk acceptance criterion may lead to accept the results irrespective of its robustness. This means a lean disproportionate weight is given to further risk reduction process like ALARP (As Low As Reasonably Practicable). Safety decision contexts require different decisions with respect to uncertainties. In case of high uncertainties measures following cautionary principle are normally implemented.

In reducing the risk beyond minimum acceptance criterion following ALARP, current practice uses cost-benefit analysis where a single grossly disproportionate criterion is used for all decision contexts. This way the ALARP principle turns out to be static. To be an appropriate principle in safety context, ALARP should be dynamic in the sense that ranges from one extreme, where decisions are made following only cost benefit analysis in some decision contexts, to another, in which the cautionary principle is adopted with no reference to cost-benefit analyses for others.

A new method to achieve an improved decision on design accidental explosion load with some changes in the current practice to comply with risk reduction principles outlined in in the Framework regulations §11 is established. This method follows (A, C, U) perspective that holds uncertainty as a main component of risk and use both risk acceptance

criteria and ALARP principle in establishing design accidental explosion loads taking uncertainties. In the suggested approach probabilities are only considered as tools that describe the epistemic-based uncertainty factors i.e. factors that could cause surprises relative to the assigned probabilities and expected values. The uncertainty factors related to the applied knowledge will be identified and assessed for its influence on the total risk following a semi-quantitative method. In addition to the uncertainty factors assessment, guidelines need to be established by the decision maker to decide the decision context that shall be applied to implement ALARP.

The suggested method is expected to improve the ALARP by making it dynamic and optimise the margins in the design accidental loads by uncertainty analysis of the parameters. The method is elaborated in detail for a decision problem related to explosion event and a case study is presented wherein the principles of the suggested method is applied.

Preface

This thesis has been written during spring 2016, as a requirement to my master's degree in offshore technology in the specialization of Risk Management at the University of Stavanger. Doing a master study after few years of industrial experience is both exciting and demanding. Indeed, this provided me a valuable insight on present on-going research in the areas of risk and uncertainty management for the challenges faced by the industry.

The challenges that I came across at my industrial work and the theoretical knowledge gained during this master programme challenged me to discuss about the practical issues associated in establishing the design accidental loads and its suitability to maintain the risk level on the installations as per authorities' requirements. The selected topic demanded communication among the operator, engineering contractor and risk analyst consultants. The discussions that I have had with them are valuable experience through which I have gained increased insights into the Norwegian regulatory system and how it has been handled at current practice across the industry.

I would like to thank my supervisor at the faculty, Professor Eirik Bjorheim Abrahamsen, for his valuable guidance during the discussions. I would also like to thank Dr.Knut Eirik Gilyarhus, Senior consultant and Raymand Nedland, Principal consultant at Lloyd's Register consulting for guiding me on the task by sharing their invaluable experiences and suggestions in making this thesis complete.

Further I would like to thank Line Johansen (Conocophilips Norway) who helped with her colleagues, by sharing their knowledge and answering relevant questions. I thank my colleague Dr.Andrew Fitch (Aibel) for sharing his experience through discussions and providing suggestions to the report and my lead Ana Maria (Aibel) for her approval related to case study in this thesis. I would like to thank Dr. Hari Bhagwan Kanegaonkar (Aibel) for his support through review and feedback to improve the quality of the thesis.

I would like to thank Dr.Amutha Ramachandran, my lovable wife, who supported my initiative on this study and encouraged me throughout the program, especially relieving me from the family commitments. This section cannot be ended without addressing two smartest princesses Preethi (6 years) and Jeiswagathi (2 years), my very lovable daughters, for their joyous at me that boosted to find the time to complete this program successfully. I would like thank the Almighty and my father (late) without his generous love and blessings this intensive work would not have become possible.

Stavanger, June, 2016
Krishnasamy Chinnusamy

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 General

All activities have risks and it is never been practically possible to eliminate them completely but to accept at a level. The use of risk analysis to estimate the risks in the oil and gas industry is increasingly important. In the Norwegian offshore oil and gas industry, risk analyses have been in use for more than three decades and play a major role in the design of safer installations. Risk analysis among other inputs to the installation design provides information to decision making process during all phases.

The risk analysis, namely quantitative risk analysis (QRA) for a new installation is normally being carried out well ahead of design phase. A completed installation comprises of different modules, complex set of geometric elements, different equipment, large amount of piping in various sizes, etc., and limited information is available at the early stage in order to use in the risk analysis.

Despite the lack of detail and information, the risk analysis shall provide input to the design loads that form the basis for installation design. Hence, necessary information for the analysis is taken from similar installations from the past, available statistics for the events worldwide or the region, etc. The dimensioning events, for example, explosion, fire, dropped object, etc., are determined, which form the basis to establish dimensioning accidental loads (DALs) for the accidental events (NORSOK, 2010).

1.2 Background

Currently no clear guidance exists in the industry on how the design accidental loads are selected based on DAL determined by the risk analysis. A discussion with operator staff and QRA specialists indicated that there is no stipulated guidance on the selection of design accidental loads from the DALs calculated through risk analysis (Chinnusamy, 2016).

DAL is defined as "an accidental load that a function or a system shall be able to withstand for a given period of time to meet the defined acceptance criteria for risk" and design accidental load as "accidental load used as a basis for design" (PSA, 2015a).

According to NORSOK Z-013 (NORSOK, 2010), the applied design accidental load may sometimes be the same as the DAL or more conservative based on other input and considerations such as ALARP (As Low as Reasonable Practicable) i.e. the design accidental load may be more severe than the DAL (NORSOK, 2010).

Along with QRA results, DAL, typically with an annual frequency of $1x10^{-4}$ is communicated to the decision maker. The decision maker decides on the design accidental load that shall be used in the design. Following the decision, a design accidental load specification is prepared including loads that shall be used for designing and operating the installation, systems and equipment.

Cost plays a major role in deciding the design accidental load to be applied for the installation design. The operator or engineering contractor normally set a margin to cover the uncertainties and to ensure that the implemented design accidental load is equal to or higher than as-built dimensioning accidental loads. A discussion with an engineering contractor identifies that in the field development projects, no allowance for future modification is normally considered while selecting the margin, unless it is specifically asked by the operator (Chinnusamy, 2016).

1.3 Problem description

One of the major risks on offshore installations is explosion risk. Preventing escalation of an explosion is of prime importance. The assessment of the explosion risk is a complex process. The probabilistic analysis used in the assessment is a collection of statistical models, geometrical models and physical models and the outcome of these models interact together to produce a result of interest. Due to complex nature of the event, an explosion risk analysis is based on several assumptions and thus produces results with uncertainties.

The present work sets out to understand how uncertainties are accounted for in establishing the design accidental explosion load following DAL. Influence by minor modification projects on early phase DAL is discussed to show their importance in establishing design accidental explosion load. To approach the problem effectively, the focus include suggesting a suitable approach to establish design accidental explosion loads taking these uncertainties into account.

1.4 Purpose

The purpose of this thesis is to address the following:

1. To discuss and understand uncertainties in the establishment of DAL for explosion and its influence by minor modification projects.

2. Suggest an effective method following ALARP principle that will take uncertainties into account in establishing design accidental explosion load.

1.5 Limitations

This thesis aims to discuss the above mentioned topics for fixed installations on Norwegian Continental Shelf (NCS) and based on current applicable regulations. Where applicable, authors experience, knowledge gained from discussions among operators risk management staffs, colleagues, and external supervisors from Lloyds register consulting is used in addressing the uncertainties and describing risk level of existing installations in this thesis.

1.6 Report structure

The remainder of the thesis is structured as follows: Chapter 2 contains theoretical background from literatures and regulations on risk perspectives and risk reduction principles. An overview of gas explosions, how design accidental load is established and uncertainties in the explosion risk analysis is explained in chapter 3. The parameters influencing the design accidental load is discussed in chapter 4 followed by need for alternate methods to take uncertainties into account in chapter 5. New method to establish design accidental explosion loads is described in chapter 6. A case review with new method in done in chapter 7 followed by discussion in chapter 8. Finally a conclusion and suggestion for further work in chapter 9. Appendix provides the summary of discussions had with operator, engineering contractors and risk analysts on this topic.

1.7 Abbreviations

ALARP	As Low as Reasonable Practicable
CFD	Computational Fluid Dynamics
DAL	Dimensioning accidental load
DAE	Dimensioning accidental event
FAR	Fatal accidental rate
FEED	Front End Engineering Design
HC	Hydrocarbon
JIP	Joint Industry Project
LEL	Lower explosive limit
NCS	Norwegian Continental Shelf
NORSOK	Norsk Sokkels Konkuranseposisjon
P&ID	Piping and Instrumentation diagram
PLL	Potential loss of life
PSA	Petroleum Safety Authority
QRA	Quantitative Risk Analysis
RAC	Risk Acceptance Criteria
RRM	Risk reducing measure
UEL	Upper explosive limit

2 Theoretical Framework

Offshore operations involve many risks. One of the most devastating events is an explosion. An explosion risk assessment is a complex process that involves many uncertainties (Vinnem, 2007).

This chapter gives the reader an overview of different risk perspectives that deals with uncertainties, the risk perspective currently followed in Norwegian offshore industry, authorities' choice for safer installations, industry current decision making practice on risk reduction approach and regulatory needs following ALARP approach. While describing industry practice, focus is limited to explosion.

2.1 Literature survey

The starting point for the current thesis is from the authors experience on installations where DAL has exceeded the design load of the installation in its life time. The DAL is established using risk analysis and decision maker decides the design accidental load taking various factors into account including uncertainties.

The literature survey on this topic among other articles resulted in a similar thesis (Matland, 2013a). This thesis discuss on the confusion due to switched use of terms dimensioning accidental load and design accidental load across the industry. Discussion includes how Petroleum Safety Authority's (PSA) updated risk definition *(Risk means the consequences of the activity with associated uncertainty)* may impact the current way of establishing accidental loads from explosions and fires. Further methods to establish accidental loads that will be in compliance with risk definition in PSA's framework regulations have been suggested. To avoid confusion due to switched use of terms, it suggested to define both terms similarly as "an accidental load/action that a facility or an installation shall be able to withstand for a defined period of time" and maintain a single term.

2.2 Risk perspectives

There are different concepts of risk in professional and scientific contexts. Risk is understood as an expected loss (Willis, 2007), combination of the probability of occurrence of harm and the severity of that harm (NORSOK, 2010), combination of probability of an event and its consequences (ISO, 2009), a combination of events/consequences with associated uncertainty (Aven, 2008a) etc. Some common definitions can be found in (Aven, 2008a). The common element in all risk definitions are events (A) and consequences (C).

These different views can be grouped into two main perspectives (Aven, 2011), namely (a) based on probabilities and (b) based on uncertainties. Recent literatures questions on the effectiveness of probability based which uses only probabilities and expected values in describing uncertainty, in providing the real risk picture (Aven, 2008a; Flage & Aven, 2009).

2.3 Probability based risk perspective and risk description

A probability is interpreted in two ways namely a relative frequency perspective and Bayesian perspective (Aven, 2011)

2.3.1 Relative frequency perspective

The risk (R) based on probability (P) is described as below (Aven, 2011):

$$R = (A, C, P)$$

Where, A represents the events, C the consequences of "A", and P the associated probabilities of events P(A) and consequences P(C).

In this description, P(A), the probability of an event "A", is the relative fraction of times the event "A" would occur if the situation analysed were hypothetically repeated an infinite number of times. This is called as the relative frequency interpretation method.

The value of P(A) is not known and need to be estimated. Risk analysis uses models and simulations to repeat the situations hypothetically and determines the estimate P*(A). It is not known how closer the estimate P*(A) to the true value of P(A) that is unknown.

2.3.2 Bayesian perspective

In Bayesian perspective, no true value exists for an event to occur. Probability of an event P(A) is a measure of uncertainty about occurrence of event "A" seen through the eyes of the assessor and based on some background information and knowledge (Aven, 2008a).

Let us consider that the probability for event A to occur is 10%. In this approach, there is no uncertainty in the assigned probability as it expresses the analyst's degree of belief about the event "A" based on the background knowledge. This subjective probability can be related to drawing a particular ball out of an urn consisting of 10 balls (Aven, 2008a).

Among these two perspectives, the relative frequency approach is widely used in offshore QRAs.

2.3.3 Risk description for relative frequency method

The basic risk description by the relative frequency approach is represented as (Aven, 2011):

$$R = (A, C, P_f)$$

Where, P_f is the relative frequency interpreted probability. P_f is not known and is estimated by the analysis and the estimate is P_f^*. The uncertainty about how closer the estimate P_f^* is to the true value of P_f introduces a second-order uncertainty $U(P_f^*)$ for the background knowledge (K) that the estimate and uncertainty description is based on.

The subjective probability "P" is used to describe analysts' epistemic uncertainty $U(P_f^*)$ i.e. lack of knowledge about the true value of P_f (Helton & Burmaster, 1996). Hence, the second level definition of risk i.e combined with first level (A, C, P_f), is given by (Kaplan & Garrick, 1981):

$$R = (A, C, P_f^*, P\ (P_f), K^*)$$

Where, K^* is the background knowledge that the estimate P_f^* and subjective probability distribution P (a second order probability) is based on.

Risk quantification by QRAs, which has many assumptions, often involves a mixture of relative frequency approach and Bayesian approach. A standard risk assessment description includes second order probabilities, like “P” in the above description. This assigned probability is based on certain background knowledge and could vary in many respects. Hence a risk description should be able to capture the uncertainty hidden in the background knowledge and need to see beyond the subjective probabilities “P” (Aven, 2008a). This leads to uncertainty based perspective that is described in sec. 2.4.

2.4 Uncertainty based risk perspective and risk description

Uncertainty is understood as a lack of knowledge about unknown quantities (Flage & Aven, 2009). When the probability measure as described in sec.2.3.3, is used to describe uncertainty, the strength of knowledge that the probabilistic analysis assumptions are based on are not reflected. According to (Aven, 2013) surprises may occur based on the knowledge of the analyst conducting the analysis.

2.4.1 Uncertainty based perspective

A risk (R) based on uncertainty (U) is described as below (Aven, 2011):

$$R = (A, C, U)$$

Where, A is an event, C is consequences of event “A”, and U is the associated uncertainties of events U(A) and consequences U(C).

The event A is however, part of the consequences C and the risk can be denoted as:

$$R = (C, U)$$

In this way the risk is understood as a two-dimensional combination of (a) Events A and their consequences C, and (b) the associated uncertainties (U) about A and C, including uncertainty underlying phenomena influencing A and C.

2.4.2 Uncertainty based risk description

The basic risk description of uncertainty based approach is represented as (Aven, 2011):

$$R = (A, C, U, P, K)$$

Where, P is a subjective probability expressing uncertainty “U” based on the background knowledge (K). This perspective holds uncertainty as main component of risk rather than probability.

Following two-dimensional combination risk, the risk description based on uncertainty including the event can be represented as (Aven, 2011):

$$R = (A, C, C^*, U, P, K, S)$$

Where,

A represents the event,

C is the consequence of event “A”,

C* is the prediction about “C”,

U is uncertainty about occurrence of event “A” and the consequence “C”, P is a probability tool used to express uncertainty about occurrence of event “A” and the consequence “C”.

K is the background knowledge of the analyst about the event “A”, consequence “C”, probability “P”

S is sensitivity analysis to represent a change in risk picture for altered inputs.

Under uncertainty based description, there are no second-order probabilities. When we use subjective probability measure to describe uncertainty following Bayesian perspective as mentioned in sec. 2.3.2, probabilities are not uncertain but only the background knowledge the probabilities are based on is uncertain (Aven, 2011).

2.5 Risk regime in Norway

The Norwegian oil industry risk management approach for offshore installations builds on the principles of Framework and management regulations laid by the Petroleum Safety Authority of Norway. This section describes the parts that are relevant for design accidental explosion loads.

2.5.1 Risk perspective by Authorities

In Norwegian offshore oil industry, the risk analysis is done following the risk definition by NORSOK Z-013 (NORSOK, 2010) as “combination of the probability of occurrence of harm and the severity of that harm”. In this definition, the uncertainties associated with the events (A) and consequences(C) are addressed using the probabilities (P). The severity is used to characterise the consequences. This definition follows the (A, C, P) risk perspective as described in sec. 2.3.1.

The risk picture following (A, C, P) perspective, which uses only probabilities and expected values to describe uncertainties, the background knowledge (K) is not reflected in the decision making process (Aven, 2011).

PSA have updated the risk definition as *“the consequences of the activities, with associated uncertainty"* (PSA, 2015b). This definition is in line with uncertainty based perspective (C, U) as described in sec. 2.4. In this definition, the term “consequences” is a collective term that describes all potential consequences of the activities not limited to final consequences of the activities but also includes conditions and incidents that can result to or lead to this type of consequences. “Associated uncertainty” is related to the potential consequences of the activities i.e., uncertainties associated both with the causing factors and resultant consequences.

This new definition is expected to put increased demand across Norwegian offshore oil industry in the way uncertainty is considered in the risk analysis. This may mainly include taking account for the background knowledge (K) of the risk analysis in the decision making process for major accidental risks.

Currently, the industry follows probability based perspective (A, C, P) as described in sec. 2.3.1 which is in line with NORSOK Z-013 (NORSOK, 2010). However, it is expected that this standard will reflect PSAs' new definition in the next revision.

2.5.2 Risk reduction principles

According Framework regulations §11 (PSA, 2013), the risk reduction principle involves two levels of requirement, risk acceptance criteria and ALARP.

The first level requires that the risk to people, environment and asset shall be prevented or limited including acceptance criteria for major accidental risks and shall be met regardless of cost. In the second level, the risk shall be further reduced to the extent possible, meaning that, the risk shall be reduced beyond the risk acceptance criterion by implementing technical, operational or organisational solutions if it can be done without unreasonable cost to the benefits gained.

In case of any uncertainty on the effect of a proposed measure to people, environment and asset, alternate solutions that will reduce this uncertainty following cautionary principle should be chosen. Cautionary principle states that in the face of uncertainty and risk, caution should be a ruling principle (HSE, 2001).

It is claimed that in reducing the risk, the first level i.e to meet minimum acceptance level, has gained more focus than second level that requires the risk shall be further reduced to the extent possible following ALARP (Hokstad, Vatn, Aven, & Sørum, 2004).

A formalised approach in reducing risk following the understanding of Framework regulations (PSA, 2013) is outlined in Figure 1.

2.5.3 Risk reduction priorities

In risk reduction principle, selection of an appropriate risk reducing measure is vital. Risk analysis shall identify possible risk reducing measures and assess their effect on reducing risk including risk associated in implementing the measure. According to NORSOK Z-013 (NORSOK, 2010), risk reducing measure assessment should follow the priority as given below:

- **Inherently safer design (eliminate or reduce hazards rather than controlling)**
  In applying inherent safer design principle like reduction (reducing HC inventories), substitution (substituting hazardous materials with less hazardous), attenuation (limiting hazard potential) and simplifications (simpler design) are normally applied.

- **Probability reducing measures(Prevent or reduce hazards)**
  These measures reduce the occurrence probability of an event and reduce the development of events into hazardous situations.

- **Consequence reducing measures (Prevent or reduce consequences)**
  Consequence reducing measures ensures the safety of the installation in terms of escalation after an event.

In evaluating possible risk reducing measures, qualitative assessments (i.e. inherent safety principles, best available technology and cautionary principles) and quantitative or qualitative assessments of cost, benefit and effect of measures in terms of robustness and effectiveness (cost-benefit or cost effectiveness analysis) should be used.

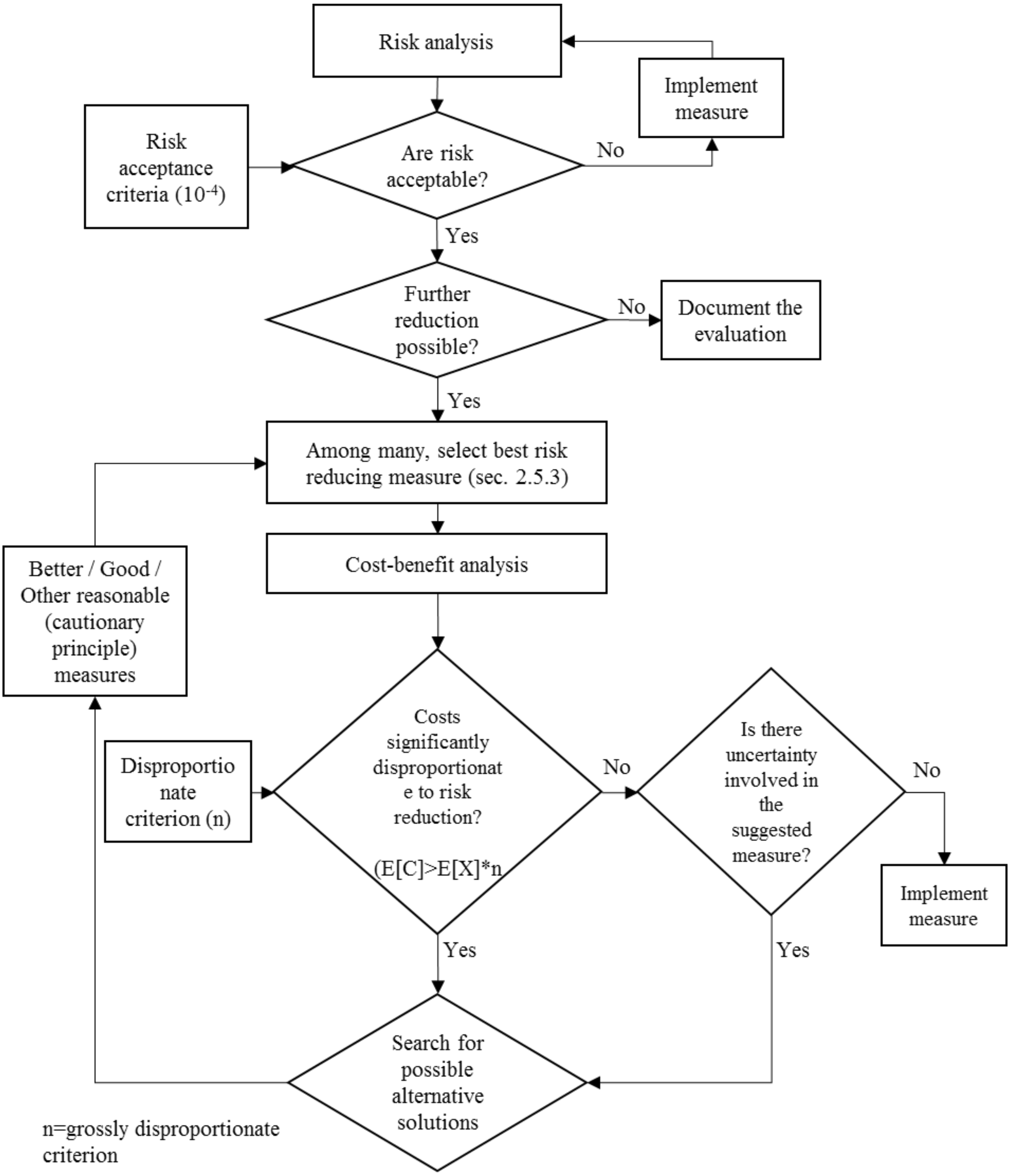

Figure 1. Risk reduction principle in Norway (PSA, 2013)

However in practice, it may be difficult to document the probability reduction aspects as these depend on operational measures and are considered less reliable, for example prevent gas leaks from operations. It is difficult to quantify the probability reduction measures in the risk analysis. On the other hand, evaluations of consequence reducing measures are easier and are reliable (Vinnem, 2007).

