Risk Information for Operational Decision-Making in the Offshore Oil and Gas Industry

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# Abstract

Operational planning decisions, which are characterized by relatively short time lag between decision and implementation, have received little attention in risk and safety research in offshore oil and gas industry. The overarching objective of the paper is to find out how to provide good risk information for such decisions. The discussion starts from description of what good risk information is, followed by a proposal to use Activity consequence risk (ACR) - the effect that performing an activity will have on the risk level after the activity has been completed; Activity performance risk (APR) - the risk associated with performing the action; and Period risk (PR) - risk for a plant or facility over a period of time, to structure a complete risk picture. A simplified example is given to show how the proposed criteria can assist in providing better risk information. Challenges to provide such information are thoroughly discussed. The main conclusion is that current practices in the industry lack the accuracy and capability to provide such a risk picture.

# Introduction

During operation of an offshore oil and gas installation, decisions about operations are made more or less continuously, and many of these decisions can have an impact on the risk associated with major accidents. Examples of decisions may be:

* Is this operation safe to perform in the situation we have right now?
* I have 50 different jobs on-going already – is it safe to add another job?
* I know that I have an isolation valve with an internal leak – do I have to repair it now or can the repair be postponed until the next scheduled shutdown?
* The weather is getting worse – can I start the work as planned?
* Alternative ways of solving a problem are available – which one is safest?

Experience has shown that operational decisions can have a significant influence on risk. In the Macondo blowout, a number of decisions led to failures of a series of safety barriers (Hopkins, 2012; NCBP, 2011):

* Decision to use six centralisers instead of 21
* Decision to declare success of integrity test
* Decision to offload return mud from the well directly to a supply vessel instead of the mud return pit where volume out can be measured and compared to volume in.

Similar examples can be found in a flammable gas explosion at the Yerkes chemical plant (CSB, 2012):

* Decision to repair a leak in a line in a flash tank after process restarted, instead of during next shutdown.
* Decision to sign off hot work permit without acknowledging the hazard of existing flammable gas.

Sarshar et al (2015) looked at 24 investigation reports for incidents with major accident potential and found that planning factors was a contributor in 18 of these cases. A large proportion was related to operational planning.

Operational decision-making can be contrasted with strategic decision-making. These two terms have their origin from organization and decision theory and are used to differentiate levels of decision-making in an organizational context (Marakas, 2003). Operational decision-making is the focus in this paper, and specifically we will concentrate on what we call operational planning decisions, i.e. operational decisions that are based on a certain level of planning. What we mean by the term “Operational planning decisions” is discussed in more detail in Section 2.

Generally, we can talk about two areas of focus in safety research on decision-making (Hayes, 2013):

* Management decisions made in offices and meeting rooms (at the “blunt end”).
* Decision-making at the “sharp end”, based on field observations (i.e. control rooms, flight decks, and emergency rooms)

The operational planning decisions that we are focusing on in this paper fall somewhere between these two. This just underlines the need to look at this in more detail.

There may be several reasons why poor decisions that later lead to accidents are made. It is however highly unlikely that poor decisions are made “on purpose”, even if hindsight may show that a different choice should have been made. The decisions that were made, most likely appeared to be the best choice based on the information available at the time of making the decision. One hypothesis is therefore that the information about risk that was provided to the decision-makers was insufficient. This is not to say that more and improved information would have given different decisions in all situations, since information also may be incorrect, it may be misinterpreted or it may be overlooked. In general, we can however assume that better information is more likely to give better decisions. Making sure that all useful information about risk is available is therefore important.

In the oil and gas industry in Norway, different types of risk information may be available for operational decisions. Quantitative information about risk on plant level is available in the QRA (Quantitative Risk Assessment) for the installation. Examples of use of the results from the QRAs are for quantifying overall basis risk level of the plant, for prioritizing risk-reducing measures and for comparing alternative designs. These can support decisions that have long-term effects and a long time lag from the decision is made until the effects are experienced.

Operational planning decisions are characterized by relatively short time lag between decision and implementation and will mainly have short-term effects. A QRA, which provides average risk over a long period, does not necessarily give all the necessary information. In practice, QRA information is therefore used to a very limited degree in operational planning decisions.

Instead, information from Job Safety Analysis (JSA) may be used, although they tend to focus more on occupational accidents than major accidents (Andersen and Mostue, 2012), and links to the overall risk picture is missing (Vatn and Haugen, 2013). Another source of information is the Work Permit System[[1]](#footnote-1), which is also used for daily operational planning. However, this will not give information about how the risk level is affected by number of work permits (Almklov et al., Unpublished results). Other types of information, such as information about barrier status (DNVGL, 2014) and procedures will also be used.

The objectives of this paper can be outlined as follows:

* Describe what good information is to make operational planning decisions.
* Evaluate current practices in the oil and gas industry to see how well they can provide the information.
* Describe challenges to gather the information that is not provided today.

Some important limitations of the work are presented as follows:

* We have used processes and decisions from the Norwegian offshore industry as examples in this work. However, we believe that this work may be transferable to process industry in general, with suitable adaptations.
* We have focused only on major accident risk (process safety), not occupational accidents (personal safety).
* Many decisions can influence risk, but we are concentrating only on operational planning decisions.
* The decision-making process itself is not covered, only the risk information that is used as input to the decision.
* Risk information can be presented in many different ways, using various numerical or graphical risk metrics. Risk communication is clearly important for the outcome of a decision-making process. The purpose of this paper is however not to look at how the information is presented and communicated to the decision-makers, but to describe what information is useful, and how to get this information.
* It is acknowledged that risk analysis is just one input to decision-making process, in recognition of the fact that decision-maker may have other preference (e.g. cost, schedule) while making operational planning decisions.

The rest of the paper is structured as follows. In Section 2, we describe operational planning decisions. This is followed by a discussion of what is perceived as good risk information for this type of decisions. Section 4 discusses further how different aspects of risk can provide such good information, which is followed by an example in section 5. In Section 6 challenges to provide this information are discussed, based on current practices in the oil and gas industry. The paper ends with conclusions in Section 7.

# Operational planning decisions

Although this paper focuses on information to be used for decision-making and not the decision itself, it is still necessary to describe decisions briefly. The main purpose is to ensure that we understand the context where the information will be used and the decisions that are made.

We have chosen the following definition of decision-making: “*the process of reaching a judgment or choosing an option, sometimes called a course of action, to meet the needs of a given situation*” (Flin et al., 2008). From this, the main elements of decision-making can be described as:

* Situation assessment/Defining problem
* Generating and considering one or more response options
* Selecting and implementing an option
* Outcome review

For our purpose, a decision refers to a choice that individuals or a group make among two or more alternatives. One of the alternatives can also be to do nothing.

For the purpose of this paper, we define an operational planning decision as “*a choice of action to be implemented within a short time interval in the operational phase of an existing plant. The time lag is relatively short from the need to make a decision arises until the decision is made, but long enough that alternative actions can be considered*”.

