Dynamic Risk Analysis for Operational Decision Support

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Abstract

Quantitative risk assessments for offshore oil and gas installations have been developed and used to support decision-making about major hazards risk for more than 30 years. Initially, these studies were used to support the design process, aiming to develop installations that could be operated safely throughout their lifetime. As installations were put into operation, the studies were updated with as-built and operational information to provide a basis for making decisions also in the operational phase. This was however only partially successful, and the general impression has been that the studies have not been very actively used in operations. Many explanations have been given, the most common being that the reports were too complicated and written for risk analysis experts, not operations personnel on offshore installations and that the results could not be updated sufficiently often to reflect changes in risk on a day-by-day basis. This may be part of the explanation, but in this paper, we have looked into the decision context and the types of decisions made in operation, compared to those in the design phase. Based on this, it is concluded that the focus of existing models need to be extended to cover activity risk in a more detailed way, as well as the risk associated with the technical systems. Instead, a revised methodology for developing quantitative risk assessments is proposed, focusing on the parameters and activities that change during operation. The methodology has also been tested on an offshore installation, to investigate the feasibility in practice.

Keywords

Operational risk, Dynamic risk, Instantaneous Risk, Decision-support, Work planning

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1. Introduction

1.1 Background

In high-hazard industries such as process facilities and oil and gas producing installations, there is an inherent risk of major accidents, mainly due to the handling of highly flammable, explosive and/or toxic materials. The risk is associated with the plant and facilities as such, in combination with the activities taking place at the facility. The equipment is usually stable, changing primarily with modifications to the equipment and with slow degradation due to corrosion, erosion, fatigue, and other degradation mechanisms. However, activities change continuously, with various operational activities, maintenance and inspection tasks etc. ongoing at all times. These activities may also lead to temporary changes to the plant and equipment, e.g. because of work being performed on the equipment. Examples can be bypass and isolation of parts of the process plant or bypass of safety systems. This means that the risk level can vary considerably with time.

Managing risk in an operational setting therefore broadly focuses on two aspects: Firstly, maintaining the technical integrity of the plant and secondly, managing the activities such that the risk level for the plant is within acceptable limits. This requires a good understanding of the status of the plant and facilities as well as the activities, how they interact and where there are weaknesses in our protection against accidents. Some examples of decisions that have to be made are:

- Is it necessary to perform this maintenance work now or can it be postponed until the next major shutdown?
- We have a diffuse leak of gas in a flange that cannot be repaired without shutting down part of the plant. Can this repair wait?
- Is it acceptable that gas detectors in the area with the diffuse gas leak have gone past their due date for testing?
- We are planning to replace a crude pump tomorrow, at the same time as performing cutting to remove structures not required anymore. Can this be performed simultaneously?
- There are 18 work permits planned for tomorrow in one area. Is this activity level too high for one process operator to manage?

A common tool and a key element for providing information to support risk management are risk analysis. In ISO 31000, Risk Management – Principles and Guidelines, it is explicitly stated that "Risk management is part of decision-making", as one of the key principles (ISO 2009). Typically, decisions of the type mentioned above are to a large extent supported by fairly simple analyses, such as Safe Job Analysis (SJA) or predefined templates of allowable activities at the same time (SIMOPS matrixes). The information that we get from this is largely qualitative and therefore, ensuring decisions that are consistent with regard to risk may be quite difficult.

1.2 Objective

This forms some of the backdrop for the MIRMAP project (Modelling Instantaneous Risk for Major Accident Prevention). The main objective of the project was to provide better support for decision-making in operations of hazardous facilities such as chemical process plants and offshore oil and gas facilities. The starting point was that quantitative risk analyses that were performed for these installations did not provide a good picture of risk on a day-to-day basis. The initial focus was therefore on improved risk modelling, but it was also quickly realised that the types of decisions made, the information required to make decisions and the decision criteria are different in these situations. The project therefore also looked into the context in more detail, to ensure this was clearly understood before starting the risk modelling. Improving decision support is a key measure in being able to prevent major accidents (Kongsvik et al., 2015).

The focus in the project was on hazardous facilities with a potential for major accidents occurring, using the oil and gas industry as an example case. The project was limited to consider only major accident risk and did not look at occupational accidents (personal accidents/injuries).

In recent years, a lot of other work has been performed in this field, e.g. by Paltrinieri et al (2014, 2015). More about this is described in Section 3.

Decision-making about risk is of course hardly ever a question of risk only. In most situations, we are weighing risk against a set of other criteria, such as cost, production, availability of resources, time etc. Multi-criteria decision-making is comprehensively covered in many other publications, e.g. in De Almeida et (2015). However, this paper is only concerned with input to decision-making, and specifically risk input. Even if other inputs are equally important and need to be considered, it is not within the scope of the paper to look at how different criteria influence decisions. We have therefore chosen not to cover this topic in any detail.

The objective is to describe some of the work that has been done in the MIRMAP project, with emphasis on the decision context and the associated decisions themselves, and how this must form the basis for the risk modelling and the subsequent presentation of information to the decision-maker. It is underlined that the decision-making process itself, including the stakeholders involved and the process of understanding the decision and clarifying objectives is not covered in this paper. The focus is only on the risk information that is necessary to make sound decisions about risk. Obviously, there usually will be many other factors that also influence decisions and that need to be taken into account to make sound decisions.

The structure of the paper is based on the above, where we in Section 2 examine the decision context, the types of decisions and the decision-support required. This is followed by Section 3 where we look at earlier work that has been done on dynamic risk analysis. In Section 4, we describe the principles of the risk model developed in the project, followed by discussion and conclusion in Section 5 and 6 respectively.