2.6 Dimensioning accidental load and Design accidental load

2.6.1 Dimensioning accidental load

According to Facilities Regulations §3 (PSA, 2015a) and (NORSOK, 2010), DAL is defined as "an accidental load that a function or a system shall be able to withstand for a given period of time to meet the defined acceptance criteria for risk".

Further, section §11 (PSA, 2015a) states that "Installations, systems and equipment that are included as elements in the realisation of main safety functions, shall as a minimum be designed such that dimensioning accidental loads with an annual likelihood greater than or equal to $1x10^{-4}$, shall not result in loss of a main safety function".

Following this, DAL is understood as typically the load that occurs with an annual probability of $1x10^{-4}$ and is generated as part of quantitative risk analysis. It is normally defined based on Dimensioning accidental event (DAE), i.e., accidental events that serve as the basis for layout, dimensioning and use of installations and the activity at large (NORSOK, 2010).

An overview of an interaction among major stakeholders of DAL (Operator, engineering contractor and QRA analyst) and design accidental loads is shown in Figure 2.

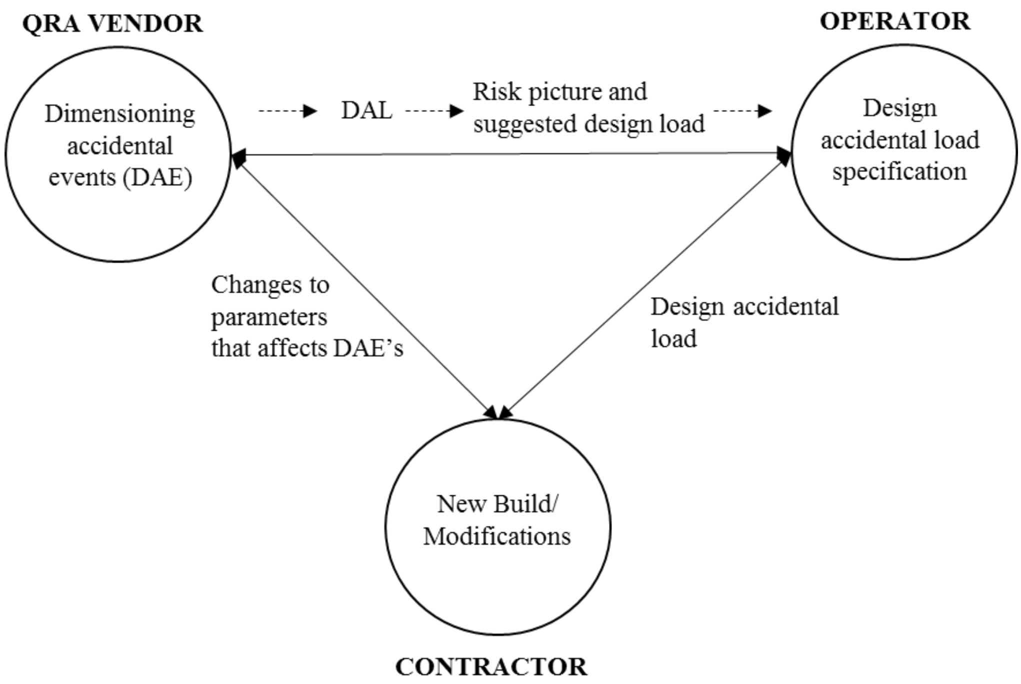

Figure 2. Dimensioning load and its stakeholders

2.6.2 Design accidental load

According to Facilities Regulations §3 (PSA, 2015a), Design accidental load is defined as "accidental load used as a basis for design". Further, section §11 requires that "the design loads that will form the basis for design and operation of installations, systems and equipment, shall be determined". The design loads shall ensure that relevant accidental loads that can occur on installations do not result in unacceptable consequences, and shall, as a minimum, always withstand the dimensioning accidental load.

According to NORSOK Z-013 (NORSOK, 2010), it is defined as "chosen accidental load that is to be used as the basis for design". Further, the design accidental load should as a minimum be capable of resist the DAL.

Facilities regulations §11(PSA, 2015a) states that the design loads shall be determined following risk reduction principles outlined in the Framework regulations §11 (PSA, 2013).

Following the DAL by risk analysis, establishment of design accidental load is based on additional assessments such as ALARP and further considerations. As seen in sec.2.5.2 ALARP is a requirement by PSAs risk reduction principles (PSA, 2013).

2.7 Decision making of design accidental load

The Management Regulations §17 (PSA, 2015c) requires that risk analyses shall form part of the basis for making decisions in identifying which accident loads are to be used in the design of the installation. A decision maker considering other factors makes a decision on the design accidental loads that shall be used in the design. A simple model for decision making under uncertainty is shown in Figure 3.

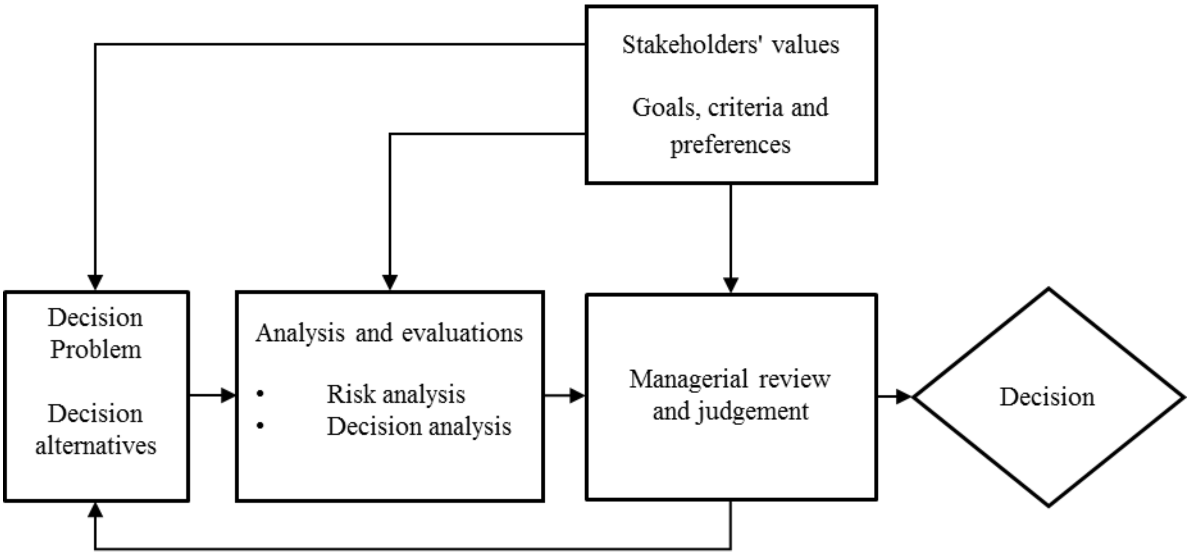

Figure 3. Model for decision making under uncertainty (Aven, 2009)

In decision making, the starting point is the decision problem where choices between different alternatives, concepts, and risk reducing measures, etc. should be taken. Analysis and evaluations, includes risk analysis, cost-benefit analysis, etc. that provides decision support. The decision maker must perform a review and judgement of different alternatives considering constraints and limitations. Managerial review and judgement implies that the basis is viewed in a larger context and then final decision is made.

2.7.1 Risk acceptance criterion

Management Regulations §9 (PSA, 2015c) requires that an acceptance criteria that expresses the upper limit for the acceptable risk shall be established and used when assessing results from risk analysis. For major accidental risks, a maximum probability of $1x10^{-4}$ per year is assigned.

Risk acceptance criteria is a concept being used in the decision making process to assess whether the identified risk can be accepted or not. This simplifies the decision making process. In the current practice of describing risk using (A, C, P) perspective (Aven, 2011) without taking the background knowledge into account, the risk acceptance criterion may accept the higher risk and limit implementing possible additional measures.

For a risk acceptance criteria, a typical explosion risk analysis will conclude that the risk is acceptable as long as the calculated risk is within the acceptable criteria. Refer to Figure 4, the condition "A" which has a calculated risk higher than the acceptance criteria. According to risk reduction principles, this is not acceptable and risk reducing measures shall be implemented regardless of costs to reduce the risk level below the acceptance criteria.

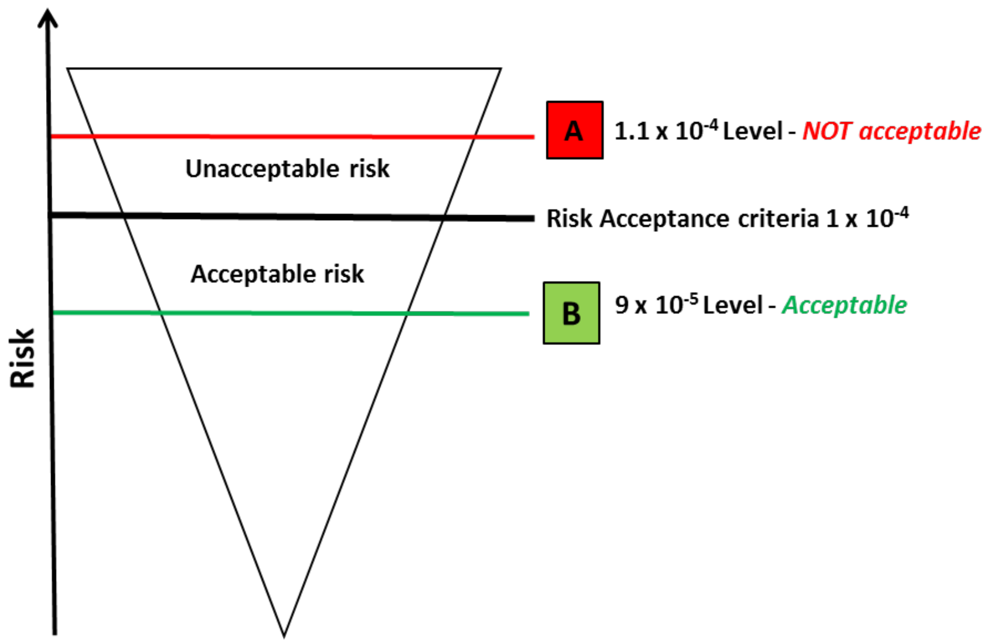

Figure 4. (A, C, P) risk perspective and risk acceptance criteria (Chinnusamy, 2014)

On the other hand, the condition "B" is considered acceptable as the calculated risk is below the acceptable criteria though it has literally no or low margin between the calculated and acceptable risk levels. This low margin has the potential to increase the risk level above the acceptance criteria, if the background knowledge used in the risk analysis is relatively weak.

2.7.2 ALARP approach

Following risk reduction principles described in 2.5.2, the risk acceptance criterion is the starting point for ALARP process. ALARP principle requires that a risk reducing measure should be implemented provided it cannot be demonstrated that the costs are grossly disproportionate relative to the gains obtained (HSE, 2001).

NORSOK Z-013 (NORSOK, 2010) requires that ALARP evaluations should follow a “reversed onus of proof” approach. This means, in implementing a measure it should be proved why it is justifiable not to implement a proposed measure rather than proving its merits.

In reducing risk, framework regulations §11(PSA, 2013) requires that the risk shall be further reduced to the extent possible following ALARP principle. The ALARP triangle represents the reduction in proportional benefits as the risk is reduced further.

The ALARP approach following NORSOK Z-013 (NORSOK, 2010) has two regions as shown in Figure 5.

a) the risk is so high that it is intolerable
b) a level where the ALARP principle applies

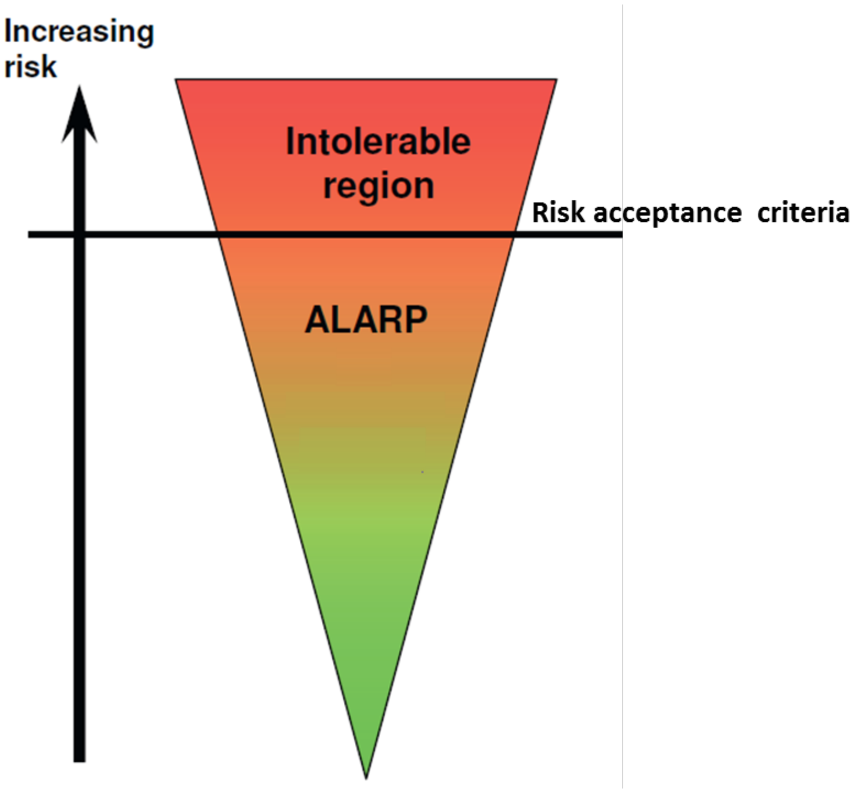

Figure 5. ALARP approach in Norway (NORSOK, 2010)

There is no lower value for acceptable risk is defined. This does not mean that the risk should be reduced to zero but ALARP should be demonstrated regardless of the risk level. This also implies the need for an effective ALARP evaluation and documentation.

2.7.3 ALARP demonstration

An ALARP demonstration process consists of the following steps (NORSOK, 2010):

i. Identification of potential risk reducing measures
ii. Evaluation of risk reducing measures
iii. Decision-making
iv. Documentation of accepted risk reduction measures and rejected measures

Risk analysis provides information for the identification and evaluation of potential risk reducing measures. NORSOK Z-013 (NORSOK, 2010) suggests using cost-benefit analysis in making decisions regarding whether or not a risk reducing measure should be implemented.

2.7.3.1 Cost-benefit analysis - Net present value

A cost-benefit analysis is an approach to estimate the benefits and costs of a project using a common scale. This method assigns monetary values to burdens and benefits and an expected net present value E[NPV] is estimated as the sum of the discounted flows of costs and benefits over the presumed lifespan of the project. The formula used to calculate NPV is (Aven, 2009):

$$\text{NPV} = \sum_{t=0}^{n} \frac{a_t}{(1+i)^t}$$

Where,

a_t - the cash flow at year "t"
n - time period considered (in years)
i - the required rate of return (discount rate) at year "t"

The use of expected values in decision making under uncertainty is justified by the portfolio theory, which states that the value of portfolio of projects is equal to the expected value of portfolio plus the systematic risks. This theory justifies the ignorance of unsystematic risk associated with a project. The systematic risks relates risks that are common to all projects and unsystematic to specific project (Levy & Sarnat, 1994) as cited in Abrahamsen, Aven, Vinnem, & Wiencke, 2004.

When applied, a proposed risk reducing measure should be implemented when E[NPV]>0.

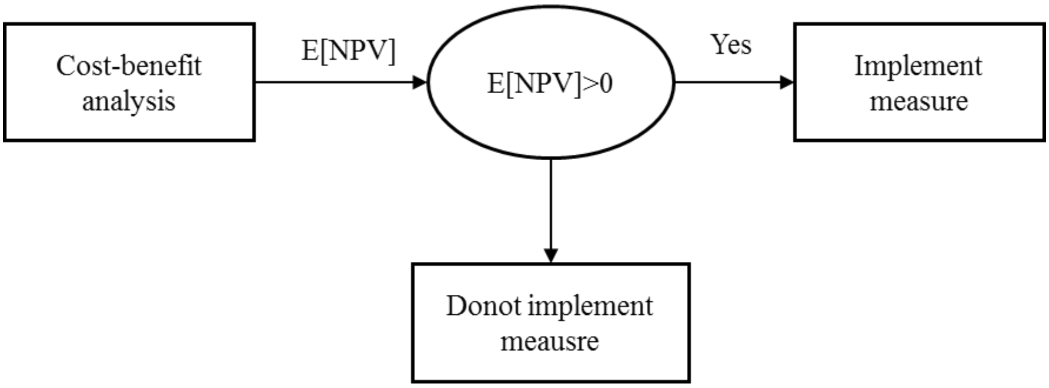

Figure 6. Cost benefit analysis –NPV (Aven, 2009)

But the expected values are based on an average of large populations and give little weight to extreme events i.e. low probabilities with very high consequences. It is particularly important to see beyond expected values in safety context decisions, as average of a large population of activities may be dominated by events of extreme consequences. Hence use of E[NPV] means extreme events are not given enough weight than the product of probability and consequence (Aven, 2009).

2.7.3.2 Cost-benefit analysis – Grossly disproportionate criterion

In the cost-benefit analysis, when applied to verify ALARP, the costs can be defined as grossly disproportionate to the benefits, if the expected cost is considered "n" times higher than the expected benefit, and "n" represents grossly disproportionate factor. This can be represented as below (HSE, 2001):

$$\frac{E[C]}{E[X]} > 1 \text{ x n}$$

Where, E[C] represents the expected cost, E(Stacey) the expected benefit and "n" the Disproportionate factor and defined by the decision maker.

When applied in ALARP, one cannot conclude that costs are grossly disproportionate to the gains if the expected gain is higher than the expected costs.

When ALARP is applied, its verification by the use of traditional cost-benefit analysis that is based on expected values and ignores uncertainties to large extent, contradicts with ALARP thinking to reduce the risk to a level as low as reasonably practicable, and following (Abrahamsen, 2015), this is not considered as appropriate approach in decision making.

3 Establishment of design accidental load for explosion

3.1 A review on gas explosion

One of the major risks on offshore installations is explosion risk. A gas explosion is a process where combustion of a premixed gas cloud (fuel-air mixture) causes rapid increase of pressure (Bjerketvedt, Bakke, & Van Wingerden, 1997). Preventing escalation of explosion consequences is of prime importance to order ensuring personnel safety outside the immediate vicinity of the event.

3.1.1 How explosion occurs?

Upon accidental release of combustible gas or evaporating liquid, several events must occur before a gas cloud can explode. The events both before and after a gas explosion process is shown in Figure 7.

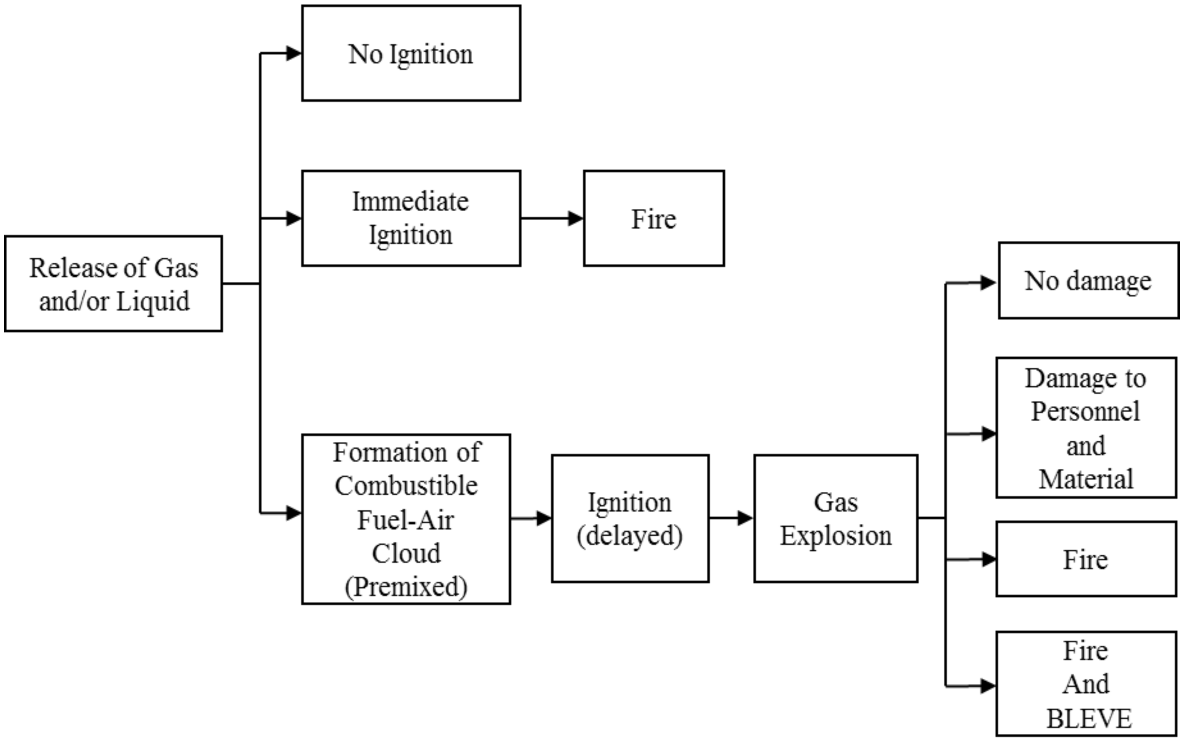

Figure 7. Chain of events leading to explosion (Bjerketvedt et al., 1997)

The gas cloud formed following a gas leak may not get ignited if the mixture is not within the flammability limits or if there is no ignition source. Further, the gas cloud may be dilute and disappear. Depending on the circumstances ignition may occur immediately or may be delayed by up to tens of minutes. Immediate ignition will result in a fire and delayed ignition may result in explosions (Bjerketvedt et al., 1997).