Defining specific types of decisions is not easy and it has been claimed that “*today, there is no systematic methodology to structure decision situations and to find out the relevant information and other needed factors in the process industry*” (VTT, 2008). Some dimensions that we can use to clarify the above definition are:

* **Available time** (including the degree of emergency) (Orasanu, 1995). Planning decisions imply that there is relative short time (from days to weeks) from the need for a decision arises until the decision must be made. This gives some time to establish a systematic basis on which to make the decision. Decisions that have to be taken immediately are outside the scope of operational planning decision. Automatic, subconscious reactions (e.g. emergency braking when a kid runs across the road in front of a driving car) also fall outside the scope as described above.
* **Available knowledge.** When making operational planning decisions, we may have quite detailed information about relevant factors that may influence risk available. In theory, we can have information such as technical conditions of the safety barriers, who is going to perform the work, competence of the workers, available resources, weather conditions, and so on. The level of detail in the information that may be available is therefore high. However, another question may be whether this knowledge/information is actually gathered and structured in an effective way.
* **Decision-making level (in an organization) and decision-maker** (Kelly 2011). Typical for operational planning decisions is that they are made by middle level managers, engineers (designer), operational managers and front-line operators (non-management). In some cases, high-level management may also be involved.
* **The consequence (or effect) of the decision**: Activities that are the main focus on operational planning decisions are typically of relatively short duration, and there may therefore also be a tendency to focus primarily on the short term effects. However, these decisions may have long term (e.g. years), medium term (e.g. months to weeks) and/or short term (e.g. day) effects.

# 3. Relevant risk information for operational planning decisions

## 3.1 What is risk information

In this paper, we have adopted the definition from Kaplan and Garrick (1981), who define risk as the answers to following three questions:

1. What can happen?

2. How likely is it that it will happen?

3. If it does happen, what are the consequences?

From this definition, risk information is directly or indirectly linked to evaluation of a set of scenarios with corresponding likelihoods and consequences. Direct information is about the immediate causes. Indirect information is related to the factors that may influence those immediate causes, which may be a wide range of factors.

## 3.2 Aspects of risk that need be presented

Collecting risk information aims at providing a basis for making robust decisions about major accident risk. High quality risk information should be able to clarify decision situations in a valid way to enable selecting from alternatives, and make it possible to take actions that can improve the alternatives.

In order to capture different aspects of risk, we have earlier proposed a classification scheme of risk information into average risk, site-specific average risk, activity risk (activity performance risk and activity consequence risk), period risk, and time-dependent action risk (Yang and Haugen, 2015). The reason behind this classification is that we need different descriptions or expressions of risk, to make decisions in different situations. In the context of operational planning decision-making, risk input to decision-making are:

* **Activity consequence risk (ACR)** - the effect that performing an activity will have on the risk level after the activity has been completed. This is in other words the updated basis risk level (the designed risk level) for the plant after the activity has been completed. One example could be if we make a repair to a safety system that has malfunctioned, then the risk will be reduced after the repair because presumably the system will now function. As required by ISO/TS 16530-2 (ISO, 2013), risk assessment should “*identify the change in risk level(s) via use of a risk assessment matrix or other means*” to assist in Management of Change (MOC). After the Macondo accident, PSAN (Petroleum Safety Authority Norway) has formulated needs for improved risk analysis tools to reflect and communicate changes in risk levels (PSAN, 2011). According to Cox (2013), a robust risk analysis is “risk analysis that delivers recommendations that are robust to deep (and other) uncertainties, especially about the correct probabilistic relation between acts and consequences”. ACR aims at reflecting the consequences due to the activities from a risk perspective, especially for decisions related to changes in the configuration (e.g. modification) or status of the plant. Particularly, ACR captures change of status of essential technical systems (e.g. adding or replacing pumps) and technical safety barriers (e.g. upgrade of the gas detection system) into the risk picture. Calculating ACR implies an update of the total risk picture, but this may be very simple to do since most activities will influence only a small part of the total risk model.
* **Activity performance risk** **(APR)** – this is the risk associated with performing the action, in addition to basis risk of the plant (risk during the activity). If we refer back to the previous example of repairing a safety system, the repair may perhaps involve lifting of some heavy equipment. If this is dropped, an accident may be the result. This would be an element of APR. According to PSAN (2015), experiences gained in the petroleum activities have amply demonstrated the risks inherent in the activities. For instance, major maintenance work on process equipment represents a clear increase in risk. It may be argued that it is the activities that govern the real risk level during operation, with system condition as a constraint on what can be done (Haugen and Vinnem, 2015b). This reveals the importance of analysing and evaluating APR.
* **Period risk (PR)** – risk for a plant or facility over a period of time, taking into account all activities and all equipment at the plant. This implies that we consider not just the repair of the safety system, but also all other activities taking place at the time when the repair is conducted. Different activities may influence and interact with each other and PR gives us the total risk during the period when the activity is performed. This aspect of risk aims at capturing the effect of mutual dependencies between different activities, as required by PSAN (2014a). It demonstrates variations of risk level over time (i.e. per day, per week, or per month). PR is particularly useful to support decisions such as approving a total daily plan or monthly plan.

Information about the above risk aspects is required to give us a complete description of the effects of the decision on risk, both in the short term (temporary) and the long term. A more thorough and comprehensive risk picture is provided to better support decision-making.

To illustrate these risk aspects further, consider the following situation. Barrier A is found to be degraded and repair it is necessary. The repair work will take one day, and hot work (work with an open flame that may act as an ignition source) will be required. Originally, 50 other jobs are also scheduled for the next day, including lifting, and maintenance of hydrocarbon systems. Let us assume that we have only three alternative actions:

1. Repair barrier A the next day, postpone all other jobs but continue production as normal otherwise.
2. Repair barrier A the next day, without making any changes to the other 50 jobs
3. Wait until next scheduled shutdown to repair barrier A.

For this situation, the different risk aspects for each alternative are described in Table 1. We can see that the different alternatives have different combinations of ACR, APR and PR. This illustrated that we will not have a comprehensive understanding of the risk unless we evaluate all three aspects.