3.1.2 Physics behind explosion

An explosion event involves interaction of many variable parameters. Due to complex nature of the event, an explosion risk analysis is based on several assumptions and thus produces results with uncertainties. Hence, to recognize uncertainties in explosion risk analysis, it is important to understand the physics behind explosions.

A gas or vapour cloud explosion may escalate a small gas release into a major accident. Following ignition of an unconfined flammable gas mixture, the flame consumes the unburnt gas ahead of it, leaving the hotter burnt gases behind with a volume greater than that of the unburnt gas. The expansion of the hot burnt gas gives rise to a flow of gas ahead of the flame. This expansion ratio (burnt to unburnt gas volume) is higher in stoichiometric gas cloud mixture. Stoichiometric mixture is a composition where the amounts of fuel and oxygen (air) are in balance such that there is no excess of fuel or oxygen left after the chemical reaction (Vinnem, 2007).

Under combustion of stoichiometric mixture, any restriction for expansion of burning gases will create overpressure. The level of overpressure is controlled by balance between the rate of production of volume by the flame (pressure increase) and the rate of escape of volume through any openings and/or vents (pressure decrease).

In offshore modules, explosions are of partly confined type due to congested enclosures. In partly confined explosions, the flame will interact with obstacles like process equipment, piping, supports, etc. This interaction process generates turbulence which may accelerate the flame front up to several hundred meters per second. This may generate flame speeds where the inertia of the surrounding atmosphere and the drag of the flow on the obstacles are sufficient to generate severe overpressures even without any confining walls (Bjerketvedt et al., 1997) (Vinnem, 2007).

The mechanism of flame accelerations due to obstacles causes turbulence and creates a strong positive feedback loop as Figure 8, and thus results in increased explosion overpressure.

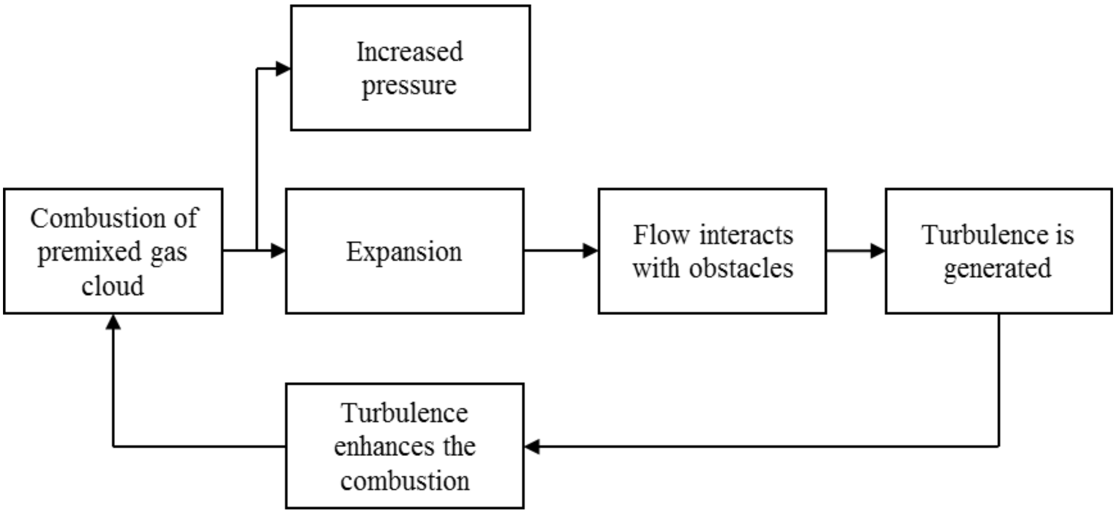

Figure 8. Positive feedback loop causing flame acceleration due to turbulence (Bjerketvedt et al., 1997)

Thus, explosion is a highly complex event with generation of overpressure being governed by the combustion process, flow-obstacles interaction, turbulence generation and turbulence-combustion interaction.

3.1.3 Explosion loading

The way explosion loading is taken into the design is divided into two components.

- **Overpressure loads** which results from increase in pressure due to expansion of combustion products
- **Drag loads** which result from the flow of air, gases and combustion products past an object.

A generic pressure curve with key terms in explosion loading like peak overpressure, rebound pressure, rise time, and blast impulse times etc. is shown in Figure 9.

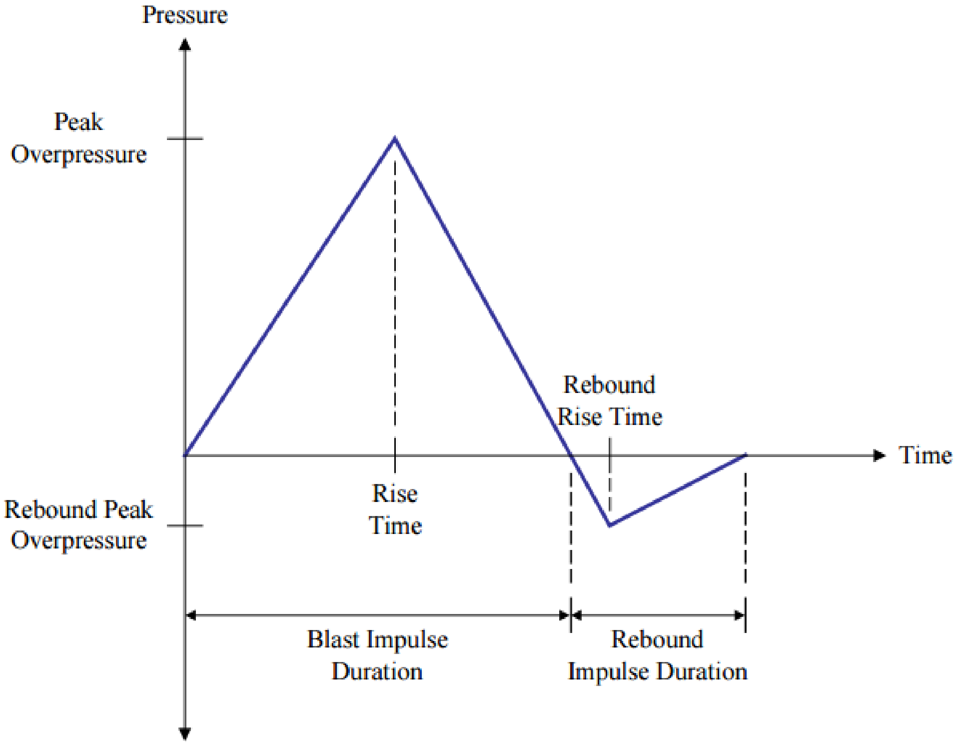

Figure 9. Generic pressure curve with key parameters (Shipping, 2013)

3.2 Explosion risk assessment

The main objective of explosion risk assessment is to determine DAL and provide decision support in establishing design accidental loads.

NORSOK S-001, the technical safety standard section 4.7 (NORSOK, 2008) suggests using a probabilistic explosion simulation procedure described in NORSOK Z-013, Annexure F (NORSOK, 2010) to determine DALs. The analysis results in an exceedance function of an overpressure level, which is defined as the annual frequency of exceeding a specified overpressure level. A schematic of explosion risk analysis by NORSOK Z-013 is shown in Figure 10.

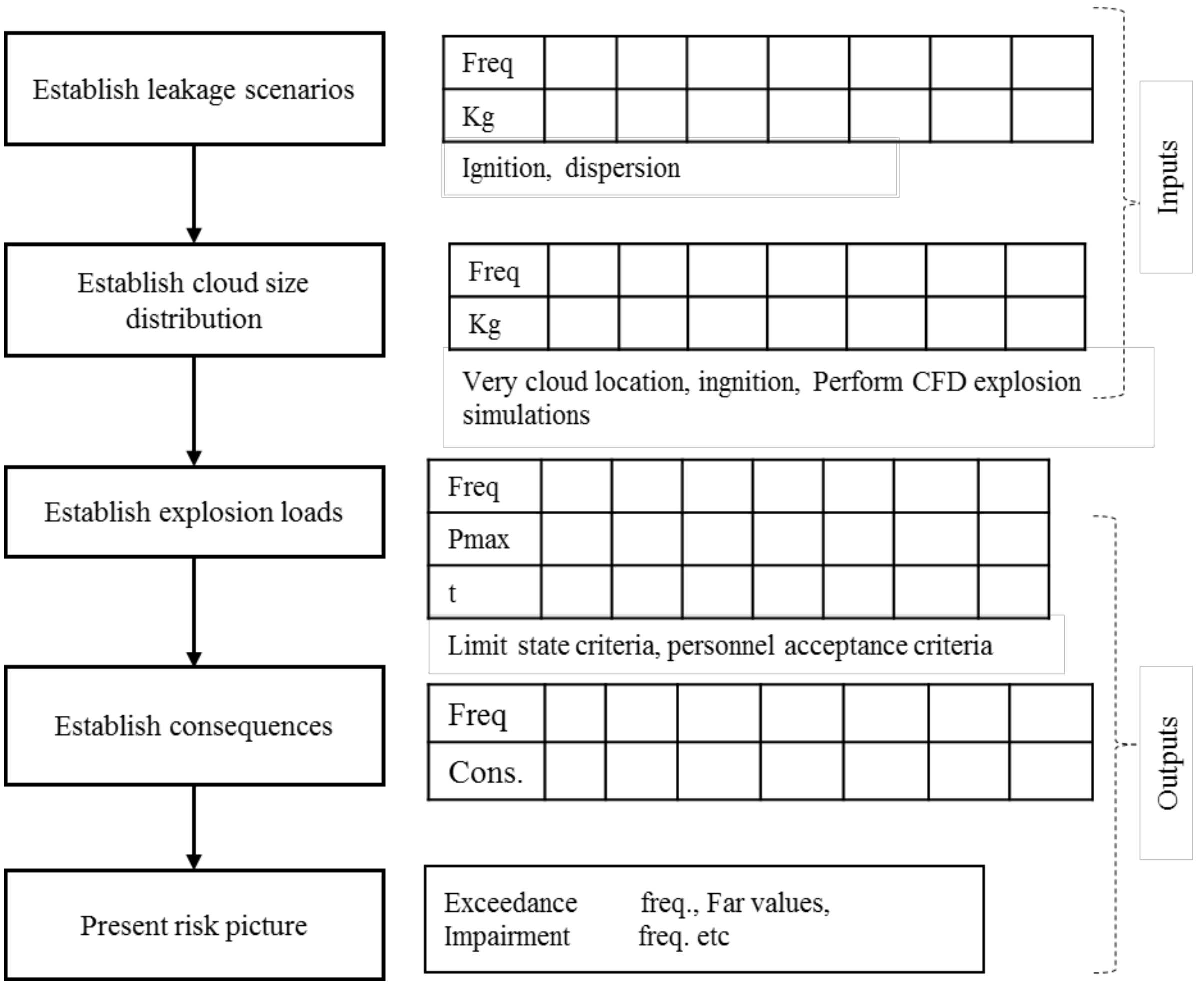

Figure 10. Schematics of procedure for calculation of explosion risk (NORSOK, 2010)

Following the above procedure, different analysis involved in a typical explosion assessment to establish DAL is shown in Figure 11.

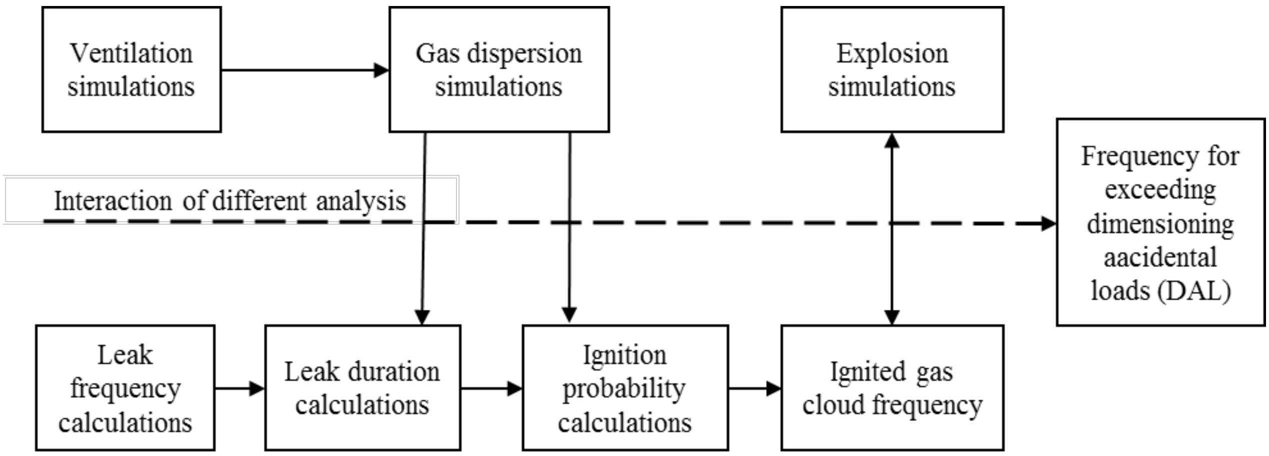

Figure 11. Different stages of probabilistic explosion analysis (Consulting, 2016)

3.3 Establishment of DAL and Design accidental load

3.3.1 Establishment of DAL

NORSOK S-001 requires that DAL for explosion shall be established based on quantitative risk analysis and the comparison of estimated risk with risk acceptance and/or design criteria” (NORSOK, 2008). A schematic of probabilistic analysis approach used for this purpose is shown in Figure 10 above.

The analysis results in an exceedance curve, which is a plot between explosion overpressure and against cumulative frequency, i.e., the sum of the frequencies of events leading to a specified overpressure value or greater.

In offshore oil & gas installations, overpressure exceedance curves are used to determine the DAL (i.e., comparing estimated load with the risk acceptance criteria) and to assess the performance of risk reducing measures (i.e. comparing exceedance curves for scenario with and without mitigating measures). A typical pressure-frequency (p-f) curve to select the dimensioning load is shown in Figure 12.

Facilities regulations §11 (PSA, 2015a) has established impairment frequency for main safety functions. Consequently, the industry practice for dimensioning accidental load for explosion is typically the load that occurs with an annual probability of $1x10^{-4}$, even though PSA states that greater than or equal to $1x10^{-4}$.

According to (Vinnem, 2007), the exceedance function established in explosion analysis has significant level of uncertainties mainly related to gas cloud characteristics and ignition point location and its strength. Hence, proper treatment of uncertainty in establishing DAL is important to provide a strong decision support in establishing design accidental load and evaluating risk reducing measures.

3.3.2 Establishment of design accidental load

Design accidental load refers to the accidental load that is chosen based on DAL (NORSOK, 2010). Along with QRA results, the engineering contractor and/or risk analyst presents recommended design loads to the decision maker and discusses the margins applied with respect to uncertainties in input data, methodology, future changes in the project phase from FEED to as-built, etc.

The decision maker, normally the operator, decides on the load that shall be used in the design. There is no common guidance available on the selection of design accidental load. Some companies may have their own internal guidelines. Following the risk description by QRA, the decision maker may choose the DAL as design load or a conservative value through ALARP approach or other processes. A selected design accidental load should have sufficient margin to account for uncertainties in the analysis, changes during detail engineering or execution phase of the project, to accommodate any increase in risk there by maintaining the total installation risk within acceptable limit.

A discussion (Chinnusamy, 2016) with an operators risk management staff depicts that to be on the conservative side, the company's internal guide suggests basing the design loads corresponding to lower frequency considering uncertainties into account, for example a load corresponding to an annual probability of $1\text{-}5x10^{-5}$ instead of $1x10^{-4}$.

Figure 12 shows dimensioning accidental load against risk acceptance criteria and possible ways of deciding on design accidental load.

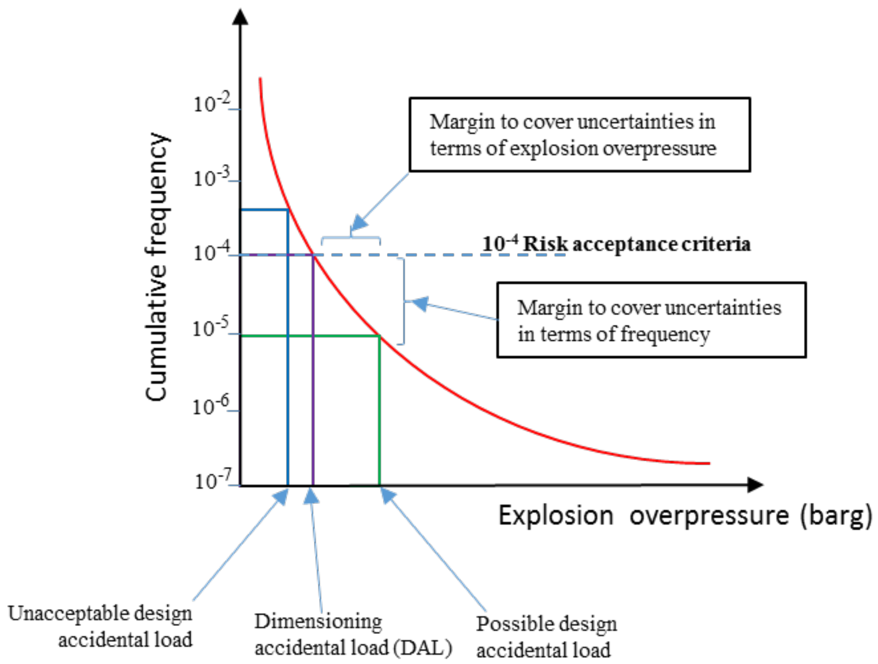

Figure 12. Typical pressure-frequency curve margin for uncertainties (Bjerketvedt et al., 1997)

The chosen design accidental load is normally implemented in the design and used throughout the installation life period (around 35-40 years). All modification projects done at later stage will use this value in the design unless there is a change. The detail about how minor modifications influences the DAE and DAL there by the design accidental load decision process in discussed in sec. 4.1.

3.4 Uncertainties in explosion analysis

An explosion risk assessment is a complex process which involves many parameters with significant uncertainties. The uncertainty reflects the insufficient information and knowledge about the phenomena. Large amount of uncertainties exists at the initial project phase and will start reduce with project progresses. But there will always be some uncertainty about what may be the outcome of accidental events even after the platform is put in operation (Vinnem, 2007).

Among others, key uncertainties in a typical explosion analysis are discussed with respect to main steps in the analysis and is given below:

i. Leak frequency analysis
ii. Dispersion analysis
iii. Ignition analysis
iv. Explosion analysis
v. Establish exceedance curves

This discussion is mainly used later in this thesis to generate uncertainty factors, an input to the suggested method.

3.4.1 Leak frequency analysis

The objective of the analysis is to establish a leak frequency profile for a given area based on estimated leakage points and categorised into leak sizes (normally low, medium and large).

3.4.1.1 *Equipment count and leak sources*

Leak sources of initiating events are calculated based on equipment count approach that identifies number of possible leak sources per process segment/area. Typical equipment include: valves, flanges, bends, instrument connections, welds, piping, pressure vessels, compressors, pumps, coolers, etc.. P&ID's are normally used in this process, however, it should be noted that P&ID's do not provide exact number of small equipment, especially items like flanges, bends, all instruments, drains, etc.. In particular, vendor P&ID's will not be available before detail engineering phase. Further, fully welded pipes in new builds often replaced with flanged items in modification projects later in operational phase there by introducing additional leak sources and these details are not known at the early phase design.

This lack of information is normally compensated by adding a margin to the equipment count in the design. But no guidance exists and the level of conservatism considered in the equipment count differs amongst risk analysts.

The challenge associated with this approach is for example how to ensure that pre-estimate of equipment count at the FEED phase will reflect changes til as-built and operational phase modifications. Also relatively low experienced personnel are often deployed in the task and the challenge on how to verify that the leak sources count is independent of risk analysts introduces some additional uncertainty.

3.4.1.2 *Leak frequency and leak rate*

Leak frequency is calculated by applying the generic component failure data to the equipment count of a segment and factor in the segment pressure (Vinnem, 2007).

In applying the failure data for equipment, the leak frequency models are established using the Hydrocarbon Release Database (HCRD) (HSE, 2002), which is based on UK offshore data. It is found that (Vinnem, 2007), when using only data from the HCRD to establish leak frequencies, the calculated leak frequencies of released quantities above a given magnitude to be higher than actually experienced in NCS. In order to align the risks with actual experience, risk analysts uses their in-house leak frequency models in applying the historical generic leak frequencies for equipment.

Different solutions by different analysts can lead to QRAs having inconsistent frequencies despite being based on the same HCRD dataset. The uncertainty is in how close the fitted leak frequency distributions by different analysts can represent the actual leak frequency. Further, the leak durations considered for liquid and gaseous releases can vary significantly from realistic leak durations (Vinnem, 2007).

Further, uncertainty in equipment count as described in 3.4.1.1 also has influence on the leak frequency and leak rate. In some safety cases, where the equipment count had not been done properly, subsequent review has shown higher leak rate prediction and uncertainties in the leak rate can amount to a factor of 2 (Brighton, Fearnley, & Brearley, 1995).

3.4.2 Dispersion analysis

The objective of a dispersion analysis is to determine a time dependent flow profile of a given medium. For ventilation analysis this means to provide a time dependent profile of air following wind speed and wind direction. For a gas dispersion analysis this will provide gas cloud profile following the leak rate and ventilation conditions including ignitable range of the developed cloud.

3.4.2.1 *Geometry model*

The geometry has a large influence on the explosion overpressure. However, the FEED phase geometry does not have all information especially smaller equipment and piping, cable trays, etc. A pre-set level of congestion is modelled by experience and a sensitivity analysis is carried out to study the effect of change in congestion level.

It is vital that the geometry model used in the explosion analysis includes as much of all smaller diameter piping as possible. This is also emphasized by NORSOK Z-013 (NORSOK, 2010) that all objects should be modelled independent of size and shape in order to get the realistic model as possible. The cluster of smaller diameter piping and its accessories like valves, have significant impact on the explosion pressure by generating turbulence in the accelerating flame front (Vinnem, 2007).

The congestion in the model will increase until as-built stage of the project. It is not certain whether the pre-set congestion in the model will reflect the as-built congestion level.

3.4.2.2 *Ventilation analysis*

Ventilation has significant influence on the dispersion of gas leak in a naturally ventilated area and the resulting gas cloud. In stagnant areas a small amount of gas leak may escalate the situation if not dispersed quickly. CFD tools are normally applied to study the natural ventilation of a given module, which uses geometry models combined with wind speed and direction from wind rose diagram for the installation.

Variations in wind conditions demand increased number of simulations. Due to time taken to simulate all cases and to limit the number of scenarios, very often simplifications in the form of symmetry considerations and evaluations based on understanding of physics and geometry are used. The simplification may introduce considerable uncertainty, which is difficult to estimate.

Ventilation is significantly affected by the degree of congestion in area, in the sense that more congestion will produce resistance to air flow there by increasing the dispersion time. As the level of congestion in not known and assumptions are made at the initial phase, there is an uncertainty on how the congestion in the final layout will impact the results.

3.4.2.3 *Gas dispersion Analysis*

The gas cloud characteristics (volume, homogeneity and gas concentration) are a prime starter of the event and have a major significance on the explosion overpressure. The volume of the flammable gas cloud is determined by leak rate together with the ventilation rate for the area. Larger cloud results in a higher overpressure.

Gas dispersion simulations determine the size of possible flammable gas clouds from HC leaks in an area and takes the following parameters into account (Vinnem, 2007):

- Location of the leak source
- Gas composition characteristics

- Leak rate
- Direction of leak flow
- Unrestricted gas jet or diffuse gas leak

Due to variations in above parameters, possible leak scenarios in reality consist of an infinite number of different leak rates, directions and positions combined with different weather conditions. It is not possible to carryout gas dispersion simulations for all possible combinations, hence, representative cases are chosen for analysis. The selection of representative case involves a strong amount of arbitrariness and is based on the analyst background knowledge. Experience is the key role in selecting representative scenarios, which is obviously different among risk analysts (Vinnem, 2007).

It is also uncertain whether the selected numbers of representative cases for dispersion simulations are sufficient enough to describe all possible real situations in estimating final gas cloud size and its mixture. The interpolation/extrapolation used for other scenarios generates some uncertainty as well.

Further, accuracy of simulation results is greatly dependent on the modelling techniques employed. This is acknowledged in the gas dispersion analysis study (Scandpower Risk management, 2012) that slightly different results among different analyst group are inevitable with the same tool. The uncertainty linked to the user is larger for CFD tools, which has many user specified parameters (e.g. the grid resolution, the release conditions and the boundary conditions). The well-established CFD tools (KFX and FLACS) have less degree of freedom and with good training one is expected to get good predictions.

Gas dispersion is significantly affected by the degree of congestion in area, in the sense that more congestion will enhance the fuel-air mixture. Since the level of congestion in not known and is assumed at the initial phase, there is a significant uncertainty associated with the final risk results due to variation in congestion level at as-built scenario as well as the modification projects in operational phase.

3.4.3 Ignition analysis

Ignition source with sufficient strength is required to ignite a gas cloud. The ignition energy depends on the type of fuel and its concentration and is minimum for stoichiometric mixture. For a strong ignition source, the gas cloud will be ignited when the edge of the flammable cloud contacts the ignition source. When the ignition source is weak, this may not ignite the cloud in the early phase of dispersion or ignite only a small part of the cloud. This may lead to larger homogeneous cloud as the source of release is emptied allowing the weak source to ignite the cloud. This shows the complexities involved in assessing the ignition probability and formation of explosive gas clouds (Vinnem, 2007)

The objective of an ignition analysis is to determine the probability of gas cloud being exposed to ignition following transient cloud development profile from gas dispersion analysis.

3.4.3.1 *Ignition model*

In QRA's, JIP ignition model (DNV, 1998) is normally used to estimate the ignition intensities. This model is based on historical data from the Norwegian and British shelf and the ignition intensities are based on events with ignited HC leakages which are very low in the data set (Vinnem, 2007):

Ignition source location relation to the obstacles that generate turbulence increases the flame front velocity and the resultant overpressure. Hence increase in congestion as described in sec. 3.4.2.1, may influence the transient gas cloud modelling results used by the ignition model.

Sensitivity analysis is done by varying the ignition point locations to see the result on the explosion pressure however the base uncertainties associated with whether or not the estimated ignition intensities represent real situation still exists. Hence the uncertainties associated in the results due to ignition intensities which are based on lean dataset and analyst knowledge cannot be avoided.

3.4.4 Explosion Analysis

The objective of the explosion analysis is to predict maximum explosion overpressures as well as a distribution of overpressures with associated probability of occurrence.

3.4.4.1 *Explosion modelling*

Upon completion of gas dispersion analysis, number of explosion scenarios is reduced by eliminating scenarios that are considered non ignitable and categorising similar scenarios. A difficult task is to identify the dispersion scenarios that will able to reach ignitable atmospheres but upon explosion insufficient to produce significant blast i.e. weak explosions (Vinnem, 2007).

Further, a representative set of explosion simulations are performed to reflect consequences of explosions generated by leakages, given ignition. There is no evident way to select these representative scenarios that can be real representative of the risk picture.

For a given leak, only the part of the cloud that has ignitable concentrations i.e. between lower explosive limits (LEL) and upper explosive limits (UEL), is considered in the explosion modelling. Module filled with stoichiometric fuel-air mixture is assumed as worst case scenario in most overpressure predictions. But it has been shown that the highest pressure results from somewhat higher than the stoichiometric value (Vinnem, 2007). Further turbulence induced by high-pressure releases (Brighton et al., 1995) also enhances the explosion overpressure.

One of the most uncertain aspects of modelling is transferring data from experiments. For example, real gas clouds will be extremely different from homogeneous ones, but most of experimental data are based on homogenous and stoichiometric clouds. As cited in Vinnem, 2007, the dispersion tests done at Spade Adam, UK (HSE, 2005) showed the real gas cloud may be further away from homogenous clouds that thought previously.

3.4.4.2 *Degree of confinement*

At the early phase of the project, only relatively large scale objects are included in the explosion model and scale of congestion due to small objects is not normally known. A margin is assumed in the analysis in the form of obstruction factor based on experience. But the degree of confinement of the vapour cloud and congestion in the path of the flame front has significant influence on the explosion strength than the size of the cloud (Raman & Grillo, 2005).

3.4.5 Exceedance curve establishment

The probabilistic explosion analysis is a collection of statistical models, geometrical models and physical models and how the results of these models interact together to produce a result of interest. An overview of interaction of different models in a typical explosion analysis tool is shown in Figure 13.

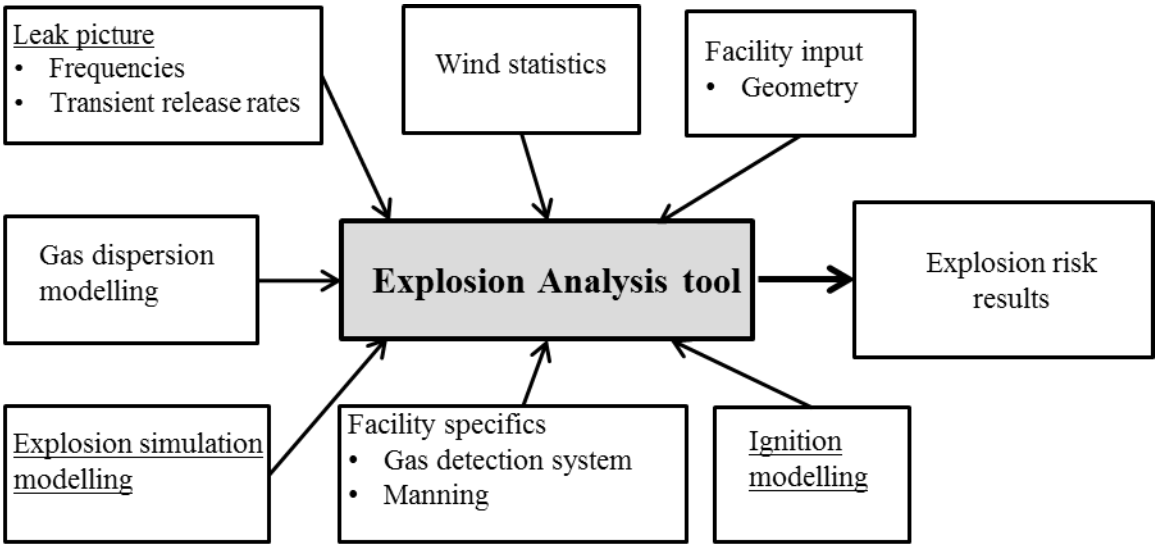

Figure 13. Interaction of different models and inputs in explosion analysis tool (Register, 2016)

For instance, to obtain a leak frequency for a segment, a statistical model based on the HCRD (HSE, 2002) database is used. In order to simulate the actual installation the geometry model is required. To calculate ventilation conditions over an area, gas dispersion and explosion characteristics, a physical model is required. Further, simplifications are made to the geometry models for different analyses models due to the computing time and resources it takes for simulations. Gas dispersion simulations will take more resources than explosion simulations for a given geometry.

From use of different models, simplifications, interactions and different knowledge level of the analyst in the use of these models, it is obvious that the results from a typical explosion analysis has significant degree of uncertainty. This additional source of uncertainty in addition to uncertainties associated with the values of the basic parameters is referred as modelling uncertainty (HSE, 2006b) which is difficult to estimate.

3.5 Sensitivity analysis in treating uncertainties

The importance of assumptions in a QRA is analysed by performing sensitivity analysis. For example, in the explosion analysis, the location of ignition point in the gas cloud is rarely known. Hence, the ignition point location is varied in simulations to study how sensitive the explosion load is to different ignition locations while keeping other parameters constant (Vinnem, 2007).

In answering the uncertainty problem, it is a common practice across the offshore industry to perform sensitivity analysis. However sensitivity analyses differ from uncertainty analyses in the sense that it determines the contributions of individual uncertainty analysis inputs to the analysis outputs. But the uncertainty analysis determines the uncertainty in analysis outputs due to uncertainty in analysis inputs (Aven, 2010). However, the sensitivity analysis provides a basis for the uncertainty analysis.

Regulations require that necessary analysis for sensitivity and uncertainty to be performed for major accidental risks (PSA, 2015c). When there is no separate uncertainty analysis made, how the relevant uncertainty factors are assessed and have been accounted for in the explosion analysis to reflect the real situation is questionable.

3.6 Risk reducing measures for explosion

A general safety perspective in avoiding major accident risk is risk prevention than mitigation (Vinnem, 2007). Accordingly in establishing design accidental explosion load, probability reducing measures should be prioritized than consequence reduction measures.

In the current risk regime, risk acceptance criteria for a selected safety function implies that it is applied for the safety function in total (PSA, 2015a). In practice it allows a better trade-off in meeting acceptance criteria in the sense that it not necessarily that a measure shall improve the weakened aspect of the contributing factor to the risk but implementing other easy measures that will improve other aspects of risk. Care should be taken in deciding a measure as a selected measure may reduce the safety level in other aspects of risk.

For instance, in reducing the risk below acceptable limit ($1x10^{-4}$) due to increase in leakage points, possible measures could be installing more gas detectors that will reduce the detection time there by the possible cloud size, preventing high blockage by removing peripheral structures there by increasing pressure relief or increasing the blast resistance of the wall rather than reducing the leakage points by changing out the design without leakage points. Alternatively the selected measure may have reduced the performance of other measures. Selection of measure to reduce the high blockage by removing external structures may reduce the effectiveness of gas detection especially for small leaks.

In reducing explosion risk, a few possible risk reducing measures and its influences on other aspects of risk is described below (Vinnem, 2007). This introduces the challenges associated with in choosing a correct measure at the early phase of the project where available information is insufficient to make robust decisions.

Probability reduction measures:

- **Prevent gas leaks:**
  In the design phase, gas leaks can be reduced through suitable design (using welded joints instead of flange) and in operational phase, preventing gas leaks from operations through implementing operational barriers.

  Reduce potential number of leak sources, typically number of flanges. Though this measure is easy to implement in the new design, the experience is that very often fully welded pipes are replaced with flanged items in the operational phase modification projects due to issues like time, access, level of seriousness, etc.

- **Prevent ignitable concentration:**
  Maintaining extensive natural ventilation is a best measure to avoid formation of ignitable concentration. Sufficient care is normally given in the new builds for ventilation but there are cases that operational aspects introduced temporary blockage of ventilation in the form of placing the equipment in the path of ventilation. Further many smaller modifications done on the installations causes a reduction of ventilation which is in most cases are permanent. In most cases, removal of weather cladding, changing the solid decks to grated floor is considered as a main option in providing natural ventilation. But, decision on increase in

ventilation is a trade-off between reduced ignition probability and worsened working conditions (due to low temperatures).

- **Prevent ignition:**
  In practice, preventive measures in terms of ignition has attained maximum improvements in the sense that limiting hot work activities, replacing hot works with colder methods, selecting equipment according to hazardous zone classifications etc.

Consequence reduction measures:

- **Prevent high turbulence:**
  Designing installation to prevent high turbulence can be overcome through established good practices for example optimising multiple pieces of equipment, installing pipe racks with respect to ignition sources etc. It should be noted that smaller sized objects appears to have large effect on the module congestion in the long run.

- **Prevent high blockage:**
  Measures implemented to increase ventilation may also reduce the blockage and there by resultant explosion pressure.

- **Installing blast walls:**
  Installing blast walls will reduce consequences of escalation between modules. This also may reduce the ventilation, resistance to dispersion, reduction in explosion relief etc.

4 Parameters influencing design accidental explosion load

According to (Fløttum & Svidal, 2013), a robust risk analysis shall provide the project with DAL values at the end of the FEED phase which is likely to be valid when “final as-built” deliverables are completed. Engineering contractors have confirmed in a discussion that future modifications are not taken into account in determining base DAL and establishing design accidental load. This should be addressed by the future modification projects by updating QRA and implementing risk reducing measures when necessary.

Following management regulations §25 (PSA, 2015c) requirements, major modifications are normally assessed for its feasibility with respect to risk and acceptance level by performing sensitivity studies.

It should be noted that, the sensitivity analysis is typically based on base model in order to see the percentage of increase in risk. Many smaller modifications could have happened in the area before the sensitivity analysis is conducted for a major modification proposal. Even in cases where the models have been updated; it is not certain whether models reflect all updates. The equipment count based on P&ID in sensitivity analysis may not reflect real picture of new equipment offshore. Further the update in leak frequency data between the |base case and sensitivity case may also have impact on the results based on whether the leak frequency has increased or decreased.

4.1 Minor modification projects and DAL

Minor modification projects are such that in isolation they do not represent any marked influence on the risk level (Vinnem, 2007). Hence, the evaluation is normally a qualitative as it is obvious by experience that it will not increase the risk beyond acceptance criteria.

The quantitative effect of these modifications on total risk level are may be calculated as a part regular QRA update process. It is acknowledged that operating companies have their own plan in updating the installations QRA regularly; for example, Statoil has a recommendation to evaluate the need for updating QRA every 3 years as cited in Vinnem, 2007. The level of updated information used in the regular updates of QRA to reflect all the changes carried out offshore is questionable.

4.1.1 Typical assumptions in explosion analysis

Where applicable the minor modifications are built in line with the design accidental load but no review of assumptions made in establishing DAE's are considered in the design. The following assumptions in explosion risk analysis are discussed here in the light of the above (Vinnem, 2007).

- **Number of leak sources**
  As the exact number of leak sources are not known assumptions are made in analysis to calculate the leak frequency and leak rate. The change in number of leak sources influences the risk measures directly.
- **Level of congestion**
  Obstruction factor, a factor used in the dispersion models to describe the equipment density in the area. This has a value between 0 (for complete ventilation) and 1 (for full confinement). For given ventilation, higher obstruction factor will reduce gas

dispersion and may result in denser cloud. The selection of this value has influence on explosion frequency and demand increased risk reducing measures.

- **Ignition sources**
  Number of hot works (in terms of hours) are normally assumed for the base case analysis and any increase than the considered value will increase the risk. Changes in ignition source distribution in hazardous areas will also increase the explosion risk.

- **Gas detection**
  Number of gas detectors in a given area will have influence on ignition probability. Higher number of detectors will reduce ignition probability through less detection time and there by enable quick isolation of ignition sources.

- **Explosion relief openings**
  It is normally assumed that weather cladding has porosity that equals a percentage of open area. The way the walls have openings may have impact on the resultant explosion pressure. Further it should be noted that the use of relief panels rely on the operability at the demand to limit explosion consequences.

- **No credit from deluge system**
  No credit from deluge/fire water is taken into account related to reduction of explosion (over) pressure. A deluge effect may dilute a rich cloud (gas concentration is above UEL) into a flammable mixture and increase the cloud size.

All assumptions to an extent generate uncertainty. Some uncertainty factors are more sensitive to the resultant risk than others.

4.1.2 Influence on assumptions by minor modifications

A typical minor modifications projects will involve improvements to the existing system in terms of change out of existing piping, minor re-routing, installing a temporary skid, relatively large work in non-hydrocarbon systems etc. Experience shows that relatively major modification projects have been divided into many smaller projects to avoid doing quantitative analysis and at lower costs.

For a given area, an individual minor modification, will not have significant influence on DAEs and DAL. But after few years, when many smaller modifications being carried out in an area, this may impacts the parameters like leak sources, segment volume, area congestion and dispersion scenario. All these have the potential to threaten overall risk level of the installation. This is described as the *"salami principle"* in guidance to safety case regulations (HSE 2005) as referred by (Vinnem, 2007), by which several individual modifications, not individually considered to have significant impact on the total risk level, but together and over time result in significant increase in risk level. The safety case regulations (HSE, 2005) require that this increase in risk due to smaller modifications should not be overlooked.

It is not clear how much these kind of modifications have influenced the installations risk level. But discussions with operators, engineering contractor and QRA analysts (Chinnusamy, 2016) revealed that the explosion risks of installations that were originally designed for a design explosion load and which was considered to have enough margins have exceeded their levels. This increase has been revealed in the QRA update either during regular update or for major modification evaluation demanding more robust risk reducing measures.

The results that are relevant for the discussion from series of tests with large scale models by "Blast and Fire engineering for topside structures (BFETS) programme (Selby & Burgan, 1998) as cited in Vinnem, 2007 is:

a. results shows that overpressure from large scale blasts can be much higher than previously thought following medium scale tests
b. Blast loads of several tests exceeded the design limits resulting damaging the module
c. Congestion inside the module received more importance than previously thought

When the module congestion was increased from 7.5% blockage (low congestion) to 9.5% blockage (high congestion), the peak overpressure is increased by a factor of four (Vinnem, 2007).

Hence, due to complex nature of explosion phenomena, the minor modifications has the potential to influence dimensioning scenario and may even contribute to the risk increase in more than one ways, for example increase in leak source and also increase in congestion. This may include increased equipment count and leak frequency, increased congestion and increased exposure to manual intervention, etc.

An example of how the modification projects consume the available margin level in the design accidental load by influencing the DAL over the periods of installation lifetime is shown in Figure 14. This is just for an understanding and referenced values do not have any statistical basis.

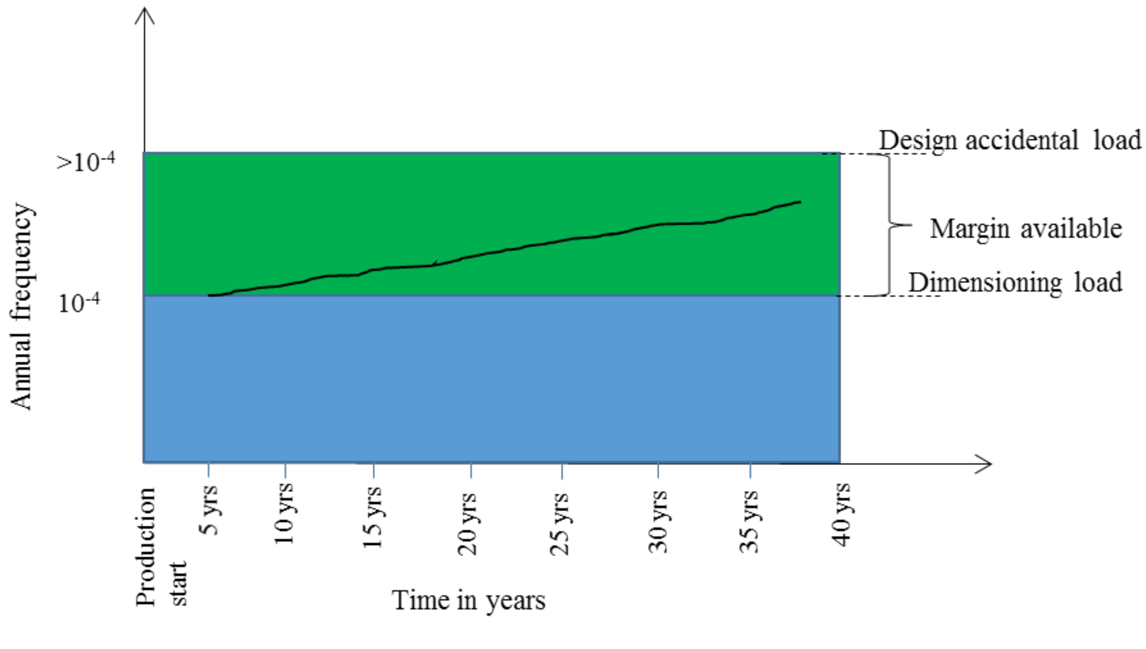

Figure 14. Schematic relation of DAL to design accidental load in a life cycle

When the risk increase is identified beyond the acceptable level, compensating actions are taken to ensure that risk level is reduced to its original level or lower. However, this may not be easily possible for explosion loads where the measures are limited, like removal of weather cladding (a common solution) but will have impact on working environment and may deviate from requirements. This demands the decision maker to follow principle of compensation during the original design.