Table 1 Descriptive ACR, APR and PR for three alternatives

|  |  |  |  |
| --- | --- | --- | --- |
| Alt. | Activity Consequence Risk | Activity Performance Risk | Period Risk |
| A1 | ACRA1: Risk level after Barrier A is repaired  | APRA1: risk of repairing Barrier A, WITHOUT interactions from other jobs  | PRA1: risk level over next day, with only repair of Barrier A done. Barrier A is absent in the period of the repair. |
| A2 | ACRA2=ACRA1: Risk level after Barrier A is repaired.  | APRA2: risk of repairing Barrier A, WITH interactions from other 50 jobs | PRA2: risk level over next day, with repair of Barrier A plus 50 other jobs done. Barrier A is absent in the period of the repair. |
| A3 | ACRA3: Risk level WITHOUT repairing Barrier A (No repair action) | APRA3: risk of repairing Barrier A, WITH production shutdown | PRA3: risk level over next day in normal schedule, with 50 jobs done, with degraded function of barrier A |

## 3.3 What is good risk information

In the previous subsection, we described specific risk aspects that need to be available to the decision-maker to give the full risk picture. More general, we can also specify a set of criteria for good risk information, which will apply to all the risk aspects identified above. The following criteria are proposed:

1. Information should enable comparison with “stop” criteria
2. Information can be used to compare and rank alternatives
3. Information should clearly elucidate risk contributing factors
4. Information should be updated to reflect current operational situation
5. Information should reflect future activities
6. Information should be well-structured

Within a Risk-Informed Decision-Making Context, we understand that risk is only one of the dimensions that are used as decision-input. However, for this purpose, we limit ourselves to look only at risk.

A potential weakness of the decision-making in operational planning decisions is that the decision basis often is largely qualitative and that the risk level actually accepted from one decision to another may vary significantly. As far as possible, the information should therefore be provided in such a way that it can be compared with criteria that are independent of alternatives. This will enable more consistent decision-making. If the risk level exceeds the acceptance criteria, the alternative should not be selected, or actions need to be taken to improve the alternative before execution. If all or several alternatives are within an acceptable range with respect to risk, we may also use criteria from other objectives (cost, schedule, etc.) to choose among alternatives.

In addition, risk information is expected to clearly elucidate the most important risk contributing factors; so that effort and resources can be put on the most appropriate measures to effectively reduce the probability of an accident, and/or to minimize the consequences of a possible accident.

A robust decision should be made based on sufficient technical evidence given the latest state of knowledge (Zio and Pedroni, 2012). This means risk information is expected to reflect current operational situation in a valid way (Njå and Braut, 2011), and be continuously updated while new evidence comes in.

Furthermore, the influence of future activities should also be reflected in the risk information, to support decision-making at the current point. The interactions of those activities may increase the risk to an unacceptable level. With reference to the degraded barrier A example mentioned earlier, we may aassume that both ACRA1 and ACRA3 are within acceptable risk level, when we only take into account the current status of safety critical equipment and barrier systems. If we know there will be an activity next week where barrier A plays a role to control risk, this future activity should also be taken into account when making the decision about postponing the repair work of A or not.

Last but not the least; the information should not be in pieces, but well-structured and definitive so that the decision-maker will have a complete risk picture that incorporates top contributing factors before making the decisions (Pidgeon and O'Leary, 2000).

# How different aspects of risk can provide good risk information

In this section, we discuss how different aspects of risk (ACR, APR and PR) can meet the above criteria from an idealized point of view. The potential challenges associated with doing this in practice are discussed in Section 5.

## 4.1 Expressions and acceptance criteria

Risk expressed in terms of statistically expected loss over a long period of time is a good input to strategic decisions such as how the layout of a facility should be designed. It is however not necessarily useful for operational planning decisionsas was commented in the beginning of the paper. For ACR, APR and PR, other expressions may be more useful to evaluate against acceptance criteria, and among alternatives.

##### **Activity consequence risk**

ACR is a reflection of risk level over current system configuration, with a focus on activities that influence essential technical systems and safety functions. Yang and Haugen (2015) has proposed three possible ways to express ACR, which are statistically expected loss, frequency of occurrence of a specific catastrophic failure scenario, and status of integrity of safety barriers.

Current QRAs typically provide risk results in terms of expected loss (e.g. Fatal Accident Rate (FAR) value), by averaging a range of different consequences. Vinnem (2014) pointed out that fatality based risk metrics are insensitive to many barrier functions. Nguyen (2012) has done a case study to look into three QRAs that use event trees to model safety systems. A sensitivity analysis was done by assuming that all safety functions have failed. The resulting changes in FAR values are quite small (1.39 to 1.45 for installation A and 2.39 to 2.42 for installation B – less than 5% increase in both cases). Nguyen (2012), points out that there are a few modelling reasons behind this; still, this indicates FAR may not be sensitive enough to express ACR. We may need something other than expected value.

In nuclear power plants, the status of the various system and/or components (for example, whether there are any components out of service for maintenance or tests) is monitored and point-in-time risk is calculated by Risk Monitors, to present influence of changes of the plant configuration (IAEA, 1999). The point-in-time risk is “*the level of risk that arises from a specific plant configuration”* (OECD, 2004), with the assumption that the plant configuration would continue for a whole year. Two frequencies are typically calculated to express the risk; Core Damage Frequency (CDF), and Large Early Release Frequency (LERF). The concept of point-in-time risk may be regarded the same as ACR. Correspondingly, ACR may be expressed through the frequency of occurrence of a specific catastrophic failure scenario with a given consequence. Figure 1 illustrates how ACR may be derived, through a combination of event tree and fault trees, following the same principle as point-in-time risk in nuclear industry. ACR of activity 1 can then be expressed by a frequency of fatalities in the illustrative example. Target frequencies of occurrence of the relevant catastrophic failure scenarios have to be established to be able to use these values to determine if risk is acceptable or not. This can be similar to CDF = 1⋅10-4/year per reactor established by the US NRC for commercial nuclear reactors (Azizi, 2014). Another possible way to evaluate acceptability can be to look at increase over a base case value. A scale with thresholds (e.g. 30 times increase is unacceptable) then needs to be established (ERIN, 2013).

Figure 1 Illustration of possible method to derive ACR

ESD: Emergency Shutdown

A qualitative expression of risk used in the nuclear industry that can be applicable to express ACR is logic trees (Safety Assessment Trees and Plant Transient Trees) (OECD, 2004). A logic tree approach has usually been used to assess the level of redundancy, diversity, defense-in-depth, etc. available for any plant configuration. Factors such as activities being carried out on the plant and weather conditions that may increase the likelihood of certain initiating events are also taken into account in some models. An example is shown in Figure 2. The logic tree approach provides a link between barrier status and risk level. Behind the nodes (i.e. containment status, gas detection system status, etc.) are fault trees taken from the QRA model. The end states can be represented by one of the four colors, in which red is unacceptable risk, orange is high, and yellow is moderate and green is low risk. However, the allocation of the endpoints (color coded bands which are acceptance criteria in nature) is subjective and relies heavily on expert judgement.



ESD: Emergency Shutdown

Figure 2 Illustrative example - Logic tree relating to containment status.

##### **Activity performance risk**

Yang and Haugen (2015) suggested expressing APR by giving the status of a selection of critical safety parameters that influence risk. The argument for choosing this is that for a specific activity, the number of critical parameters is usually relatively limited. Provided we keep control of these, we will also keep control of risk. Another argument is that the decision-makers will expect to have information which helps them understand what the critical barriers are and what the status of these barriers is (MIRMAP, Unpublished results).