5 Need for alternate methods to account for uncertainties

5.1.1 Overview of current approach

In todays practice, probabilistic analysis is used to establish DAL. This means probabilities and expected values are used to describe uncertainties and are assigned based on historical data and by expert judgements. When the uncertainty is expressed using (A, C, P) perspective, efforts made through enhanced and deeper level analyses often introduce different form of uncertainty, like further assumptions.

Further, the approach and methods used for the development of pressure exceedance curve varies amongst QRA analysts and are not completely consistent in all aspects.

Risk reduction following ALARP is not a new aspect in the regulations/standards due to change in risk definition to include uncertainties. The requirement to reduce the risk further exists from before and suggests using cost-benefit analysis in evaluating ALARP (NORSOK, 2010).

In reducing risk related to explosions, the design accidental load for explosions selected today is more based on the suggestion by the analyst and estimated DAL. It should be acknowledged that it is the analyst who has more information about the analysis and the level of conservatism included than the decision maker (operator or engineering contractor). The operator staff in the discussion (Chinnusamy, 2016) said that normally the analyst expresses his/her confidence on the suggested value and very often, the suggested design accidental load is accepted by the decision maker. This supports the claim (Aven & Vinnem, 2005) that when the risk evaluation uses minimum risk acceptance criterion will reduce the focus on further risk reduction following ALARP.

When the risk acceptance criterion is met with small margin, when it is supported by the analyst's confidence, there is no or little encouragement for the decision maker to focus on further risk reduction measures. If this happens in the early phase of the project it may result in exceeding acceptance limits demanding more risk reduction measures before the installation is put on operation. This situation has been acknowledged by the risk analysts and this result in contractual difficulties between the engineering contractor and the operator for the installation in question (Aven & Vinnem, 2005).

Hence the design accidental loads established without taking uncertainties properly into account is debatable whether this will maintain the installation risk level below acceptance criteria during its operational life period.

5.1.2 Challenges with current approach

Currently, in QRA's, risk is typically described using probabilities and expected values, potential loss of life (PLL) and fatal accident rate (FAR), impairment frequency, etc., (Vinnem, 2007).

Despite so many analyses, there are installations that have experienced higher risk than acceptable limit. It could be either due to selection of low design accidental loads at earlier phase or allowing the increase through many smaller modifications where the increase in risk per project is accepted through qualitative evaluation.

The weaknesses of the current risk regime approach in treating the uncertainties and reducing risk, which is also applicable for establishing design accidental explosion loads is described below (Aven & Vinnem, 2005; Vinnem, 2007):

1. The explosion analysis based on probabilistic approach uses probabilities and expected values in describing uncertainties. Further, the results do not reflect the knowledge dimension used in assigning the probability values, which can be different amongst different risk analysts.

2. The estimated risk is compared to a risk acceptance criterion ($1x10^{-4}$) in selecting the DAL. With the focus received by the industries, the risk acceptance criterion drifts the risk analysis purpose from decision support tool in reducing risk to a verification tool in estimating risk (i.e., to maintain minimum safety level).

3. The risk description without taking uncertainties into consideration and decisions following risk acceptance criterion may lead to accept the results irrespective of its robustness. This means a lean disproportionate weight is given to further risk reduction process like ALARP. In cases where ALARP is done following company's internal guidance, it is verified through a traditional cost benefit analysis that contradicts with ALARP thinking to reduce the risk further to practicable level.

The probability based risk analysis regime focuses more on detailed level of analysis like probabilities and frequencies, models and simulations. Detailed models and calculations continue to illustrate the problem more in detail at micro level. Hence PSA's shift on the risk definition based on uncertainties (A, C, U) can be seen more relevant in the decision making process of risk reduction principles than the detailing the decision on DAL based on (A, C, P) perspective (Aven, 2011).

5.1.3 Methods from literatures

Two methods have been suggested by (Matland, 2013a) to establish design accidental loads that will be in compliance with the new definition of risk. A brief summary of these methods is given below.

First method is based on use of current risk acceptance criteria approach and a qualitative assessment of the strength of the background knowledge that the analysis is based on and assessments of surprises, so-called black swans. The selection of the design accidental loads will be a decision made by the decision-maker, where the strength of the background knowledge and the potential surprises that may occur are taken into consideration. In addition, ALARP-evaluations following (Aven, 2013) should be performed based on the results from the assessment of the strength of the background knowledge and the potential surprises.

Second method is based on designing the installation for as high design accidental loads as reasonably practicable and without taking reference to risk acceptance criteria. The idea is to start with worst-case scenarios and move downward and find an area of severe explosion load that is feasible to design. Different alternatives need to be generated and various qualitative and quantitative analyses are required to be used in the decision making process in selecting the design accidental load that shall be used in the design. In the absence of risk acceptance criterion, an important weakness with this method is that a minimum level of risk will not automatically be met unless decision maker prioritize safety in achieving necessary risk reduction.

6 New method to establish design accidental explosion loads

6.1 Basis for new approach

The intention behind the new approach is how to achieve a better decision on design accidental explosion load with minimal changes in the current practice and comply regulations. Following risk reduction principles (PSA, 2013), the establishment of design accidental load has two levels of requirement as given below:

1. Meet minimum risk acceptance criterion ($1x10^{-4}$)
2. Achieve further risk reduction (ALARP) following:
    a. Choosing a solution that offer best results based on
        i. Assessment for individual and overall evaluation of potential harm
        ii. Assessment for present and future use
    b. In case of uncertainty on the effect of solutions, alternate solutions (following cautionary principle) to be chosen to reduce the uncertainty.

Thus, this thesis suggests a method that uses both risk acceptance criteria and ALARP principle in the decision making context of establishing design accidental loads for explosion taking uncertainties into consideration.

The suggested method differs from others (Matland, 2013a) in the sense that uncertainty factors are used in evaluating the risk results and further risk reduction through context based ALARP approach. In implementing ALARP uncertainty factors assessment is used to define the decision context.

In the new method probabilities are only considered as tools that describe the epistemic-based uncertainty factors i.e. factors that could cause surprises relative to the assigned probabilities and expected values (Martorell, Soares, & Barnett, 2014). Uncertainty factors will compensate the scarcity in the knowledge in understanding and assessing a situation of interest. Further, the suggested method takes advantage from (Abrahamsen, 2015) in applying the layered approach (Aven, 2011) in the effective implementation of ALARP principle in the decision making of design accidental explosion loads.

To fulfil the need of a suggested method, we must first look in to details about identifying and assessing uncertainties and applying ALARP to varying safety context decision problems. The aspects of suggested method are explained in detail in section 6.4.

6.2 Uncertainty assessment

A risk analysis should provide a broad and comprehensive risk picture that includes uncertainty assessment to provide a decision support in accepting the risk and evaluating further risk reducing measures. The step involved in assessing uncertainty includes (Martorell et al., 2014);

I. Uncertainty factor generation

II. Uncertainty factor assessment for
    a. Degree of uncertainty
    b. Sensitiveness to risk

6.2.1 Uncertainty factor generation

Uncertainties exist with physical observable quantities like equipment count, gas cloud size/volume, ignition point location, level of congestion and ignition point location. There are no uncertainties in the assigned probabilities such as leak frequency, ignition frequency, impairment frequency etc. These are regarded as assessment group or analysts estimated values based on the available background knowledge. In the background knowledge, there will be uncertainty factors related to physically observable quantities. There can be many uncertainty factors involved in the explosion risk assessment.

The risk analyst, based on his knowledge and experience, should identify the most contributing parameters to overall risk. The importance of this input parameter on the results can be verified through sensitivity analysis as done today to verify the importance and validity of assumptions. But in practice when focussed there will be more number of uncertainty factors than just assumptions.

Identification of uncertainty factors that are not normally involved in explosion risk analysis, but may have influence on DAL need to be taken into account in establishing design accidental load. This includes details like future modifications, decision on whether to account for risks introduced by smaller modification projects, deterioration due to ageing, plan on life extension, stricter risk acceptance criteria than required by regulations, attitude towards risk reduction, etc.,

6.2.2 Uncertainty factor assessment

Upon identifying the uncertainty factors and sensitivities to know their influences on risk, the background knowledge that resulted in the uncertainty factors will be analysed. The combined judgement of the factors namely sensitivity and degree of uncertainty will determine analyst's perception of the uncertainty factor on the overall risk. In the combined judgement sensitivity assessment is prioritized followed by the uncertainty analysis. i.e. analyst's confidence on the background knowledge, as described in (Martorell et al., 2014).

Table 1 presents an example of uncertainty factors assessment following sensitivity and degree of uncertainty with respect to background knowledge and its impact on overall risk level is shown in Table 1.

Uncertainty factor	**Sensitivity**			**Degree of uncertainty**			**Effect on overall risk**		
	Minor	Moderate	Significant	Minor	Moderate	Significant	Minor	Moderate	Significant
Number of personnel in each area		x			x			x	
Occurrence of process leak			x	x			x		
Ignition following riser leak		x			x			x	

Table 1. Uncertainty factors (Martorell et al., 2014)

In assessing sensitivity and uncertainty of uncertainty factors, a semi-quantitative method as presented in (Flage & Aven, 2009) and discussed in (Aven, 2008b) is used and is given below:

Significant uncertainty, when one or more of the following conditions are met:

- Phenomena involved are not well understood; models are non-existent or known/believed to give poor predictions.
- Assumptions made represent strong simplifications.
- Data are not available, or are unreliable.
- Lack of agreement/consensus among experts.

Moderate uncertainty**, **when one or more of the following conditions are met *typically when conditions are between significant and minor uncertainty situations**:***

- Phenomena involved are well understood, but the models used are considered simple/crude.
- Some reliable data are available.
- A mixture of simplified and reasonable assumptions

Minor uncertainty, when all of the following conditions are met:

- Phenomena involved are well understood; the models used are known to give predictions with the required accuracy.
- Assumptions made are seen as very reasonable.
- Much reliable data are available.
- Broad agreement among experts.

Significant sensitivity

- Relatively small changes in base case values result in altered conclusions (e.g. exceeded impairment frequency).

Moderate sensitivity

- Relatively large changes in base case values needed to bring about altered conclusions.

Minor sensitivity

- Unrealistically large changes in base case values needed to bring about altered conclusions.

Accordingly, an uncertainty factor with a significant uncertainty combined with significant sensitivity can be concluded to have a significant effect on overall risk. This in turn may demand the decision maker to select a severe design requirement, for example severe design accidental explosion load. On the other hand, when the uncertainty is significant but has the low sensitivity to the results, the uncertainty factor can be judged to have a relatively less impact.

When it is found that uncertainty factor(s) have a significant influence on the total risk, the decision shall not be taken only based on the risk analysis results but a more detailed in-depth analysis taking these uncertainties into account.

6.3 Decision making process with uncertainty assessment

The method suggested in this thesis uses both risk acceptance criterion to have a minimum safety level and ALARP in further risk reduction process. The suggested method does not limit ALARP focus to only risk reduction context decision problems, it encourages the use of ALARP principle in a general safety related decision problems, but uses further risk reduction principles.

In reducing risk further, the ALARP principle (HSE, 2001) in general uses "grossly disproportionate" term whereas Norwegian regulations (PSA, 2013) use a term "significantly disproportionate". However the intention behind these terms is the same. i.e., to implement a risk reducing measure unless costs and benefits differ by a certain proportion. Hence no particular focus between these two terms are given in this thesis and the terms are used interchangeably.

Different perspectives exist across the industry on how much focus the uncertainties should be given for safety related decision contexts (PSA, 2013).

Following (Abrahamsen, 2015), one perspective is to use a traditional cost-benefit (cost-effectiveness) analysis, where the decisions are made with reference to an expected value. This means only limited or no focus is given to the uncertainties. Another perspective is to use cautionary principle that gives high focus to the uncertainties and without making reference to cost-benefit (cost-effectiveness) analyses. The former is referred as "extreme economic perspective" and later is "extreme safety perspective". A third category of perspective lies between these two extremes, and will be referred to as "combined perspective" in this thesis.

Measures following cautionary principle are being normally implemented when the risk is considered significant. In offshore installations, the fire water pump room shall be protected from its surroundings by A-60 fire rated wall (NORSOK, 2008). This standard approach is based on experience from similar industries and sound judgements and to have a minimum safety level. No reference to cost-benefit analysis is necessary and the decision is based on cautionary thinking i.e. any damage to fire water pumps will put the installations safety level in question including living quarters. The consequences of non-availability of fire pumps are judged to be high even though the probability of a fire to destroy the fire water pump room is very low.

Hence, the selection perspective to be used is based on the decision context and that may vary in relation to the phase, activity or system. When the uncertainty and sensitivity is minor the use of extreme safety perspective may lead to inappropriate use of resources instead extreme economic or combined approach may be more appropriate. On the other hand in situations of extreme risk, safety perspective is more suitable even if the cost-benefit analysis concludes expected costs to the expected benefits are significantly disproportionate.

In reducing risk beyond minimum acceptance level regulations (PSA, 2013) require that ALARP principle following cost-benefit analysis to be used. In case of any uncertainties associated with a proposed measure, solutions based on cautionary principle to be used.

Cost-benefit analysis to implement ALARP and grossly disproportionate criterion means, costs are defined as grossly disproportionate to the benefits, if the expected cost E[C] is considered "n" times higher than the expected benefit E(Stacey), where "n" represents grossly disproportionate factor and has a single value for all decision contexts. This is considered not suitable for safety decision contexts which require different decisions with respect to uncertainties.

This implies that the use ALARP in safety related decision making process requires a dynamic interpretation in the sense that the grossly disproportionate criterion should range from extreme economic perspective (where decision is made based on cost-benefit analysis) to extreme safety perspective (where decision is made following cautionary principle).

For the above purpose, a layered approach originally proposed by (Aven, 2011) and modified by (Abrahamsen, 2015) is used as shown in Figure 15.

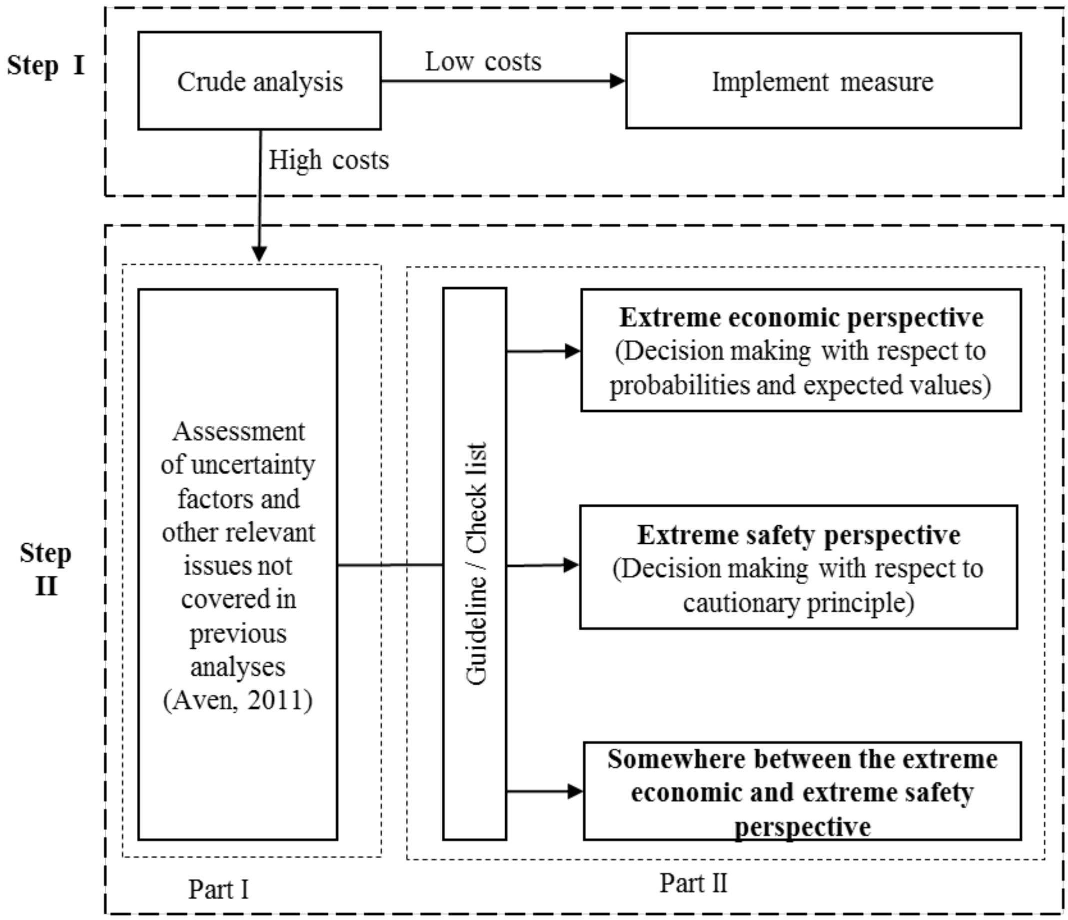

Figure 15. Layered approach in implementing ALARP in decision making process (Abrahamsen, 2015)

The approach is described as below.

i. First a crude analysis is carried out and a safety measure should be implemented when cost is low. This is represented by step I in figure Figure 16.

ii. When the cost is higher, decision making context should be made based on the uncertainty factors assessment. A qualitative guideline or check list approach to be used in selecting appropriate perspective for decision making. Step II in Figure 16, represents these aspects.

The guidelines can be of qualitative type describing the appropriateness of the different decision contexts. This may include parameters involved in establishing DALf mainly in terms of uncertainty factors and additional parameters that are not explicitly known to the vendor, e.g. details of unknown modifications, increased margin for ageing and expected change in well conditions. The decision context will guide whether ALARP to be implemented following extreme safety or extreme economic perspective and uncertainty factors assessment have major role in this process.

6.4 Aspects of suggested approach in relation to ALARP triangle

The total risk picture covering (A, C, C*, U, P, K, S) aspects as described in section 2.4.2, may provide the decision maker with a broad, comprehensive and nuanced risk picture demanding to look for different alternatives in deciding the accidental loads that shall be used in the design.

A coarse picture in describing the suggesting method is shown in Figure 16. The figure combines the ALARP triangle with different levels of uncertainty (significant, moderate and minor) and sensitivity (significant, moderate and minor) for an uncertainty factor and guiding the decision maker in selecting the appropriate approach for different levels assessment of uncertainty and sensitivity.

This would also entail the analyst to find out what can be done to reduce the significance of these parameters on the overall risk in order to make a correct decision on establishing design accidental loads and implementing risk reducing measures.

It should be noted that it is not a straight forward approach to take decisions based on uncertainty and sensitivity. A detailed guidance or check list shall be prepared for each decision problem that describes interest of relevant various parameters associated with the decision process.

From Figure 16, a situation, say "A" with (U3, S3) in terms of uncertainty and sensitivity will lead to follow extreme safety perspective in taking decisions. Accordingly the decision maker will choose a severe design accidental load than proposed by the risk analysis due to large uncertainties connected to the risk results in terms of consequences.

On the other hand, a situation "B" with (U2, S1) may allow the decision maker to choose cost benefit (cost-effectiveness) analysis to decide on implementing higher design accidental loads in the sense that implementing increased risk reducing measures.

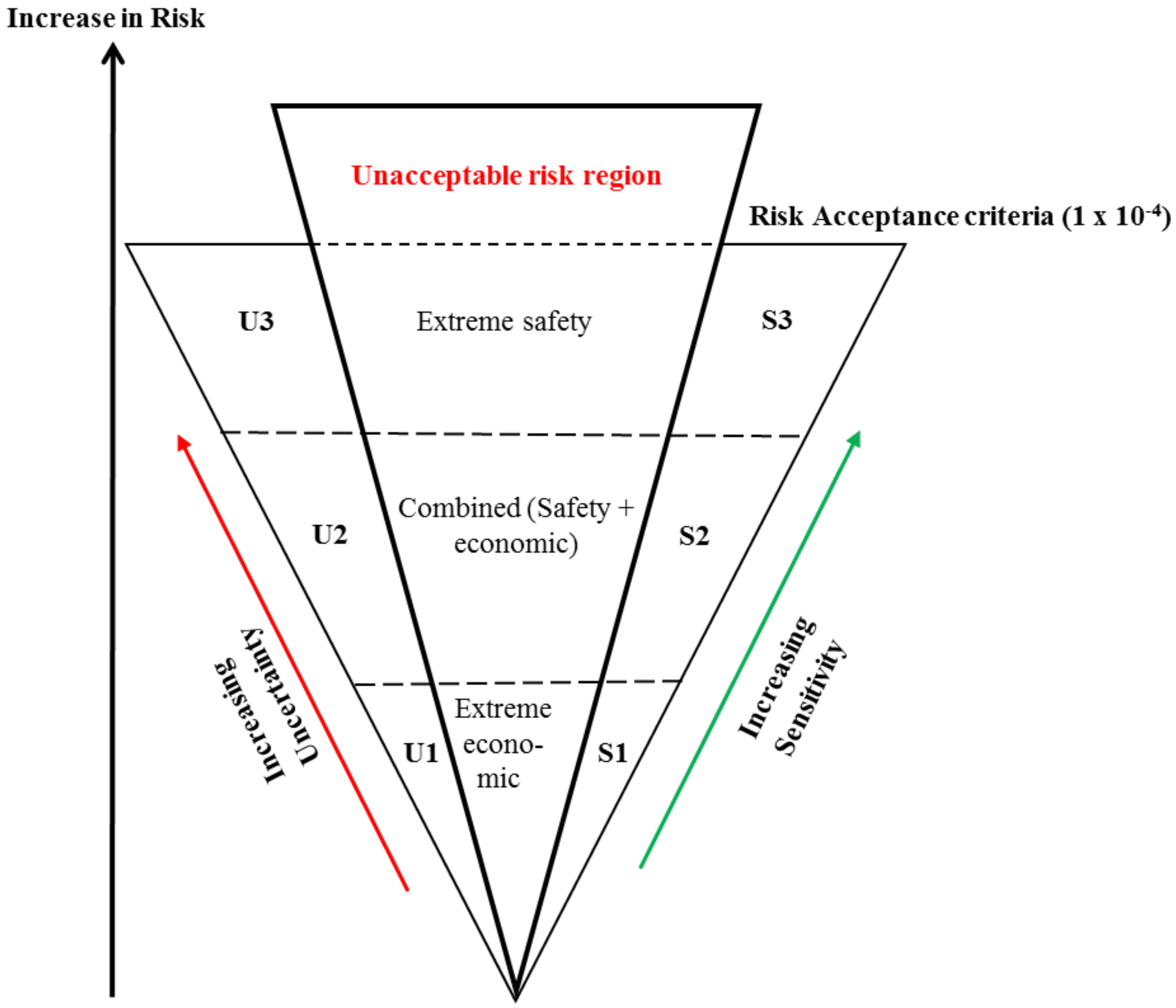

Figure 16.ALARP approach considering uncertainty factors (NORSOK, 2010)

6.4.1 Illustration of suggested method

6.4.1.1 *Flowchart of suggested method*

In establishing the design accidental for explosion, the suggested method includes both risk acceptance criterion and ALARP process in the decision making process and the approach involves two levels. An overview of suggested method is presented in Figure 17.