To use this to evaluate acceptable risk will require several approaches. First, we will have to define upper acceptable limits for all critical parameters individually. Then, if any of the critical parameters are over the limit, we can conclude that the risk is unacceptable. For example, for lifting operations, wind speed is a critical parameter to determine whether the lift can be performed or not. The lifting can e.g. only be performed when the wind speed is below 10 m/s. The wind speed is then an example of a safety critical parameter with an upper acceptable limit of 10 m/s.

When we have a number of safety critical parameters, combinations of parameters which are within their individual critical limits may however also be critical. If several parameters are close to, but no one exceeds the acceptable limits for individual parameters, what are the “stop criteria” then? To ensure consistent decisions from a risk point of view, a comprehensive analysis of combinations of parameter values would have to be done for each individual case, and specific criteria determined on basis of this. In practice, this may however be quite difficult to do. Shell has developed a “rule of three” principle that they apply in situations like this. If three or more risk-enhancing factors are present, the activity will be stopped or risk reduction measures need to be taken (Hopkins, 2011). The rule is stated in traffic light terms: three yellow lights are the equivalent of one red light. Such stop criteria draw on expertise and field experience. This may be useful as a rule-of-thumb, but will not necessarily give a decision criterion that ensures consistent decisions from a risk point of view.

##### **Period risk**

The expression of PR should reflect the possible dependencies among concurrent activities, and status of all relevant equipment in concerned periods. The period may be a day or a week, depending on the length of the period where the decision will have an effect.

PR is different from APR and ACR in that it considers many activities at the same time. Due to interactions, risk associated with a set of activities performed at the same time (PR) will not necessarily be equal to the sum of APRs.

Principally, the proposed ways of expressing ACR may also be applied to period risk, if we consider a period of one year, and if all essential technical systems and safety functions are taken into account. However, this is not the intention of proposing period risk. Besides, the level of detail of the safety critical parameters is different from ACR. Expression of PR is based on APRs of the activities that are carried out during the period, plus a further analysis of possible dependencies among those activities.

Yang and Haugen (2015) has suggested one possible way to express PR via Bow-tie diagrams, by showing how concurrent activities may influence multiple key elements of the bow-tie from hazards, triggers, proactive barriers, hazardous event, to reactive barriers, exposure and consequences. This is a graphical expression that needs further rules to act as “stop criteria”. These rules are mostly inherent in design-based analysis by engineering disciplines, or system reliability calculation (e.g. Safety Integrity Level of safety systems), or industrial standards. For instance, loss of two independent well barriers at the same time should suspend well production or injection (NORSOK, 2013). Note that we look beyond safety barriers to “safe envelope of operation”. Safe envelope is defined as “*a multidimensional space in which the activity/process takes place without damage occurring* (Hale et al., 2007). Some example of such safe envelopes are (Hayes, 2013):

* Physical parameters (e.g. pressure, temperature, composition in the case of the process plants, allowable separation distance, maximum concentration of a contaminant)
* Minimum requirements for availability of safety systems (e.g. level of redundancy) or other equipment items
* Internal parameters such as minimum numbers of people with required skills
* External environmental parameters such as maximum or minimum weather conditions
* Requirements on limits on acceptable combination of simultaneous activities

## 4.2 Risk contributing factors

Risk contributing factors associated with these three types of risk are not necessarily the same since we are looking at different aspects of risk. ACR is a reflection of the “health” of the system configuration from a long-term point of view. Therefore, the biggest risk contributing factors are the configuration changes (e.g. adding a pump), status changes of essential equipment and technical safety barriers (e.g. upgrade gas detection system). The changes may be from impaired to functioning or from degradation to failure. Another risk factor is the latent errors that may be introduced in the system as a consequence of insufficient or wrongly executed activity. For instance, the maintenance activity may leave incorrectly fitted flanges or bolts that can later lead to a leak. These latent errors may in other words increase the likelihood of active failures, or aggravate the consequences of unsafe acts by their effects upon technical safety barriers or system’s defences (Reason, 1997).

On the other hand, APR and PR are activity driven risk. APR focuses on risk control over execution of individual jobs. NORSOK (2010) emphasises that one objective for operational risk assessment is to identify *how* operational tasks and special operations may be safely carried out. Besides technical safety barriers, operational barriers, operational parameters (including e.g. weather limitations), competence etc. constitute the main risk contributing factors for APR. Monitoring APR therefore requires control of other risk factors than just barrier status and performance. This is different from ACR.

A standard checklist is recommend by Norsk NOGA (2011) to aid the identification of potential risk factors, hazards, consequences and measures. The checklist examines the job from a number of perspectives: ‘documentation (instructions/procedures) and experience’, ‘competence’, ‘communication and coordination’, ‘key physical safety systems’, ‘equipment worked on/involved in the job’, ‘equipment for the execution of the job’, ‘the area’, and ‘the work place’. One problem is that the coverage of the checklist is very wide, without specific focus on major accident. Still, it is a good illustration of the aspects which should be given attention when evaluating APR.

A hazard introduced by a specific activity is an important risk factor which needs particular attention. Many accidents happened due to failure to recognize hazards, assuming that hazardous events were not possible, or insufficient communication of hazardous events to sharp-end operators who carry out specific activities (CSB, 2007a, b, 2012; Okoh and Haugen, 2013).

Period risk is concerned with activity level, interactions of activities, and other external impacts (e.g. weather conditions, falling and swinging loads). They are the main risk factors that need to be controlled. Interactions between micro-level behaviors of activities may produce macro-level patterns, which in turn create new hazards (Dekker, 2012).

## 4.3 Reflection of current operational condition

ACR, APR and PR should be a reflection of current operational situation to support operational planning decisions. This means the status of risk factors and relationship between risk factors and prevailing risk should be based on up to date information. This will require available relevant real time data, updated with sufficient time interval to capture changes as early as necessary. For ACR, essential equipment status change (including adding and removing equipment), technical safety barrier status change, and possibility for latent failure are essential. During planning, the status of safety critical parameters which include operational barriers (e.g. quality of procedures) is used to derive APR. Before actually carrying out the activity, APR needs verification since the status of parameters may have changed since the decision was made. This means APR must be updated to reflect the actual status of identified risk factors, instead of a statistically average performance. For instance, whether the gas detector in the area is working or not, the wind speed, the experience of the personnel performing the work, etc. For PR, the APRs, and possible interactions need to be updated.

## 4.4 Reflection of future activities

When predicting the risk level over a coming period (e.g. next two weeks, until next scheduled shutdown) and making decisions about individual activities, all future activities planned in the period also play a role in the evaluation. Theoretically, this should be reflected into ACR, which takes care of the consequence of the action from a long term point of view. Hereby we need a full schedule of planned activities in near future. The near future means the period until the consequence of the action “disappear” (e.g. until barrier A is repaired).

## 4.5 Well-structured

The fact that we are considering ACR, APR and PR separately, is in itself an important contribution to present risk in a structured way. We split the risk into contributions from a long-term and short-term perspective. However, we also need to consider how these aspects of risk should be presented. This is not a key topic of this paper, but some thoughts are presented below.

A good presentation of risk information should not be only a black box that indicates end results in terms of risk expressions. It should be a well-structured risk analysis process. Event tree, fault tree, influence diagram are not only modelling techniques, but also presentation means, because they clearly reveal what influence the end results.

ACR is a direct reflection of system configuration, so a combination of event trees and fault trees may provide a good structuring, although not necessarily easy to read for non-experts. The limitations in time available for operational planning decisions may restrict the information about APR and PR to risk factors that immediately influence risk (e.g. equipment failures, human error), leaving Performance Shaping Factors (PSFs) (Reason, 1997) out of the model. A risk influence diagram is a good candidate to structure risk factors for APR and PR, with limitations acknowledged (Rosness, 1998).

A simple illustration is provided in Figure 3.



Figure 3 Risk picture for Operational planning decisions (For one hazardous event)

## Summary of relevant risk information

In Table 2 we have summarized the relevant risk information for operational planning decisions.

Table 2 Summary of relevant risk information

|  |  |  |  |
| --- | --- | --- | --- |
|  | Activity Consequence Risk(ACR) | Activity Performance Risk(APR) | Period Risk(PR) |
| Expressions | Frequency of occurrence of a specific catastrophic failure scenarioLogic tree | A selection of critical safety parameters that influencing risk | Activity Performance risk plus interactions |
| “Stop criteria” | Target frequencyof occurrence of a specific catastrophic failure scenarioRelative increase over base case | One operational parameters over limit“Rule of three” principle | Operating limits |
| Risk factors | Configuration change (e.g. adding a pump) Status changes of essential equipment and technical safety barriersLatent errors | A selection of critical safety parameters such as (Weather condition, Key safety barrier systems, Temporary barrier systems, Personnel exposure etc.) | Activity levelAPR of activitiesInteractions of activities (Area, Workplace, worker) |
| Reflect current operational condition | Updated technical condition of safety essential equipment and technical safety barriers  | Updated status of safety critical parameters | Updated APRs and interactions |
| Reflect future activities | Whether/how much these planned activities will exaggerate the ACR | Not relevant | Not relevant |
| Well-structured | Event tree/fault tree | Risk Influence Diagram | Risk Influence Diagram |

# 5. Example

In this section, the proposed risk picture is shown through a typical example of an operational planning decision scenario. The intention of the example is to show how the proposed criteria can assist in providing better risk information and corresponding challenges under the current practices in the industry. The example is simplified, for illustrative purposes only.

The example is related to an Emergency Shutdown Valve (ESDV) in a process plant. An internal leak has been observed during testing of the valve and the valve needs to be repaired. Performance of the work includes lifting of the valve and hot work. We further assume that the work will last for two days. The earliest that this can be performed (due to availability of resources is 3 days from now. In the same period, the firefighting system will be upgraded, which means the system will be out of service for one day. This introduces interaction to the maintenance work, since maintenance of ESD valves involves high probability of hydrocarbon leak. In addition, 10% of the gas detectors are 6 months beyond their nominal test interval.

A possible decision may then be: Can this work be performed safely on the day we are planning to do it?

If the repair is successfully performed, the valve will not have an internal leak anymore. This means reduced consequences (reduced volume of leak) should a hydrocarbon leak occur. This results in decreased ACR due to lower probabilities of corresponding consequences (i.e. fatalities and escalated fire/explosion).

The maintenance work includes planning, preparing equipment/system for repair, isolation of valve, gas-freeing of equipment, conducting the repair, leak-testing, removing isolations and production start-up. A leak may also occur in connection with this work, during the performance of the work or later during start-up (Okoh and Haugen, 2014). Immediate release can be caused e.g. by breakdown of isolation system during maintenance or work on equipment not known to be pressurized. This implies that APR also is introduced.

The maintenance work may also introduce latent errors, such as incorrect fitting of flanges or bolts, valves in incorrect position, wrong choice or installation of sealing services. This is not necessarily detected during the work and these errors increase ACR due to their potential for leak after the maintenance work has been done.

In Table 3, the hazardous events and risk factors for sub-activities are presented systematically.

Table 3 Risk factors of major sub-activities of maintenance work

|  |  |  |
| --- | --- | --- |
| Sub-activities | Major Hazardous event | Risk Factors |
| **Personal characteristics** | **Technical barrier system** | **Operational barrier system** | **Operational parameters** | **Personnel exposure** | **System constraints** |
| Disconnec-ting valve | HC leak | CompetenceWorkloadFatigueWork environment (e.g. vibration, noise) | Valve position indicatorLabelling of valves | SupervisionProcedureSelf-controlThird party control | Verification of isolation planVerification of emptied segment | - | Maintenance workers, operators | ESD unavailableDegraded gas detection system |
| Lifting valve | HC leak (due to dropped object) | - | Isolation of area (Secured area) | Wind speedCapacity of lifting equipmentLoad of valves | Maintenance workers, operators | ESD unavailableDegraded gas detection system |
| Hot work | Ignition  | Portable gas detector | Radio contact and fireguards | Monitoring results on combustible gas analyzer | Additional personnel- fireguards | ESD unavailableInhibited fire detection systemFirefighting system out of serviceDegraded gas detection system |
| Putting valve back in place | HC leak | - | Leak test | - | Maintenance workers, operators | ESD unavailableDegraded gas detection system |
| Resetting | HC leak | - | Written permission forRe-instatement Verification of removal of isolations  | - | Operators | Degraded gas detection system |

The status of listed risk factors are not collected in this example. More personnel will be exposed during performance of the work. This factor needs to be controlled together with other risk factors. This is particularly relevant for sub-activity hot work, due to inhibition of fire detectors which implies that radio contact and fireguards are needed to monitor possible fire. This requires additional people present.

The risk picture of ACR, APR and PR that needs to be considered is shown in Table 4. The corresponding challenges are discussed in section 6.3.