In the first level, the risk analyst or the engineering contractor establishes the dimensioning accidental load following probabilistic approach as done today. The uncertainties associated with the background knowledge applied in explosion risk analysis are evaluated following uncertainty factors assessment as described in sec 6.2. Following the assessment, the risk analyst or engineering contractor proposes a margin in the estimated load to the decision maker in the form of suggested design accidental load. A list of possible measures on reducing the risk further is proposed.

In the second level, the decision maker review the following to get an overall risk picture and taking assistance from relevant resources, which may include experts, discipline professionals etc. when relevant.

a) the results along with uncertainty factors assessment

b) risk acceptance criteria (regulations and internal)
c) other relevant uncertainty factors assessment
d) proposed risk reducing measures.

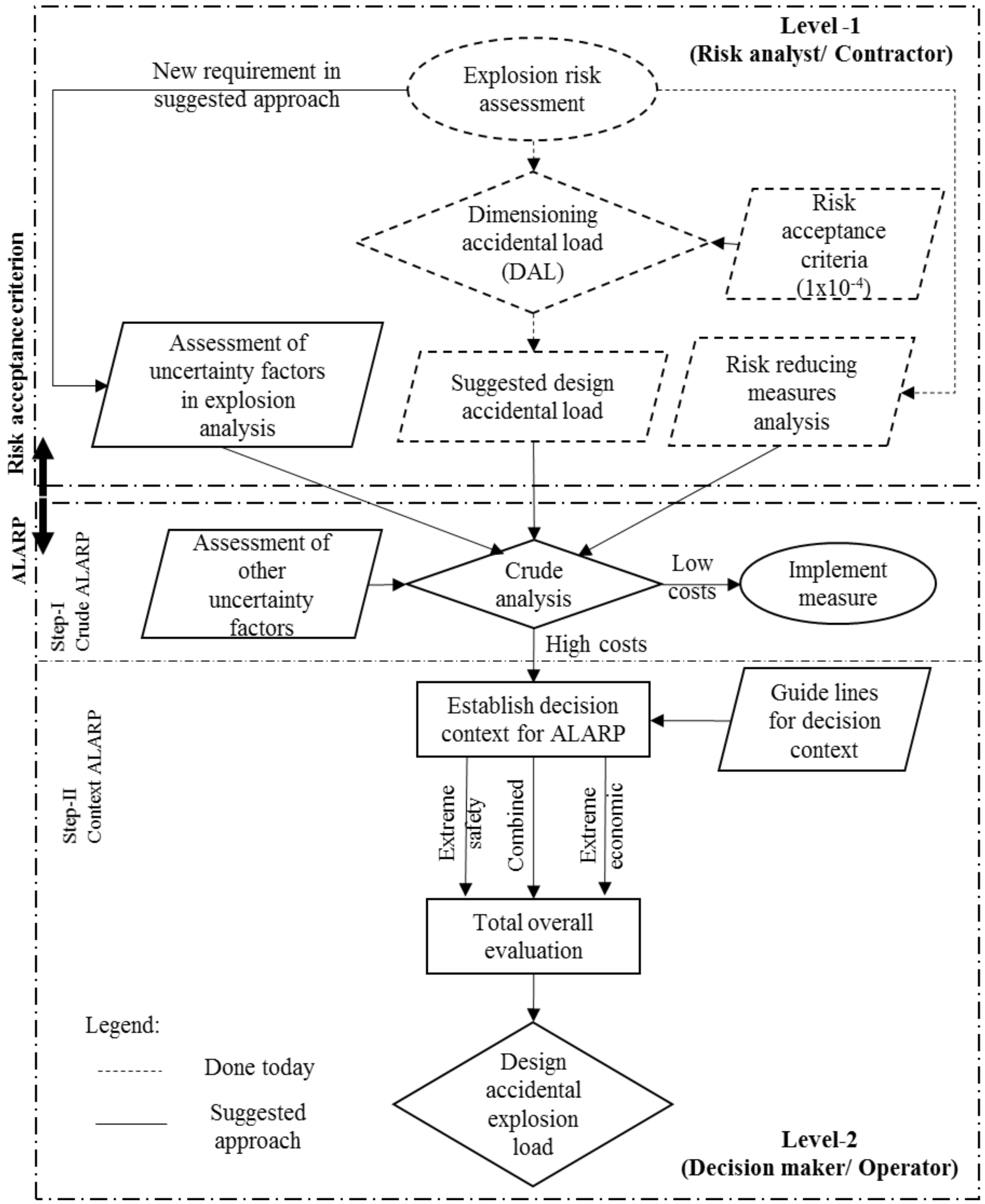

Figure 17. Flowchart of suggested method

A crude ALARP analysis to implement a severe design load than suggested by the risk analysis to be performed. In selecting the severe design load, reviews done as above, design loads of similar installations, experience will be used. The selected severe design accidental loads should be implemented if the cost of doing so is considered to be low following crude analysis.

When the crude analysis results in higher costs, a decision will follow context ALARP. The decision maker establishes the decision context following the guide line established for the decision problem.

The uncertainty factors assessment should include one related to the explosion analysis and for the parameters that are not relevant to the explosion analysis but have influence on the design accidental load. This may include for example operators risk perception, allowance for any unplanned modifications during operational time, influence of learning from other installations, reputation and not least than decision makers knowledge.

Based on decision context, an approach is to implement ALARP (Extreme economic, extreme safety or combined approach) is taken. The guide line may allow to choose either extreme safety or extreme economic perspective when the decision context evaluation results in using combined approach. Necessary cost-benefit analysis are carried out for extreme economic perspective.

The context based analysis outcome is assessed by the decision maker in a larger context considering various constraints and limitations and a decision is made on the final design accidental load that shall be implemented in the design.

6.4.1.2 *Guidelines for decision context*

Guide lines to be developed for all decision problems. These shall provide guidance to the decision maker to decide on which decision context to be used in implementing ALARP, i.e. extreme safety, extreme economic or combined perspective. A guide line will have the basis in uncertainty factors assessment, company risk perception, learning experience from own and other installations etc.

The guidelines can be of type that proposes possible uncertainty reducing measures for uncertainty factors that have a significant influence on the risk results. The guide may follow “Yes or No” type questions to make decision maker task simple and robust. Different sub contexts to include various uncertainty reducing measures is helpful. This may include category of uncertainty reducing measures (related to technical, operational or organizational, influence by future activities and issues with implementation etc.

When the guideline evaluation results in more number of “Yes” answers, the decision maker may conclude that significant uncertainty is associated with the suggested design accidental load and decide to implement risk reduction measures following extreme safety perspective in implementing ALARP. More “No” answer may allow the decision maker to choose extreme economic perspective. When the evaluation results in a combined approach, the decision maker may choose to implement ALARP following either extreme safety or extreme economic following a simple qualitative evaluation using check list.

As the risk acceptance criteria for main safety functions implies that it is applied for the safety function in total (Petroleum Safety Authority, 2015 #6). The probability reducing measures which are considered less reliable due to its dependency on operations can be part of the uncertainty reducing measures in the guideline. This will highlight the importance of operational measures in selecting the decision context and necessary actions can be planned to make the preventive measures more reliable.

6.4.2 Design accidental load for explosion following the suggested method

Following an explosion risk assessment and meeting the minimum risk acceptance criterion, QRA vendor communicates the risk in (A, C, C*, U, P, K, S) form to the decision maker. A list of uncertainty factors related to the applied background knowledge in explosion analysis is identified and assessed for its sensitivity and uncertainty on total risk.

An example of few uncertainty factors and their assessment following the steps described in 6.2 is shown in Table 2.

Uncertainty factor	**Sensitivity**			**Degree of uncertainty**			**Effect on overall risk**		
	Minor	Moderate	Significant	Minor	Moderate	Significant	Minor	Moderate	Significant
Geometry model/simplification			x		x			x	
Equipment count for leak sources	x				x		x		
Process leak rate and leak duration			x			x			x
Gas dispersion results/ representative scenarios		x			x			x	
Ignition point in the gas cloud		x			x			x	
Level of congestion (Obstruction factor)			x		x				x
Area of explosion relief openings		x		x				x	

Table 2. An example of uncertainty factors in explosion risk analysis

This in practice the risk description will include impairment frequency that that meets risk acceptance criterion, suggested design accidental load for selected barriers, sensitivity studies, uncertainty factors assessment (as described in Table 2) by the analysts and proposed risk reducing measures for further risk reduction.

The decision maker reviews these results considering uncertainty factors assessment of explosion risk analysis and other relevant uncertainty factors assessment as mentioned in section 6.4.1 into account.

A severe design load than suggested by the risk analysis is evaluated through a crude ALARP analysis. In selecting the severe design load, risk results along with uncertainty factors assessment, design loads of similar installations, resource group experience will be used.

i. Severe design accidental load should be implemented in the design if the crude ALARP analysis shows that cost of implementing a severe design accidental load is low.

ii. When the crude analysis results in higher costs, a decision will follow context ALARP. A guide line established the explosion load decision problem as described in sec. 6.4.1.2 is used by the decision maker to decide on the decision context that shall be used to implement ALARP.

    A severe design load as proposed should be implemented in the design if the decision context results in extreme safety perspective or when costs are not in gross proportion to the risk reduction by applying severe design load. Decision to follow either extreme safety or extreme economic perspective when the decision context for ALARP results in a combined approach (between extreme safety and extreme economic) may be decided based on the guideline.

The context based analysis outcome is assessed by the decision maker in a larger context considering various constraints and limitations and a decision is made on the final design accidental load that shall be implemented in the design. Upon decision, the uncertainty factors to be revisited to ensure that the chosen design accidental load is sufficient enough to cater for uncertainties and risk is ALARP.

7 A case study with suggested approach

A case study (Aibel, 2016) to apply the suggested method is presented. Applying the method on the design accidental explosion load of an installation is a huge task. A case study that has a decision problem and also influences the DAL is considered. The idea is to demonstrate how the suggested method following (A, C, U) risk description and implementing ALARP through dynamic approach is used to achieve a solution to the decision problem.

7.1 Background of the project

In treating waste water on offshore installations, containerized solutions have normally been on temporary basis. Temporary equipment's are normally exempted from complying with all requirements of a permanent system and hence have limitations on using them offshore. To meet the increased demand to treat the waste water, the company has planned to install a waste water module on permanent basis. A typical containerized temporary solution is shown in Figure 18.

Figure 18. Typical containerized solution for temporary use offshore (Aibel, 2016)

7.2 System description

The system taken for case study is installing new module on an existing installation. The project scope is to install a waste water separation system module that will separate solid, water and oil from the waste fluid stream and discharge clean water into the sea following Authority and Company regulation.

The installation of separation system module will reduce the need for drilling new injection wells, reduce risk of formation stresses in the geological formation and will discharge clean water into the sea that will protect environment. The project seen a good business case.

7.3 Design Alternatives

The installation has some space assigned for process extension in the weather deck. The platform uses the drilling rig often. When the rig is connected to the platform, there are limitations on the level of activities on the weather deck including crane access to the module. More importantly, the selected rig has a limitation on the gap between the top deck and bottom of rig cantilever. This implies a major restriction to the height of the module. This did allow using the space that is meant for extension.

Further, it looks like the specific project was not seen in the initial phase. Different solutions on technological view have been evaluated. Regarding the location of the module, solutions are discussed from different view. This includes placing near to the tanks that will feed the waste water to the module to avoid long run of piping and supports, etc. In a location where easy crane access is feasible or in a place where no restriction of space to the module size, etc.

Two concepts, which has different module sizes, have been assessed for implementation. It is decided to install the module in the same level where the slurry holding tanks are placed.

7.3.1 Alternative 1

The geometry model of the area including the proposed waste water separation module for first alternative, which is rectangular is shown in Figure 19.

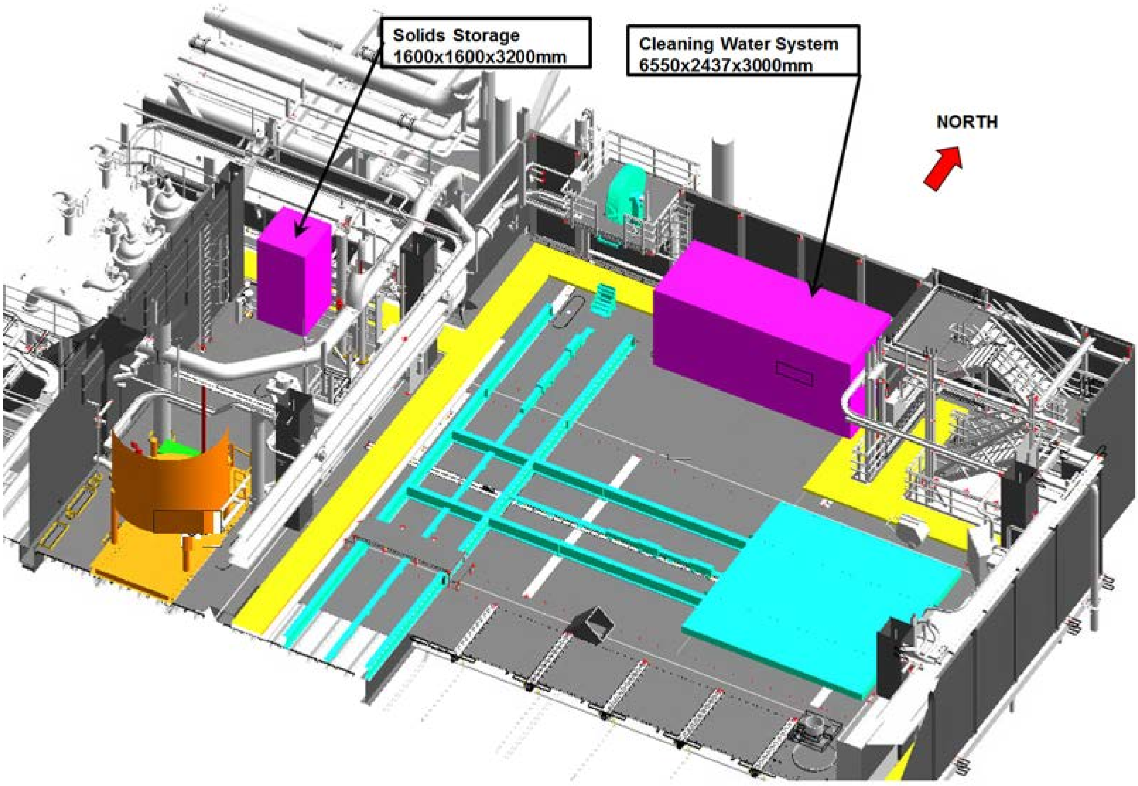

Figure 19. Model showing location of proposed module – Alternative 1(Aibel, 2016)

In the above model, escape way is shown in yellow. The cleaning module and the tanks for solid storage are shown in pink colour in the above model. The deck has a wind wall up to

3,5 meters height. The module height is three meters. A simple verification using numerical methods indicates that the ventilation is not affected to the intervention area located south side of the proposed module location. There will be new pipe routings and supports between the slurry holding tanks and the cleaning module. The congestion due to the solid storage and new piping and structure is relatively small and neglected in the evaluation. Few relevant points to this alternative are:

1. Given height may increase for higher operating capacity of module.
2. Will not interfere with the intervention activities.
3. Will not require any changes to existing escape ways.
4. Low working space inside the module unless the design will be effective.
5. Relatively cheaper than alternative 2.

7.3.2 Alternative 2

The geometry model of the area including the proposed waste water separation module for the second alternative, which is square is shown in Figure 20.

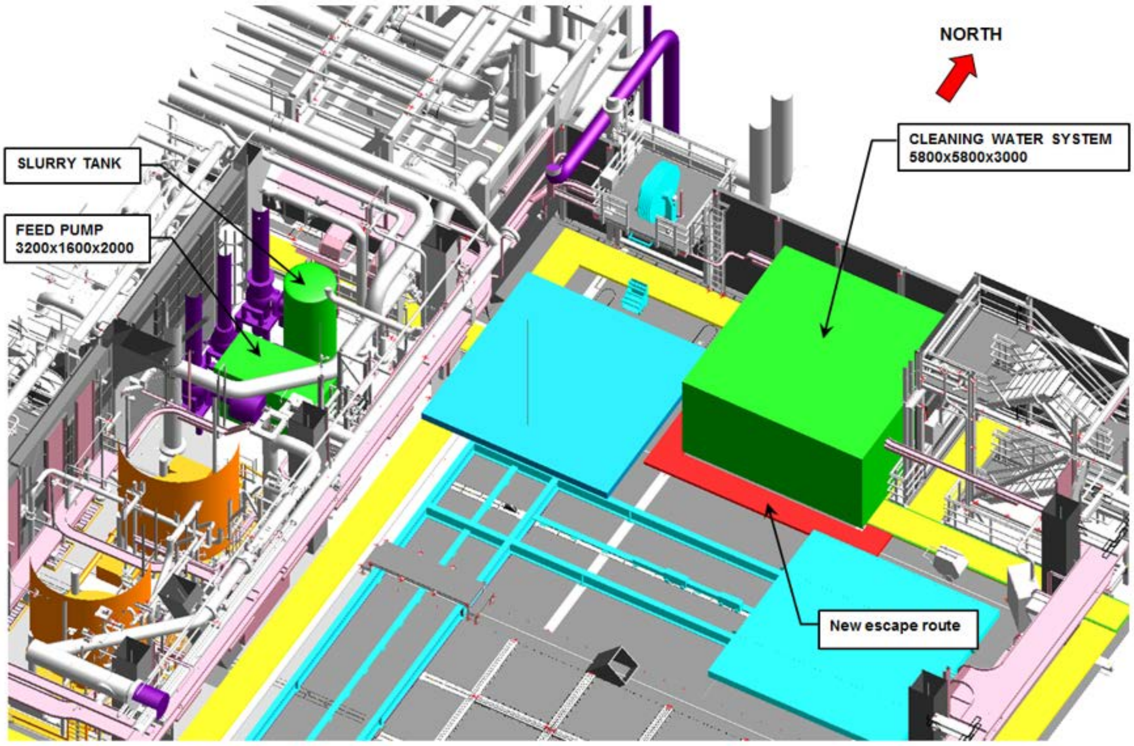

Figure 20. Model showing location of proposed module – Alternative 2 (Aibel, 2016)

The cleaning module and the tanks for solid storage is shown in green colour in the above model. This alternate needed to use feed pump additionally. As like first alternative, the module height is maximum three meters. No impact on the ventilation to the intention area identified in the simple evaluation. There will be new pipe routings and supports between the slurry holding tanks and the cleaning module. The congestion due to the solid storage, feed pump and new piping and structure is relatively small and neglected in the evaluation.

Few relevant points to this alternative are:

1. There could be a need for increased co-ordination with intervention team.

2. Will require changes to existing escape ways.
3. Sufficient operational space is guaranteed and no increase in the height is necessary
4. Have some contingencies to cater for increased operating capacities to an extent.
5. Significantly costlier than first alternative 1.

7.4 Assumptions

The risk analysis will have several assumptions due limited available information. Few assumptions related to early stage evaluation is given below.

i. Module size will not change from temporary to permanent system
ii. Non-critical system
iii. No impact on ventilation to intervention area
iv. No change in operating capacity
v. No stand-by unit
vi. Minor modification to existing structures is sufficient

7.5 Decision problem

The decision problem is to select a suitable alternative of the waste water module that is economically feasible and has lowest risk level practically possible for its operational lifetime taking uncertainties into account.

7.6 Uncertainty assessment

The steps involved in the suggested method includes:

i. Uncertainty factor generation
ii. Uncertainty factor assessment following
    a. Degree of uncertainty
    b. Sensitiveness to risk
iii. Decision making on alternative
    a. Crude ALARP analysis
    b. Context based ALARP
iv. Total evaluation and final decision

7.6.1 Uncertainty factor generation

Uncertainties exist with physical observable quantities. The identification of uncertainty factors is done only for the assumptions due to the time constraints but in practice there could more factors. A list of identified uncertainty factors for both alternatives is shown in Table 3.

7.6.2 Uncertainty factor assessment

The uncertainty factors hidden in the background knowledge for the above assumptions are will be evaluated in this section.

Assessment of identified uncertainty factors for its sensitivity and uncertainty on total risk following semi-quantitative approach given in sec. 6.2.2 is shown in Table 3. The effect on total risk for different combinations of sensitivity and degree of uncertainty for the identified uncertainty factors is based authors knowledge.

Uncertainty factor	Alternative 1									Alternative 2								
	Sensitivity			Degree of uncertainty			Effect on overall risk			Sensitivity			Degree of uncertainty			Effect on overall risk		
	Minor	Moderate	Significant	Minor	Moderate	Significant	Minor	Moderate	Significant	Minor	Moderate	Significant	Minor	Moderate	Significant	Minor	Moderate	Significant
Geometry model/ simplification			x		x				x			x	x			x		
Equipment count for leak sources	x				x		x			x			x			x		
Occurrence of process leak	x			x			x			x			x			x		
Process leak rate and leak duration	x				x			x		x				x			x	
Ignition following leak		x		x			x				x		x			x		
Level of congestion inside the module			x		x			x				x	x				x	
Level of congestion to the area		x			x				x		x		x				x	
Impact on existing ventilation			x		x				x			x	x				x	
Explosion within module	x			x			x			x			x			x		
Impact on explosion pressure in the area			x		x				x			x	x				x	
Accidental discharge of fluids to sea		x			x			x			x			x			x	
Extension of existing deluge system to protect the module	x				x			x		x				x			x	
Need on strengthening the platform deck for the load		x			x				x		x			x		x		
Operating capacity of the module		x			x				x		x			x			x	

Table 3. Uncertainty factors analysis for alternative 1 and 2

A brief of this evaluation for the assumptions in identifying and assessing its impact on the total risk is given below:

a) <u>Module size will not change</u>

Complete information about the module is not available at this phase. In alternative 1, vendor has long experience on the temporary system but either has limited or no previous experience on the design for permanent installation. The working environment requirements are stringent for permanent system. Hence vendor's statement that the size will not change from temporary to permanent system may not be valid. In case of increase in the required capacity of volume for waste water treatment, the height of the module could increase.

b) Non-critical system

The module will handle wastewater stream, which has significantly low HC. Following initial coarse evaluation, it is assumed that system has less potential to contribute to a fire and explosion hazard. This seems to be valid assumption. Still efforts in the form of procedures required to have a control of the fluid that shall be treated using the module.

c) No impact on ventilation to intervention area

The module height is lower than the wind wall height. The given height will not influence the ventilation to the area from north. For the wind direction from south, the module may give some restriction. In alternative 1 this impact is evaluated to be more due to higher length than alternative 2. No appreciable change in the explosion load is foreseen for the given module size. In case of any increase in height beyond 3,5 meters will have significant impact on the area explosion load.

d) No change in operating capacity

The operating capacity is based on the need for the specific installation where the unit will be installed. There has been some discussions whether to treat inventories from nearby installations supplied through boat. No solid decision is made on this and the plan to include nearby installations may require increasing the operating capacity and the module size. This has large impact for alternative 1 which require two levels of design to meet the increase in capacity. This will have significant impact to area explosion load and require more structural work.

e) No stand-by unit

No stand-by unit is included as any problem with the unit will be rectified in a short time. However this should be finalised based on whether or not operators wants to include wastes from nearby installations to be included.

f) Minor modification to existing structures is sufficient

A coarse evaluation resulted that no significant changes to the base structure is necessary to take care the module weight. However, any increase in capacity may require strengthening.

7.6.3 Other evaluations

i. Installing the system as open skid will avoid the ventilation obstruction problems. However equipment design in both alternatives did not allow that.

ii. A suggestion to install ventilation lovers on both north and south side discarded as it will impact the equipment design inside which are attached to the wall. Hence in both alternatives mechanical ventilation will be installed. However alternative 2 has increased possibilities to have additional louvres due to its geometry.

iii. The evaluation of ventilation is verified through simple numerical methods and may need a CFD evaluation in further phases to have more accurate results.

iv. In both alternatives, the risk associated with the module itself is considered low due to less amount of hydrocarbon involved in the process. The main decision problem is which alternative will reduce the cost and the explosion risk of the area where the module is planned to be installed.

7.6.4 Decision making on alterative

Following (A, C, P) perspective, the risk will be communicated to the decision maker in terms of probabilities. The evaluations based on the assumptions mentioned in sec. 7.4 will not show any major difference on the risk levels to the area between the alternatives. The cost of alternative 1 is relatively less compared to alternative 2. A decision based on the assumptions without taking the uncertainties hidden in the background knowledge may not result in correct decision. Due to the cost and same level of risk, a decision following traditional cost-benefit analysis would have resulted in choosing alternative 1. It should be noted that decision is valid as long as the assumptions to the decision problem holds good.

Following suggested method that uses (A, C, U) perspective, the risk will be communicated to the decision maker in terms of probabilities. Further uncertainty factors assessment will be carried out and presented along with the risk results.

The decision maker can see that alternative 1 has uncertainty factors that has significant influence on the overall results than alternative 2. A crude analysis is conducted that resulted in higher costs to implement alternative 2. Then the decision is moved to ALARP decision context.

In deciding ALARP decision context no specific guideline is generated for the case review. But normally a guideline by the management will allow to include other parameters that have indirect influence on the decision process. It is assumed there are no other indirect parameters that could affect the decision. Hence, only uncertainty factors assessment is used as input in deciding the decision context.

The cost difference between alternatives is significant. However the uncertainty factors analysis carried out both alternatives revealed that level of uncertainty associated with alternative 1 significantly higher.

In practice, there will be more analysis carried out like CFD analysis, explosion sensitivity analysis, etc., which might give increased picture about the influence of alternatives on the dimensioning accidental events to the area. It might be that the resultant DAL due to change in DAE by the influence of new module is still with in the design accidental load for the area but might have reduced the available margin.

As this area is not initially considered for any process extension, the increase in risk should be viewed critically in the decision making process. Hence taking the uncertainties associated with the module that will have on the explosion risk to the area due to reduced ventilation, choosing an extreme safety approach in the decision process selecting the alternatives will be more appropriate. Accordingly the alternative 2 will be selected to implement. A total evaluation in a larger context to be done before the final decision is made.

7.6.5 Conclusion

Summary of points that supports the alternative 2 in the decision process following the points given below:

i. Module size in alternate 2 has sufficient space to accommodate permanent system in terms of working environment issues.
ii. The size may also cater to accommodate the uncertainties in the operators decision on operating capacities

iii. The decision on stand-by unit may be accommodated but a trade-off between increased operating capacity and stand-by to be made. It is possible to use stand-by in case of any increased need following procedures.
iv. As the change in geometry is minor uncertainty, if height is not increased beyond 3.5 meters the impact on the existing explosion load to the area is considered to be minor. Still additional risk reduction measures in the form of additional louvers to be evaluated through CFD analysis.

It is acknowledged that alternative 2 involves increased work offshore in terms of re-routing escape routes and increased co-ordination among intervention team etc. This rerouting of escape ways is not a bigger task offshore as along the escape route design is not affected and is considered acceptable.

There is no direct interaction between the module and intervention activities but only in terms of use of space. Moreover, the frequency of intervention operations is low. Hence any need for increased co-ordination during simultaneous operations can be well established through procedures.

8 Discussion

In this chapter some of the issues related to establishing design accidental loads for explosion raised during, and as a result of reviewed literatures (including regulations and standards) and discussions with risk management expertise and colleagues are discussed. This discussion also uses the term risk analysis instead of explosion risk analysis in some places as the content is largely relevant to other aspects of risk where the uncertainties are involved for fire risk and related analysis.

The starting point is how the current approach in practice complies or differs from the approaches mentioned in the literature in terms of establishing design accidental loads followed by its frailness, among others, to minor modification projects and essentialness of having a new method that will be in compliance with PSA regulations. Further in discussing the suggested method, how the current approach in reducing risk through ALARP approach falls short and the aspects of suggested method that may lead to robust decisions in the decision of process establishing a design accidental load for explosion taking uncertainties into account. The challenges associated in implementing the suggested method are also discussed.

8.1 Uncertainties associated in establishing design accidental load

We have reviewed (A, C, P) and (A, C, U) risk perspectives and corresponding risk descriptions (Aven, 2011). It is highlighted that offshore risk assessment uses (A, C, P) perspective and describes risk using probabilities and expected values for the decision making. Following (Aven, 2008a), this may bring surprises if the uncertainties in the background knowledge is not taken into account in the decision process and when the knowledge used in the analysis is weak.

Refer to Figure 21, consider a situation A1, which corresponds to a risk level estimated by the risk analysis using (A, C, P) perspective and uncertainty in the background knowledge (K) is not considered in the decision process. This decision may give surprises in the years to come, for example putting the risk at A2 which has nearly no margin to the acceptance criterion demanding further measures which limits the available risk reducing measures.

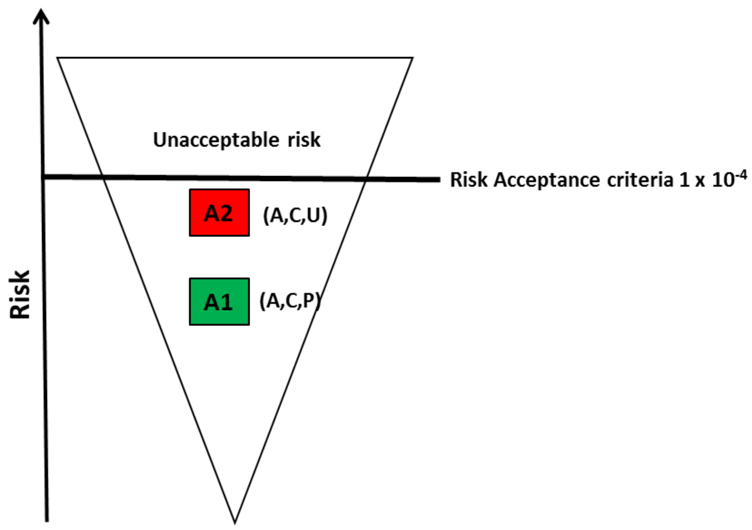

Figure 21. Risk acceptance following (A,C,P) and (A,C,U) perspective

On the other hand, if the uncertainties associated background knowledge to the situation A1 was taken into account in the decision process, the decision maker might implement additional measures already in the early phase to avoid surprises at later stage.

Referring to the case study, the decision based on assumptions without taking the uncertainties associated would have resulted in choosing alternative, which is obviously has higher risk levels than alternative 2.

It is expected the (C,P) perspective based risk definition in current NORSOK Z-013(NORSOK, 2010) will be obsolete and the new edition will reflect (C,U) perspective following PSA guidelines (PSA, 2015b). This implies increased efforts will be needed across the industry in communicating uncertainties in the risk results including explosion risk assessment, which is conducted following NORSOK Z-013 today. The main focus will be to identify uncertainty factors related to applied knowledge and account in the decision making process.

Two familiar terms across the industry in this aspect are: DAL and design accidental load. DAL is the most severe accidental load that the installation or safety function shall withstand for a specified duration to meet the risk acceptance criteria and design accidental load is the accidental load that is selected to implement in the design (NORSOK, 2010).

In contrary to (Matland, 2013b), this thesis suggests having these two terms to make a clear distinction i.e. DAL (estimated load) and design accidental load (applied load). It is also acknowledged that the acronym DAL is used by many to describe both dimensioning accidental load and design accidental load. This should be criticized as lack of focus in the use and is not in accordance with NORSOK Z-013 (NORSOK, 2010). The involved parties (operating companies, risk analysts and engineering contractors) should increase the focus in maintaining the use of terminology that represents its meaning and purpose.

Differences in the accidental load may also be expected based on contractual terms between the engineering contractor and the operator of the installation in question. For example, for a given risk results, an engineering contractor may choose a conservative load to be implemented in the design if the increase in the costs will be paid by the operator. However, the operator has the final responsibility on the implemented accidental load in the design.

There could be differences in DAL for an installation among different analysts. This variation is due to different use of models, methods and experts background knowledge. This to some extent differs from NORSOK Z-013 (NORSOK, 2010) intention to use a standardized method for explosion risk assessments across the industry that will reduce the variations among different explosion study vendors. There was not made any comparison analysis, but the discussion with QRA vendor and operators risk expertise expresses that when the complete analysis is done following established procedure, the results should not be so different to change the decision on design accidental load. This is justified on the basis that a simplification in one model may be compensated through increasing conservatism in the approach (Chinnusamy, 2016).

Further, ageing of the installations are significant on the decision on design accidental load. It is normal for QRA to base that the barriers and structures will maintain its integrity during its operational period. This means, risk analysis results are conditioned on barrier integrity, which may lead to increase in risk level when the assumption changes. It is the operator who is responsible to maintain its integrity and it is acknowledged that management of barriers are in practice in maintaining validity of assumptions (Vinnem, 2007). Despite regular maintenance, deteriorations due to continuous exposure to varying environmental conditions may reduce structural ability to withstand dimensioning scenario there by increasing the risk above acceptance criteria. The deteriorated connections on the existing blast barrier is shown in Figure 22.

Figure 22. Deterioration of blast wall connections(Stacey, 2010)

Ageing issues of a typical installation, for example, structural deterioration, changes to the hazard profile changes, modifications, and improvements in knowledge may have a strong influence on asset life extension beyond the original design life putting questions regarding its suitability for continued service (Holmes, Connolly, Wilday, Hare, & Walsh, 2010).

Discussions with operators risk expertise and risk analysts(Chinnusamy, 2016) have highlighted that, in some of existing installations, QRA update has revealed that risk level has exceeded acceptance limit ($1x10^{-4}$) during its operational period demanding more robust risk reducing measures. It is understood that they are relatively older installations and during the design, neither knowledge about the explosion phenomena had not developed so much like today nor sophisticated models were available to use in the design. This may not be a significant problem in the newer installations but it will take many years to gain such an experience.

The increase in risk beyond acceptable limit shows that surprises based on the knowledge of the analyst may occur (Aven, 2013). There are some rare cases where installations have been scrapped prematurely because they did not make margins in the design phase to cater for uncertainties (Vinnem, 2014). And there is no strong reason not to believe that this may happen in future as well, for the decisions already have been made based on current knowledge.

In the case study, it can be seen that the decision without taking hidden uncertainties in the applied knowledge would have resulted in a poor decision.

In conclusion, risk analysis based on (A,C,P) perspective should be replaced with (A,C,U) perspective that holds uncertainty as main component of risk. Probabilities will still be used as a tool and will be considered as epistemic based expression of uncertainty, i.e. expressions of uncertainty following analysts' background knowledge (Aven, 2008a). It is one of the requirements by the suggested method that uncertainty factors in the applied background knowledge is evaluated and expressed to the decision maker.

8.2 Influence of post design modifications on design accidental load

During the decision on the accidental load in the early phase risk analysis, a certain margin is considered to account for uncertainties associated with available information.

It is understood that in selecting a margin focus is to ensure that the as-built DAL will be within selected design accidental load (Fløttum & Svidal, 2013). This contradicts with the requirements stated by regulations for example, facilities regulations section §11(PSA, 2015a) requires that design loads shall always withstand dimensioning accidental loads and management regulations section §17 (PSA, 2015c) demands that analysis should be suitable to provide decision support related to upcoming processes, operations or phases. This may imply that risk analysis should anticipate and account for the future changes as well in order to ensure that design loads will not be exceeded in operational phase.

Modifications (both minor and major) in the operational phase may impact the original risk level. The engineering contractors' argument is that it is not possible to account for future modifications as these information will not be available in the early phase and feasibility on modifications should be evaluated individually following sensitivity analysis. This also implies that the margin considered in the base analysis for uncertainties should be maintained throughout installations life time. In practice very often, the available margin is consumed by the modifications (increased risk will reduce the available margin) and it is not transparent whether further risk reducing measures are evaluated in every modification as this may postpone or reverse the project due to increased cost. Further the way the sensitivity analysis is done may leave some risk unaccounted due to non-availability of exact updates offshore.

It is claimed by the QRA analysts (Chinnusamy, 2016) that, in a risk analysis, conservatism is maintained in the assumptions (e.g. increased congestion, increased equipment count, etc.) and choices selected in the models and analyses are considered sufficient to take care of uncertainties in the early phase design. It should be acknowledged that there is no practical and robust approach available today to verify whether the conservatism can overcome the inherent uncertainties and to see how this is reflected in the estimated risk level.

Despite conservative approach, it questionable if the decisions based on these results are robust. Large scale gas leak dispersion tests carried out at Spade Adam in the UK has indicated that the design accidental event that the structure should withstand without increasing risk level of the installation has in some cases increased the design load from the range of 0.5 to 1 bar to 1.0-2.5 bar. It may not be safe to rely on other conservative assumptions inherent in the design process to counterbalance any non-conservative assumptions related to the design against explosions (HSE), 2006 #19).

Major modifications, as discussed earlier, are normally assessed for its impact on existing risk level quantitatively and have a good control in maintaining existing risk level. However, significant challenge remains in the uncertainties associated with minor modifications in the operational phase that will have on the design accidental load. The minor modifications which individually do not represent any marked influence on the risk level, very often handled through qualitative assessments like HAZID, HAZOP and Safety evaluation. Further, the geometry model is not updated for every smaller modification. When the model used in later stage as a base for QRA update or sensitivity, analysis will produce risk with uncertainties. The current way of making decisions without considering uncertainties associated with minor modification projects may allow deviations occurring in later phases.

Hence, for the existing installations where the risk has exceeded above the acceptable limit, it cannot be said that only the knowledge about explosion phenomena might have resulted in risk increase. There is no reason not to think the significant risk increase might be by minor modifications on these installations. It is seen that (HSE, 2005) that minor modifications which are believed to have no impact on risk level on individual basis, but in cumulative may introduce a significant contribution to the total risk as cited by Vinnem, 2007.

When minor modifications are omitted in the risk analysis (Aven, 2008a) surprises could occur based on the current knowledge in later phases. In conclusion the uncertainties associated with minor modification projects should be taken into account in the decision making process of design accidental explosion load.

8.3 Design accidental explosion loads using suggested method

Establishment of design accidental loads for explosion following (A,C,P) risk perspective, describing the uncertainties using only probabilities and expected values and without taking the background knowledge into account, should allow the decision maker to anticipate deviations and encourage the decision maker in implementing risk reducing measures. However, the decisions following pre-defined risk acceptance criterion has reduced the ALARP focus to reduce the risk further beyond acceptance criterion (Aven & Vinnem, 2005).

The intention behind the suggested method is how to achieve a better decision of design accidental explosion load with minimal changes in the current practice and comply with PSA requirements on risk definition and risk reduction principle i.e. risk acceptance criterion and ALARP.

The establishment of design accidental load for explosion today following (A, C, P) perspective has the following issues.

a) *The explosion analysis based on probabilistic approach uses probabilities and expected values i.e. (A, C, P) perspective, in describing uncertainties. The risk description does not reflect the uncertainties hidden in the applied background knowledge, which can be different amongst different risk analysts (Aven, 2011).*

The suggested methods uses (A, C, U) perspective, in describing uncertainties. Uncertainty factors associated with the background knowledge will be identified and assessed for its impact on the overall risk. This will supplement the risk results to the decision making process.

The risk results following existing and proposed approach is shown in Figure 23.

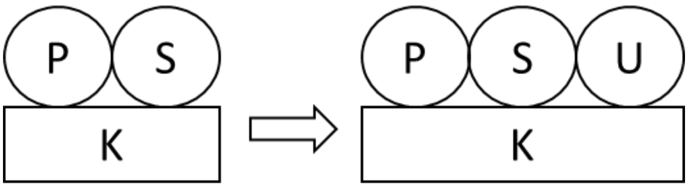

Figure 23. Risk picture form (A, C, P) to (A, C, U) perspective (Flage & Aven, 2009)

Where,

P represents probability based risk indices, e.g. 1x10^{-4} impairment frequency
S is the sensitivity studies used currently in place of uncertainty analysis
K is the background knowledge
U is the uncertainty related to the background knowledge

In this way the risk analysis will be a strong decision support tool. The decision maker will not accept the results when the uncertainty factors assessment shows a significant uncertainty in the applied background knowledge. Based on the level of uncertainty, the decision maker will decide to implement the risk reducing measures.

It can be noticed from the case study that the risk assessment including uncertainty factors analysis would provide a strong decision support in choosing the correct alternative i.e. alternative 2.

b) *In reducing risk further the current practice uses cost-benefit analysis in implementing ALARP and gross disproportion criterion (Aven, 2011).*

There are limits in terms of practicality and cost in investing safety in order to maintain the risk level. This limit depends on when the decision is taken and will vary. For example, a decision to implement a risk reducing measure at later phase of the design may be more restrictive in both practicality and cost compared to early stage. This is largely relevant for the explosion loads that shall be used in the design.

The risk reduction following (A, C, P) and (A, C, U) perspectives when cost benefit analysis is used in implementing ALARP is shown in Figure 24 and Figure 25.

Consider a situation A in Figure 24, which corresponds to a risk level estimated by the risk analysis. In line with PSA regulations on risk reduction this is considered to meet the first part in the sense the risk is below acceptance criteria and is considered acceptable.

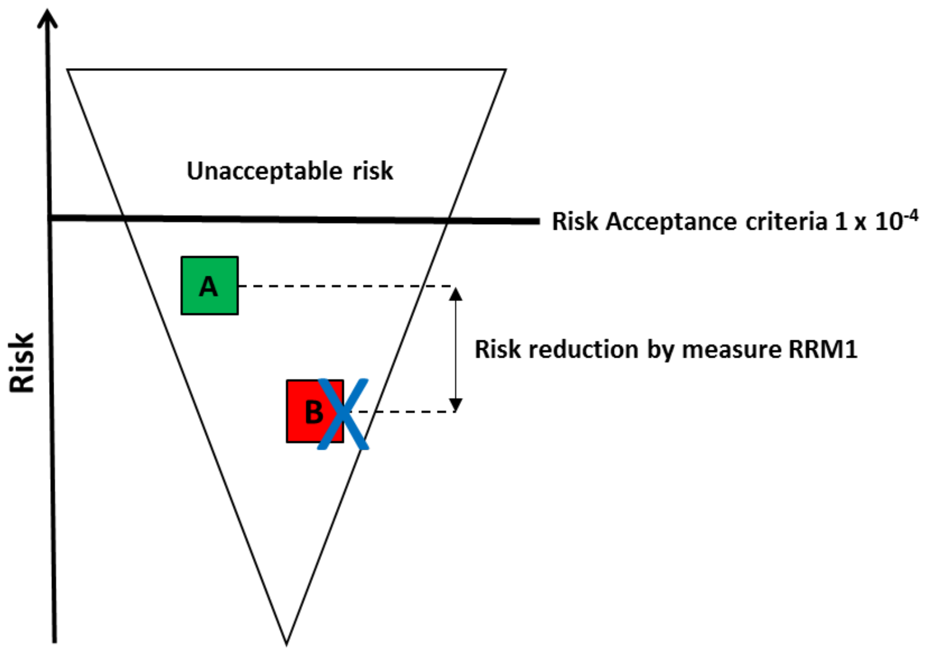

Figure 24. Risk reduction following (A, C, P) perspective

Further in risk reduction, let us consider a risk reducing measure "RRM1" is proposed which can reduce the risk from A to B. Following the current (A, C, P) perspective, an evaluation based on cost-benefit analysis is made which resulted in costs are grossly disproportionate to the risk reduction, and decision is made not to implement the measure.