Table 4 Risk picture for example decision scenario

|  |  |  |  |
| --- | --- | --- | --- |
|  | Activity Consequence Risk(ACR) | Activity Performance Risk(APR) | Period Risk(PR) while firefighting system is out of service |
| Expression of risk | Frequency of occurrence of fatalities/fire or explosion/-non-ignited leak | The set of risk factors listed in Table 3 | APR of hot work and absence of firefighting system in the working area |
| “Stop criteria” | Target frequencyof occurrence of a specific consequence (e.g. 1×10-4 per year) | One operational parameters over limit-Lifting: wind speed over limit-Hot work: detectible reading of portable gas analyzer“Rule of three” principle on selected risk factors | Operating limits – temporary increased FAR value  |
| Risk factors | Status changes of selected valves (e.g. reduced internal leak rate for repaired valve) | Listed in Table 3 | Activity levelAPR of hot workInteractions of activities (i.e. area) |
| Reflect current operational condition | Updated average PFD of basic event “gas detection fail” in Figure 1  | Updated status of identified risk factorsInhibited fire detector due to hot workFirefighting system out of service | Updated APR of hot work and interactions |
| Reflect future activities | Not relevant | Not relevant | Not relevant |
| Well-structured | Event tree/fault tree(See Figure 1) | Risk Influence Diagram based on selected risk factors identified in Table 3 | Risk Influence Diagram based on selected risk factors identified in Table 3 plus interactions |

# 6. Challenges of providing good risk information in the industry

The previous sections discuss how systematically collected risk information can improve operational decision-making. It is worth noting that we are not proposing a new method to do the risk analysis, but a systematic way to show relevant risk information for operational planning decisions. The example in section 5 gives a very simple introduction to how this can be done. The example is only for illustrative purposes, with many details such as how to identify risk factors, how to collect status of risk factors, etc. not shown. The risk picture is not necessarily easy to obtain in practice. In this section, we discuss some of these challenges. The challenges are identified following the same structure as in Section 4. Since some challenges are common for all aspects of risk (e.g. monitoring barrier status), we do not always distinguish between ACR, APR and PR in the discussion.

## 6.1 Awareness of different aspects of risk

We are proposing to present three aspects or dimensions of risk as a basis for decision-making. This will clearly give a more comprehensive understanding of risk. However, a challenge may actually be that this is a way of thinking which few decision-makers are familiar with. Presenting risk like this may therefore confuse the discussion and make decisions more difficult, even to the point where decisions are not improved but actually become worse.

A challenge is therefore to be able to present the different aspects of risk in such a way that it is easy to understand and recognize what they actually present, and how they differ from each other. This problem should be overcome as users get more familiar with the terms and the way of thinking, but must be addressed when this is introduced.

## 6.2 Identification of risk factors

Identifying risk factors for ACR is primarily about identifying safety critical equipment, and the relationship between the safety critical equipment and risk. It is not possible to model all the equipment into accident scenarios, thus a criticality analysis for equipment from major accident prevention point of view is a precondition to model accident scenarios. This is a challenge in practice, since the criticality of equipment is predefined mainly from production point of view, instead of major accident prevention point of view.

A potentially important risk factor to ACR, latent errors introduced during performance of the activity (e.g. incorrect fitting of flanges, valves in wrong position), should be identified together with evaluation of APR. The point is to bear in mind is that the expected consequence of the activity may not be achieved as a result of latent errors. Identification and quantification of these aspects require input from Human Reliability Analysis.

For APR, identification of risk factors (i.e. safety critical parameters) influencing various activities is resource and time consuming. In a large process plant, hundreds of jobs may be performed every day. Activity specific risk factors will vary among different activities, i.e. risk factors that are defined for one activity might not apply for another activity. We are lacking a good understanding of what barrier systems are relevant for the activities and how important they are. Currently there are no systematic methods/guidance to identify a set of safety critical parameters to express APR for critical activities. Another thing is that the basic underlying conditions to introduce risk factors to describe the risk picture are (Rosness, 1998):

* It is possible to identify all risk influencing factors (RIFs).
* The risk can be determined by the state si of a specified number *r* of RIFs.
* The risk can be controlled by controlling the changes of RIFs.

It is difficult to know to what degree we are able to meet these conditions. In addition, even though the risk factors are limited to only those directly influencing APR, the list may still be long. This may introduce another challenge, how to select the most important contributing factors among all those identified.

For PR, no guideline or method to illustrate how to systematically identify interactions while planning is the primary challenge. In practice, it mainly depends on experts’ experience to identify additional risk after adding new activities (Hirsch-Maclean et al., 2015). The interactions are rendered visible with hindsight, because “people know what to look for, where to dig around for the rot, and the missing connections” (Dekker, 2011). Hindsight does not help much, but similar accidents/incidents may help us see how interactions could happen. This needs a broad and structured review of investigation reports to develop a guideline to identify interactions. Also, interactions can be identified via safety critical parameters of simultaneous activities. In other words, we can try to look into how the safety critical parameters of those activities may interact with each other, to see how the activities can interact. Still, this needs further systematic analysis after identification of the parameters.

## 6.3 Status of risk factors

For technical risk factors such as barrier systems and safety critical equipment, the most desirable means to report status is through continuous condition monitoring. For some barriers, this is applied, but it is not common in the industry for all types of technical barrier elements. PSA has highlighted the importance of monitoring barrier status (PSAN, 2014b). Still, the major information source for barrier status currently is from audit, maintenance system, and findings from inspections. Therefore, the time perspective for updating is relatively long for many barriers (from 6 months to 5 years). This is not sufficient for operational planning decisions. One practical challenge is then how often the status of factors should be updated, since more frequent tests/inspections implies increased cost.

Safety critical parameters for APR have broader scopes which integrate also external factors and operational and organizational factors. Preferably the status of key physical safety systems, temporary barriers, test methods, equipment etc. involved in the job should be confirmed. This means that we shift the probability of failure of certain system/equipment (e.g. whole gas detection system) to probability of failure of single item (e.g. the gas detector in the area). This also applies to human and organizational factors, such like the competence of the worker, and quality of the procedure. This is not easy since lots of preparation work is needed before making the decision.

Furthermore, a risk factor is a theoretical construct, that needs operational/measurable representations such as risk indicators (Øien, 2001). If we say that degradation of a barrier is a risk factor, one possible indicator that can say something about the degradation is overdue preventive maintenance/testing. Another example is the risk factor operator competence, which can be measured in terms of years of experience. A challenge in relation to this is to select indicators which cover the most important characteristics of the risk factors (Øien, 2001).

## 6.4 Explicit modelling of different aspects of risk

To express ACR, APR and PR (Section 4.1), explicit modelling of risk factors is necessary. It is possible to model ACR using QRA methods, but current QRAs do not necessarily contain all the details required.

The top three contributors to major accident risk in the oil and gas industry on the Norwegian Continental Shelf is process leaks, ship collision and blowout (PSA 2014). There are significant differences in how they are modelled. For process leaks and blowouts, the focus in the modelling is very much on the consequences of the hazardous events, with very limited modelling of the causes of the events. On the other hand, modelling of ship collision focuses almost exclusively on the causes and not very much on consequences. There is therefore no guarantee that the QRA will include all important risk factors for ACR.

Also, current QRA in offshore platforms has largely been limited to analysis of consequence reducing technical barriers. As a result, few changes in factors influencing the probability of hazardous events will actually have significant impact on QRA results (Vatn and Haugen, 2013).