This is what claimed by (Aven & Vinnem, 2007) that under risk acceptance criterion, focus on ALARP is reduced. When possible risk reducing measures are identified; they are quickly disregarded under ALARP approach following coarse cost-benefit analyses.

With the suggested method that uses (A, C, U) perspective, let us review the situation explained in Figure 24. The updated situation following suggested method is shown in Figure 25. Following the approach, assessment of uncertainty factors of applied background will be performed by the QRA analyst and will be submitted along with the risk results to the decision maker. The decision maker while reviewing the results at situation A along with uncertainty factors may conclude to implement the risk reducing measure RRM1.

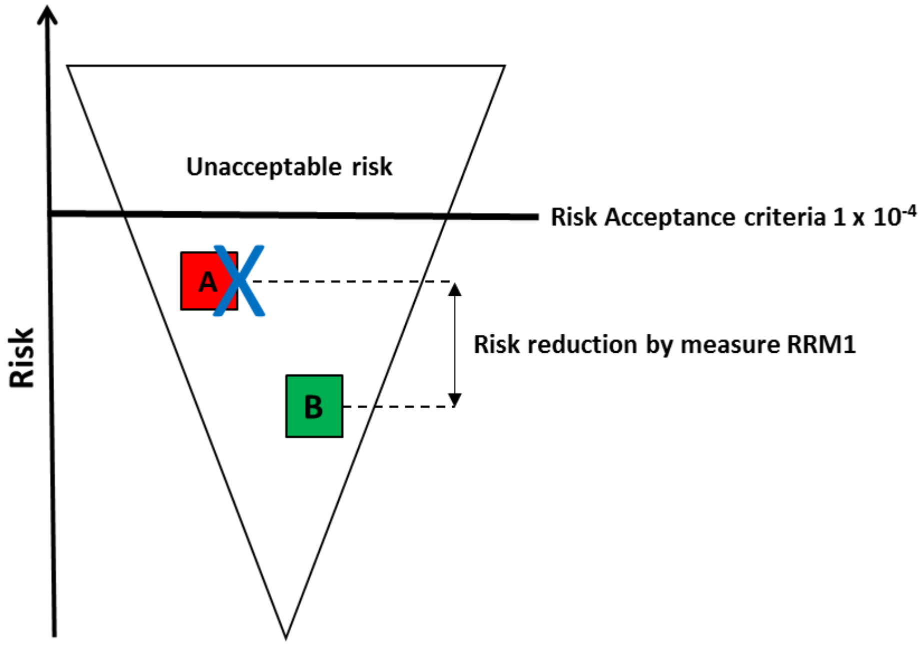

Figure 25. Risk reduction following (A, C, U) perspective

In referring to the case study, the uncertainties associated with operating capacity have large impact on the geometry. Any change in geometry will affect the area explosion pressure. This possibility of geometrical change for alternative 2 is significantly higher. The uncertainty factors evaluation of assumptions disclosed these uncertainties to discard alternative 1 from implementation.

But in reducing risk, safety decision contexts vary significantly and require different decisions. For example, in implementing a risk reducing measure for extreme risky situations, the decision maker may decide to implement the measure without doing any cost analysis or even when the cost-benefit analysis results show costs grossly disproportionate to the benefits. This likely in large uncertainty cases with extreme consequences.

Different perspectives from (Abrahamsen, 2015) that are used to take decisions in the face of uncertainty is discussed. One is “extreme economic perspective” that uses a traditional cost-benefit (cost-effectiveness) analysis, where the decisions are made with reference to an expected value and only limited or no focus is given to the uncertainties. Another perspective is to use cautionary principle that gives high focus to the uncertainties and without making reference to cost-benefit (cost-effectiveness) analyses is “extreme safety perspective”. A third category of perspective lies between these two extremes, and is referred to as “combined perspective” in this thesis.

In cost benefit analysis, costs are evaluated following expected values and uncertainties are not properly taken into account. Hence, implementing ALARP and grossly disproportionate criterion following only cost-benefit analysis is considered to be an ineffective way in reducing the risk further. For the same reason, making ALARP dynamic only by changing the grossly disproportionate factor may not be appropriate to address all situations as the uncertainties will not be properly addressed by the expected values (Abrahamsen, 2015).

This statement does not object use of cost-benefit analysis at all in ALARP demonstration. Cost-benefit analysis is considered to have importance in cases where the high knowledge is available about the situation in question with low uncertainties, by limiting inappropriate use of resources. The currently suggested method still uses cost-benefit analysis in extreme economic approach.

The availability of information at the initial phase of the project is insufficient. As project progresses from concept to operation the availability of information increases, hence, uncertainty due to lack of information is reduced but the ability to influence the cost reduces as the project phase progress (Fløttum & Svidal, 2013). This demands robust decisions on design accidental explosion loads at early phase to implement best measure at reasonable cost to achieve a required risk reduction. For the same measure, decisions at a later stage often become grossly disproportionate to the risk reduction when ALARP is implemented through cost-benefit analysis that uses a single gross disproportionate criterion.

This implies that the use ALARP in safety related decision making process requires a dynamic interpretation in the sense that the grossly disproportionate criterion should range from extreme economic perspective (where decision is made based on cost-benefit analysis) to extreme safety perspective (where decision is made following cautionary principle).

This can be viewed in the case study. The area where the module is proposed to be installed is not initially considered for any process extension. The increase in risk should be viewed critically in the decision making process. Hence taking the uncertainties associated with the module that will have on the explosion risk to the area due to reduced ventilation, choosing an extreme safety approach in the decision process accordingly the alternative 2 has been selected for implementation.

Unlike risk acceptance criterion, the ALARP principle following suggested method that uses layered approach in decision making process implies more comprehensive work than just comparing and accepting or not accepting the risk results. ALARP demonstration may require an extensive evaluation process in verifying whether or not a wide search for alternatives was assessed for risk reduction.

The various factors among others, associated with design accidental load for explosion and the decision maker should take into account in the decision making process is shown in Figure 26.

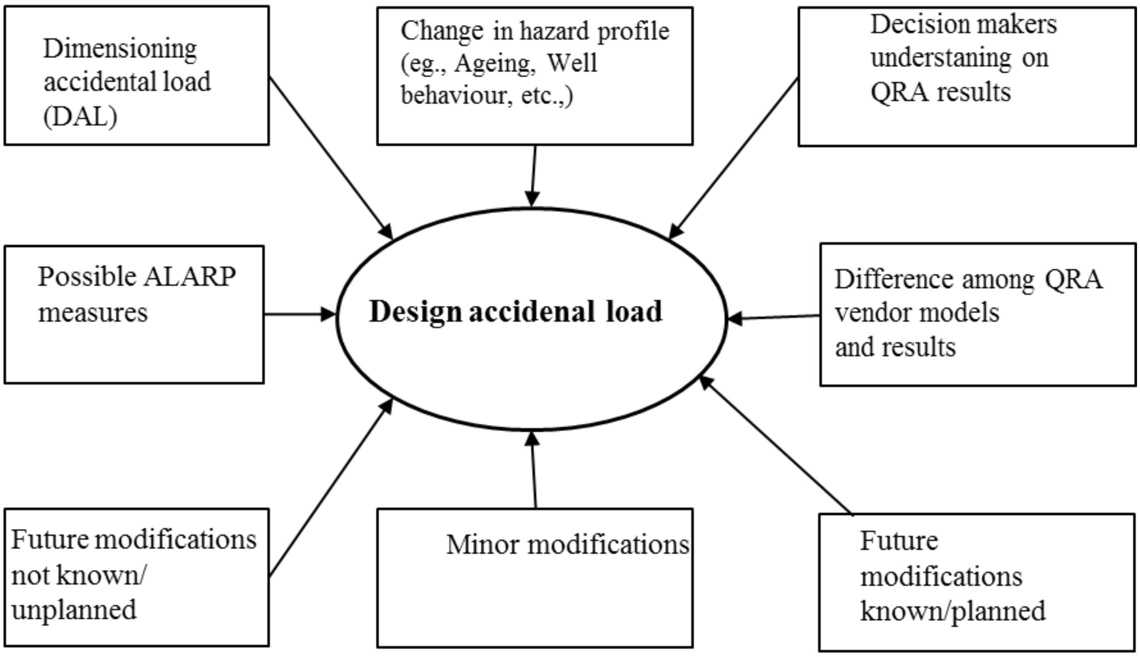

Figure 26. Factors influencing design accidental load

As a part of uncertainty factors analysis, the analysts' confidence can be used to formulate guidance for operational phases to ensure that the knowledge used in assessment of uncertainty factors are not degraded. Currently there may exists procedure that verifies and maintains assumptions used in the risk analysis. For example imposing restrictions on the amount of hot work in an area with the use of habitat. But an extensive list of uncertainty factors assessment will be useful for decisions related to implementation of risk reducing measures.

The challenge is how to account the probability reducing measures in the risk analysis, which are operation dependent, could be addressed by the suggested method. The probability reducing measures can be part of the uncertainty reducing measures in the guideline. This will highlight the importance of operational measures in selecting the decision context and necessary actions can be planned to make the preventive measures more reliable.

In review, few of uncertainties related to the selected design accidental loads are;

i. The assumptions and simplifications implemented in the risk analysis
ii. The deterioration for structural load handling ability
iii. The future smaller modification effect on dimensioning accidental load
iv. Improved understanding of the explosion phenomena in the future.

This involves a high level of analyst background knowledge in the assessment process. This means in making decisions based on the results that has uncertainties, analysis of uncertainty factors associated with applied knowledge should be included in the decision process.

In conclusion, the suggested method which uses (A,C,U) perspective in describing the risk in meeting the risk acceptance criteria and further risk reduction through modified layered approach which allows ALARP to be dynamic. Establishing design accidental loads for explosion following suggested method is considered to address PSA requirements to establish design loads following risk reduction principles.

8.3.1 Challenges with the suggested method

8.3.1.1 *Involvement of stake holders*

Successful implementation of suggested method requires active involvement of stakeholders, operator, engineering contractor and QRA analyst.

The usefulness of this extensive work depends on decision makers' attitude towards risk. This increased work on uncertainty factors assessment will result in increase of documentation if the decision maker is leaner to the risk acceptance criterion.

8.3.1.2 *Resource Increase*

The major add-on work in applying the suggested method to the existing practice in establishing DAL would be generation of uncertainty factors related explosion risk analysis results. This is not an easy task. This might involve an extensive amount of time and work to the QRA vendor based on the extent of evaluation (only a major factors or complete) and implies increased project cost. It is the operator or engineering contractor who shall decide on the level of uncertainty factors assessment based for the need for their decision making process.

The current risk analysis template may require a change to include uncertainty factors assessment. It may be difficult and challenging initially to have a common understanding on identification and assessment of uncertainty factors.

8.3.1.3 *Guideline for decision context*

It is acknowledged that the success of ALARP implementation following the suggested method is mainly depends on the selection of decision context for the given decision problem. The company should develop a guideline that describes relevant points to be taken into account and allow the decision context to range from extreme safety to extreme economic approaches. This way the ALARP will not be static and would allow decisions that will ensure to maintain the installations explosion risk level below risk acceptance criterion and ALARP.

8.3.1.4 *Decision making competence*

Today, following the analyst suggestion based this conservatism and reference to acceptance criteria, the decision making process is easier and quicker. Decisions following the suggested method that requires uncertainty factors assessment may put increased demand on decision makers' role than today in terms increased competence, interpretation of assessment results, etc.

8.3.1.5 *Improvement needs*

The use of semi-quantitative approach proposed in the uncertainty factors assessment may not capture complete uncertainty in its present form and evaluation of more parameters may be necessary. There is a level of subjectivity involved in categorising the uncertainty factors effect on risk using qualitative terms like minor, moderate and significant.

8.3.1.6 *Arguments aganist the method*

With so much improved models and techniques available today related to explosion analysis, it might be that the uncertainty is risk analysis is already at lower level. This means, there can be uncertainty factors but will not have any considerable influence on the risk results. Any uncertainty factor that may have influence on the risk level would be the due to lack of information. This lack of information has already been handled in the form of assumptions, and the decision maker is aware that the risk analysis results are subject to these assumptions. Sensitivity analysis have been carried out to provide increased risk picture to the decision maker. It can be argued that uncertainty factors analysis in the suggested method is redoing the work.

Consider an example related to congestion level in the early phase model. Since complete information is not available, analyst based on his experience considers 20% margin in the analysis which he thinks is reasonable to account for uncertainties. This assumption is communicated to the decision maker along with results. Unless the decision maker has a strong reason not to believe that 20% margin is less, this won't influence the decision. A different decision is expected only when the decision maker has more information than the analyst or more other external factors that may influence the congestion level but is not included in the analysis for example increased congestion due to modifications. The impact can be evaluated through sensitivity analysis by changing the level of congestion. But it should be acknowledged that the congestion level considered for the modifications for the sensitivity is uncertain. The increase in congestion level may increase the overpressure magnitude several times.

From this, we may conclude that sensitivity analysis alone may not be sufficient and the uncertainty factors assessment will benefit the decision maker to decide on implementing further risk reducing measures beyond risk acceptance criterion considering other uncertainty factors that are not included in the analysis.

QRA analysts' view is that the risk analysis is conservative already. For the uncertainties associated due to lack of information, it may be argued in one form or other these factors are taken into account in the decision process. But it is not transparent, how much weight is given for these factors in the decision process. For example, how much margin has been included in the design accidental load for minor modifications and how it has been followed up to ensure the risk was not increased beyond the margin?

It is acknowledged that practically it is difficult to see the conservatism in isolation for different factors but this gives input in evaluating risk reducing measures in later phases. For example, it is not uncommon to change the welded pipes built in the original design with flange joints in the modification due to increased challenges in access for welding and installing a long spool. There is not normally made any quantitative evaluation. It is not an impossible task to install it but the efforts it takes to have welded line involves more time and offshore work in building habitat and a coarse cost benefit analysis may result to use flanged joints. In situations like this, availability of evaluation of uncertainty factors, may demand to make decisions following extreme safety perspective.

9 Conclusions and Areas for further work

9.1 Conclusions

The main focus in the design of offshore installation at the initial phase of the project is to achieve a balanced solution that is economically feasible and has lowest risk level practically possible for its operational life time. This also poses a major challenge to the decision makers in the sense that taking decisions that offer a robust solution considering uncertainties. Few factors to be included in the decision process are current level of uncertainties, overview of future risk change, costs associated in risk reduction, changing field conditions, deteriorations of structures, barriers, etc.,

In establishing design accidental load for explosion, a decision needs to be taken at the initial phase of the project where sufficient information's to determine the real picture is not available. The models that are used to simulate the real situation introduce uncertainties in the analysis results in the form of assumptions.

The uncertainties associated with a probabilistic explosion analysis are studied. It is shown in this thesis that the current (A, C, P) based approach in QRA and risk description, without accounting hidden uncertainties in the analyst's background knowledge may result in the installations total risk level at variance with the reality.

A new method following (A, C, U) perspective has been suggested. This method uses both risk acceptance criteria and ALARP principle in establishing design accidental loads taking uncertainties into account and that will be full compliance to PSA requirements. In this new method, uncertainty factors that could cause surprises relative to the background knowledge used the explosion risk analysis are identified and ranked following a semi-quantitative approach. The effect of these uncertainty factors for its effect on total risk is evaluated following a combined judgement of its sensitivity and the degree of uncertainty related to the applied background knowledge.

Different perspectives in taking uncertainties in the decision process like extreme economic (limited or no weight is given to uncertainties and decisions are taken following cost-benefit analysis), extreme safety (higher weight is given to uncertainties and decisions are based on cautionary principle) and a combined approach (a zone between extreme safety and extreme economic) are reviewed.

Following the assessment of uncertainty factors, an updated layered approach has been used to implement ALARP principle in making decisions on the design explosion loads. The guidelines that will be developed by the operator for varying decision contexts, will make the basis for the selection of appropriate perspective, extreme economic, extreme safety or a combined approach that shall be used in the decision making process for design accidental explosion loads.

This suggested method by taking uncertainty factors in explosion analysis into account and in choosing an appropriate perspective in implementing ALARP in decision making comply with PSA requirement for risk reduction principles and will be in tune with the new risk definition. This suggested method is also suitable to implement in all areas of safety where treating uncertainties has paramount importance and has challenges.

9.2 Areas for further work

Explosion and uncertainty are two vast areas where there are lot need to be understood. This thesis is written within a limited period of time with limited resources and information. It is difficult to capture all the uncertainty issues related to topic. Some topics for further research are presented below.

i. ***Establish method for identifying uncertainty factors***

Identification of uncertainty factors for an offshore QRA can be very tedious. Areas of weak and strong knowledge should be identified to reduce the repetition of work in identifying these factors. Guides should be established that provides information about the impact each uncertainty factors will have on the total risk.

ii. ***Decision context process***

In order to use ALARP in the risk reduction process effectively, a decision context following uncertainty factors assessment should be established. The evaluation will require factors outside of explosion risk analysis to be included. This should be based on detailed guide line or check list which involves relevant parameters. This is an area which requires more focus in order to ensure that ALARP will be a dynamic process (range from extreme safety to extreme economic).

iii. ***Develop principles to other areas***

The suggested method can also be applied to other parts of risk analysis namely fire risk analysis, dropped object protection etc.

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Appendix A: Discussion on design accidental load

To understand major stakeholders view on DAL and design accidental load, few questions addressing the topic like basis for selection of design accidental explosion load, who is responsible to decide the value to be used in the design, how the future unplanned modifications are taken into account, how inherent uncertainties associated in the explosion risk assessment treated, etc., has been formulated and a survey has been initiated.

The responses from an operator's risk management team, risk analysts, two engineering/modification contractors is shown below and is used in describing the current practice across the industry on the explosion risk assessment.

Question #1

It looks like the risk analysis focus is to provide a dimensioning accidental load that is more likely to be valid til the as-built is completed and platform is set to production. But it is obvious that the minor modifications along installations lifetime will increase the parameters like leak sources, congestions, change in dispersion scenario, etc., Have the modifications been taken into account in establishing design accidental load to ensure it's validity throughout its life time?

a. *If yes, how this has been accounted for in the dimensioning accidental load? For example a margin (%) more than risk acceptance criteria or a value corresponding to lower frequency like 10^{-5}.*

b. *If No, Do you have any suggestions to how this can be taken into account while deciding design the accidental load?*

Response 1 (Engineering contractor)

a. In Field Development (new platforms) we do not take into account future modifications. We need to follow Scope of work. We can take modifications into account, but the then Customer need to have some ideas of the modifications. This will also increase the cost and weight. Too small margin will (as you write), make it difficult for future modifications. However, if Customer will take account for future modification, Customer must state this in the contract.

b. An updated QRA is necessary for large modifications, so yes, the updated QRA will reflect the modification. If there is a small margin between design accidental load and the dimensioning accidental load (before the modification), the modification in the area will maybe not be feasible. The modification will then not be executed (or additional risk reduction measures need to be implemented.

Response 2 (Engineering contractor)

a. There is a great deal of uncertainty in the risk analysis. One must keep a margin throughout the project to ensure sufficient design with respect to the final design loads. This margin should be used for future modifications.

b. Often it is not the design loads that are governing. For main structure often it comes down to the overall design rather than the design loads from safety. However, there might be several cases where a design load from safety applies. I do not really vote for implementing a margin reserved for future projects. This should be addressed by the future modification project. However, it is very important that the platform design and its design accidental load reports are documented in a way that clearly shows and discusses uncertainties and robustness. What are major contributors, how do they affect results and loads, what has been anticipated, is there conservative assumptions, what has been immature at the cut off as input to the risk analysis etc. If this is done properly, it may become easier to start a modification project and evaluate the contribution to the loads both qualitatively and quantitatively.

Response 3 (Risk consultant)

a. When performing a risk analysis, values and parameters that are typical or average over a year (i.e. average yearly pressure, production rate etc.) are used. Minor modifications that will be completed in the future are not accounted for. But the risk analysis is conservative, i.e. when applying parameters we use values that will give highest risk to make sure the calculated risk is not lower than "actual" risk. A margin for conservatism is not known, and difficult to calculate.

b. By selecting the 1E-05 or 5E-05 per year occurrence of the dimensioning load you will include robustness for future extra equipment.

Response 4 (Operator Risk management team)

a. Company's internal guidance has increased demand than risk acceptance criteria by regulations. Accordingly, the aim to maintain the impairment frequency in the order of 1-5E10^{-5}. This is considered to take care of uncertainties due to lack of information at FEED phase. Modifications are not included in the base analysis and evaluated case by case.

b. Refer above

Question #2

In the initial QRA (during FEED) the equipment count is based on P&ID's as drawings are not available. Will the use of P&ID's (instead of available ISO's) for the regular update of QRA's (once in 5 years) reflect the actual risk by the modifications done in that period?

Response 1 (Engineering contractor)

No response received. Informed through a conversation that P&ID's are used they are the one available in the initial phase of the project.

Response 2 (Engineering contractor)

In the old days we used a great deal of piping Isometrics. I don't think this is the norm anymore, rather a model calculating number of flanges, etc., on the P&ID. The risk analysis companies tend to forget that flanges are not shown on the P&IDs.

Response 3 (Risk consultant)

The equipment count is based on P&IDs, but in specific cases ISO drawings as requested by.

Response 4 (Operator Risk management team)

On new built, ISO drawings are usually not readily available in a FEED phase. Following current practice, if there have been minor modifications since last QRA typically P&ID's are used in the regular update of QRA's and conservative values are used in the risk analysis by the vendor. Offshore survey for equipment/leak point count could be relevant if larger modifications.