For APR and PR, there are no explicit models available today. Job Safety Analysis (JSA) is the most used risk assessment method for jobs in daily operation for APR (Andersen and Mostue, 2012), but it does not quantify changes in risk. Also, There has been criticism that JSA is personnel risk focused and unfit for assessing major accident risk (Andersen and Mostue, 2012).Today, PR is subjectively evaluated while approving work permits.

APR and PR are characterized by risk factors, so modelling with risk influencing diagram is a possible way to establish the link between them. Another challenge is whether a number should be generated out of these parameters. Quantification has both positive and negative effects. It enables simple comparison among alternatives, when multiple safety critical parameters are different from alternative to alternative. Then APR needs a comparable expression that should be sensitive to changes of safety critical parameters. A potential negative effect is that numbers may hide the fact that critical parameters are in a poor condition because most other parameters are average or good, cancelling out the effect of single negative parameters. This may clearly have a negative impact on activity risk control.

## 6.5 Define decision criteria

Currently there is no target frequency of occurrence of a special catastrophic failure scenario or relative criteria required by regulation that applies to ACR. However, it may be possible to derive criteria based on overall acceptance criteria for a plant or an installation.

NORSOK (2010) requires risk acceptance criteria for operations that are not covered by base case risk analysis to reflect the duration of the period with increased risk, the peak level of risk during this operation, whether risk increase is local or global for the installation and whether the risk increase affects the different personnel groups in the same way or differently. However, little guidance is provided with regard to how these criteria should be developed or formulated.

Decision criteria for APR and PR is even more challenging. A criterion such as “rule of three” draws from field experience which rooted in operators’ expertise. Many factors usually contribute to accidents and according to Hudson and van der Graaf (1998), it is common that more than 50 factors are identified as contributors. How can we then identify three factors that push the system to the edge? And what are the thresholds for these factors? In principle, the thresholds need to be conservative to compensate for other possible factors and potential interactions that are not considered. This can easily lead to a situation where we are nearly always above the thresholds.

We have suggested safe envelope/operating limits as acceptance limits for period risk. In today’s practice, some operating limits of the system are inherent in the design of the system. These are derived from engineering disciplines or from risk assessment in the design phase. In addition to these, operational managers often use self-imposed rules such as maximum number of work permits at any time, maximum number of exposed people on the site, etc. Without doubt, professional judgement and experience play an important role in supporting operational planning decisions. However, simple rules like this can hardly ensure consistency in decision-making about risk.

## 6.6 Comparison between different alternatives

ACR, APR and PR all together construct a complete risk picture. At the same time, it introduces a general question: what is the best alternative when ACR, APR and PR are all taken into account? These should not be evaluated together. An example of how this can be illustrated is shown in Figure 4. ACR, APR and PR for each alternative are displayed together with corresponding acceptance criteria. When presenting risk like this, we also have to take into account that the duration of the risk represented by ACR, APR and PR is not the same. The issue of acceptance levels mentioned in Section 6.5 is also relevant.

Figure 4 An idealized demonstration of risk aspects of alternatives

## 6.7 Uncertainty

When discussing risk information as input to decisions, we cannot avoid the topic of uncertainty completely. Haugen and Vinnem (2015a) point out that the uncertainty aspect of risk has been consistently neglected for a long time by oil companies and we should avoid making the same mistake. At the same time, understanding the relationship between uncertainty and risk itself is a challenging issue (Johansen and Rausand, 2014) and we do not wish to go into this discussion.

We have applied the second order definition of risk proposed by Kaplan and Garrick (1981) (Section 3.1). This includes uncertainty and completeness, through distribution of probability of frequency and probability of consequence. The degree of uncertainty depends upon the state of knowledge of the risk analyst, under the assumption that two risk analyst with the same background information and evidence will assign the same frequency to the scenarios.

As a supplement to the presentation of ACR, APR and PR to the decision-maker, a description of the uncertainty associated with these values should also be given. In the context of operational planning decision-making, we will further normally get more information about relevant parameters that influence risk as planning progresses. The uncertainty will therefore typically decrease through the planning process. We do not go further into how uncertainty can be presented in this paper.

# 7. Conclusions

The objective of this paper has been to look into operational planning decisions, what information about risk we do need when making these kinds of decisions, how can we establish this information and what are the challenges we meet when trying to do this in practice.

We have discussed how different aspects of risk are necessary to get a complete picture of the risk associated with a decision. It has been suggested that risk is presented in terms of Activity Consequence Risk (ACR), Activity Performance Risk (APR) and Period Risk (PR) to show the complete risk picture associated with a decision. ACR is a representation of updated basis risk level of the plant, as a result of the consequence of the action. APR represents the risk in addition to basis risk level while executing the action, with system conditions as constraints. PR shows the variation of risk level in the concerned periods taking into account all activities which are taking place. In practical applications today, these three are normally not addressed explicitly and even if they are addressed, they are hardly ever evaluated together.

The paper also suggests how these risk aspects can be analysed and presented to the decision-makers. Due to the different nature of the risks, alternative ways of analysing risk and alternative focus areas are proposed.

Finally, we have also looked into a simplified example and some of the challenges related to actually making this work in practice. The methods and practices applied in the oil and gas industry today are only partially able to meet the requirements laid out in this paper and considerable work is required to develop or adapt methods and tool to suit the purpose described here.

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# References

Almklov, P., Haavik, T., Haugen, S., Kongsvik, T., Røyrvik, J.O., Schiefloe, P.M., Unpublished results. Modelling instantaneous risk for major accident prevention Task 1: Analysis of decisional situations. Studio Apertura, NTNU Social Research.

Andersen, S., Mostue, B.A., 2012. Risk analysis and risk management approaches applied to the petroleum industry and their applicability to IO concepts. Safety Science 50, 2010-2019.

Azizi, M.M., 2014. PRA Application to Offshore Drilling Critical Systems, Probabilistic Safety Assessment and Management PSAM 12, Honolulu, Hawaii.

Cox, J.L.A., 2013. Improving Risk Analysis, 1 ed. Springer-Verlag New York, New York.

CSB, 2007a. Partridge Raleigh Oilfield Explosion and Fire 06/05/2006, Case Study. U.S. Chemical Safety and Hazard Investigation Board.

CSB, 2007b. Valero Refinery Propane Fire 02/16/2007. U.S. Chemical Safety and Hazard Investigation Board.

CSB, 2012. E.I.DuPont de Nemours & Co Inc. Flammable Vapor Exposion 11/09/2010, Case Study. U.S. Chemical Safety and Hazard Investigation Board.

Dekker, S., 2011. Drift Into Failure: From Hunting Broken Components to Understanding Complex Systems. Ashgate Publishing Company, UK.

DNVGL, 2014. Barrier Management in Operation for rig industry: Good Practices.

ERIN, 2013. United States Nuclear Industry Experience in Dynamic Risk Assessment, Prepared for Center for Integrated Operations in the Petroleum Industry (IO Center).

Flin, R., O’Connor, P., Crichton, M., 2008. Safety at the sharp end: A Guide to Non-Technical Skills. Ashgate.

Hale, A.R., Ale, B.J.M., Goossens, L.H.J., Heijer, T., Bellamy, L.J., Mud, M.L., Roelen, A., Baksteen, H., Post, J., Papazoglou, I.A., Bloemhoff, A., Oh, J.I.H., 2007. Modeling accidents for prioritizing prevention. Reliability Engineering & System Safety 92, 1701-1715.

Haugen, S., Vinnem, J.E., 2015a. Perspectives on risk and the unforeseen. Reliability Engineering & System Safety 137, 1-5.

Haugen, S., Vinnem, J.E., 2015b. Risk information for operational decision making in oil and gas operations, ESREL2015, Zurich, Switzerland.

Hayes, J., 2013. Operational Decision-making in High-hazard Organizations : Drawing a Line in the Sand. Ashgate Pub. Co, Burlington, VT.

Hirsch-Maclean, H.v., Utvik, O.H., Einarsen, K.H.D.R.I., 2015. Leadership teams; evaluation of a risk decision making method for total operational risk management of activities on offshore installations, ESREL 2015, Zurich, Switzerland.

Hopkins, A., 2011. Risk-management and rule-compliance: Decision-making in hazardous industries. Safety Science 49, 110-120.

Hopkins, A., 2012. Disastrous Decisions: The Human and Organisational Causes of the Gulf of Mexico Blowout. CCH Australia Limited.

Hudson, P.T.W., van der Graaf, G.C., 1998. The Rule of Three: Situation Awareness in Hazardous Situations, SPE International Conference on Health, Safety, and Environment in Oil and Gas Exploration and Production. Society of Petroleum Engineers, Caracas, Venezuela.

IAEA, 1999. Living probabilistic safety assessment (LPSA). International Atomic Energy Agency, Vienna.

ISO, 2013. ISO/TS 16530-2:2013(E) Well integrity -- Part 2: Well integrity for the operational phase, 17.4 MOC Process. ISO copyright office, Switzerland, p. 87.

Johansen, I.L., Rausand, M., 2014. Uncertainty and the credibility of risk assessment. Risk anlaysis.

Kaplan, S., Garrick, B.J., 1981. On the quantitative definition of risk. Risk Analysis 1, 11-27.

Marakas, G.M., 2003. Decision support systems in the 21st century, 2 ed. Prentice Hall.

MIRMAP, Unpublished results. Workshop about living risk analysis 2014, Trondheim, Norway.

NCBP, 2011. Macondo: The Gulf Oil Disaster, Chief Counsel's Report, 2011. National Commision on the BP Deepwater Horizon Oil Spill and Offshore Drilling.

Nguyen, T.D., 2012. Modeling of Safety Functions in Quantitative Risk Analysis. Unpublished master thesis. Norwegian University of Science and Technology.

Njå, O., Braut, G.S., 2011. Investigation of incidents in systems designed or developed on the basis of risk analysis. Safety Science Monitor 15, 1-12.

NOGA, 2011. 090 - Norwegian oil and gas recommended guidelines for common model for Safe Job Analysis (SJA), 3 ed. Norwegain oil and gas association.

NOGA, 2013. 088 – Norwegian Oil and Gas Recommended guidelines for Common model for work permits (WP), 088. Norwegian oil and gas association.

NORSOK, 2010. NORSOK Z-013 Risk and emergency preparedness assessment, 3rd ed. Standards Norway.

NORSOK, 2013. NORSOK D-010 Well integrity in drilling and well operations. Standards Norway.

OECD, 2004. Risk monitors, the state of the art in their development and use at nuclear power plants. Nuclear Energy Agency Committee on The Safety Of Nuclear Installations, p. 227.

Øien, K., 2001. Risk indicators as a tool for risk control. Reliability Engineering & System Safety 74, 129-145.

Okoh, P., Haugen, S., 2013. Maintenance-related major accidents: Classification of causes and case study. Journal of Loss Prevention in the Process Industries 26, 1060-1070.

Okoh, P., Haugen, S., 2014. A study of maintenance-related major accident cases in the 21st century. Process Safety and Environmental Protection.

Orasanu, J., 1995. Training for aviation decision making: The naturalistic decision making perspective, Proceedings of the Human Factors and Ergonomics Society Annual Meeting. SAGE Publications, pp. 1258-1262.

Pidgeon, N., O'Leary, M., 2000. Man-made disasters: why technology and organizations (sometimes) fail. Safety Science 34, 15-30.

PSAN, 2011. The Deepwater Horizon accident - assessments and recommendations for the Norwegian petroleum industry SUMMARY. Petroleum Safety Authority Norway.

PSAN, 2014a. Guidelines regarding the activities regulations. Petroleum Safety Authority Norway, p. 13.

PSAN, 2014b. Regulations relating to management in the petroleum activities and at certain onshore facilities (The management regulations). Petroleum Safety Authority Norway, p. 5.

PSAN, 2015. "Major accident risk". Retrieved from <http://www.psa.no/major-accident-risk/category1030.html>. Petroleum Safety Authority Norway.

Reason, J.T., 1997. Managing the risks of organizational accidents, 6 ed. Ashgate Aldershot, Aldershot.

Rosness, R., 1998. Risk Influence Analysis A methodology for identification and assessment of risk reduction strategies. Reliability Engineering & System Safety 60, 153-164.

Vatn, J., Haugen, S., 2013. On the Usefulness of Risk Analysis in the Light of Deepwater Horizon and Gullfaks C, In: Albrechtsen, E., Besnard, D. (Eds.), Oil and Gas, Technology and Humans: Risk Asessment Methods in Organizational Change. Ashgate, pp. 71-89.

Vinnem, J.E., 2014. Offshore Risk Assessment Vol 2 - Principles, Modelling and Applications of QRA Studies, Third ed. Springer - Verlag, London.

VTT, 2008. Operational decision-making in the process industry - Multidisciplinary approach, In: Matasniemi, T. (Ed.), VTT RESEARCH NOTES 2442, p. 133.

Yang, X., Haugen, S., 2015. Classification of risk to support decision-making in hazardous processes. Safety Science 80, 115-126.

Zio, E., Pedroni, N., 2012. Overview of risk-informed decision-making processes, 2012-10 of the Cahiers de la Sécurité Industrielle. Foundation for an Industrial Safety Culture, Toulouse, France. Available at <http://www.FonCSI.org/en/>.

1. A WP is a written document that authorizes certain people to carry out specific work, at a certain time and which sets out the main precautions needed to complete the job safely. NOGA, 2013. 088 – Norwegian Oil and Gas Recommended guidelines for Common model for work permits (WP), 088. Norwegian oil and gas association.. [↑](#footnote-ref-1)