2. Decision Support

2.1 Decision Theory

The paper focuses on information to support decisions and not decision-making as such, but a brief background on decision-making theory is provided, to position the work in relation to this.

The domain of decision theory may be broadly and dichotomously divided into either normative or descriptive classes (Bell et al., 1988). While the former aims to identify the best possible decision, considering a fully rational and ideal decision maker, the latter focuses on how decisions are made in reality, given the varied behaviour of different decision making agents.

With regard to the relevance or choice of suitable risk information for decision making, two specific decision theories are discussed here. Firstly, rational choice theory. In rational choice theory (a subset of normative decision theory), a decision is considered a choice between a fixed set of known alternatives made by an idealised decision maker (March, 1994). Critique of this perspective gave rise to the theory of bounded or limited rationality. Proponents of bounded rationality theory criticised rational choice, arguing that in reality not all alternatives are known, and therefore not all options may be considered while making a decision. Bounded rationality, therefore, claims a decision is a choice made based on the available knowledge that finally results in an action (Cyert et al., 1963). A change in the knowledge basis may also result in a change in choice or decision. Bounded rationality represents a shift into the descriptive domain of decision theory.

The second decision theory relevant to discuss here is that of naturalistic decision making. This theory looks into aspects associated with real decisions, such as time available, problem definition, information availability etc. Naturalistic decision theory is a knowledge-based approach in descriptive decision theory that aims to understand the cognitive work behind decision making, i.e. the role experienced decision makers have (Klein, 2008). In other words, naturalistic decision-making shifts focus from pure alternative selection to aspects related to the cognitive work of decision-making (Schraagen, 2008) such as situational awareness, i.e. perception, comprehension and projection (Endsley, 2016).

Rational choice and naturalistic decision theories describe two very different decision processes where different information types play different roles in supporting decisions. This also includes risk information which is an important dimension in decision-making related to hazardous processes to avoid major accidents (Yang and Haugen, 2015). The following Section 2.2 reflects on concrete decision contexts where these rather different decision theories may apply, and Section 2.3 goes further to discuss what kind of risk information is relevant for these different decisions.

2.2 Decision Context

Yang and Haugen (2015) provide a classification scheme for decisions from a risk assessment perspective. Firstly, two broad categories of decisions called *planning decisions* and *execution decisions* are defined. Execution decisions are outside the scope of the paper and are not elaborated further. Planning decisions are characterised by a time lag between decision and action that allows for identification and evaluation of various alternatives. Planning decisions may be divided into strategic or operational decisions. Strategic decisions are characterised by long planning horizons (sometimes years), that the effects of the decision will be long-term and that these decisions are relatively infrequent. Roles and responsibilities are well defined, most relevant alternatives can be identified and evaluated, and the resources and time to make the final decision are rather generous. Strategic decisions related to hazardous process facilities are made by blunt-end decision makers and typically involve decisions related to approval of projects, choice of design concepts, decisions on overall maintenance strategies etc.

On the other hand, operational decisions involve medium-level decision makers and have a shorter planning horizon (weeks/months) with medium- or short-term effects. The time to involve all relevant resources and evaluate all possible alternatives is more limited. Examples of operational decisions were given in Section 1. Operational decisions can probably best be described by naturalistic decision theory or bounded rationality theory while strategic decisions are closer to rational decisions.

In the MIRMAP project, the focus has been on operational planning decisions and the information required to support these decisions. In the following, some elaboration on the type of information required for different decisions is provided.

2.3 Risk Information for Decision Support

For strategic decisions, quantitative risk analyses along with the as low as reasonably practicable (ALARP) principle is typically used (Hayes, 2013). In these risk assessments, the focus is on the long-term averaged risk over a long period of time, usually calculated per year. This information is well-suited to support strategic decisions regarding general concept or design selection or general facility layout decisions. Yang and Haugen (2015) explain how site-specific average risk is used in quantified risk analysis, where explicit accident scenarios are modelled using generic failure statistics from data handbooks such as OREDA handbook (SINTEF 2015), PDS Data handbook (SINTEF 2013) etc.

For operational decisions, the time lag typically varies from 3 months down to 24 hours from the decision is made to work is executed. Operational decisions are often associated with short-term effects (e.g. during the performance of an activity). Therefore, averaging risk over a long period is not relevant. Instead, the information required is the Activity Performance Risk (APR). This is an expression of the risk associated with performing an activity (Yang and Haugen, 2015). APR needs to be used in conjunction with Period Risk (PR). The period risk is a measure of risk that calculates the risk of an activity over the period it is to be executed (including other simultaneously planned activities in the same area).

To clarify the use of these measures, consider first a decision about whether to perform maintenance on a shutdown valve now or to postpone it to later. This work introduces a known hazard, i.e. the incorrect/improper execution of the work may lead to a gas leak. During the work, the risk is thus increased, but once the work is completed, this additional risk is removed. This is an example of Activity Performance Risk (APR), which exists only during the performance of the work. This is the increase in risk due to the execution of the job performed without any other activities taking place at the same time.

Now consider a decision whether to perform a set of three activities simultaneously. E.g. the valve maintenance job, a welding job and a painting job. This example is typical for day-to-day operations in hazardous facilities, where there are many activities carried out simultaneously. The question is now if all these activities are safe to perform simultaneously or not as some activities may influence each other and the combined risk is not the simple sum of the risk contributions from an individual activity. Therefore, in such a situation both APR and PR need to be used. APR may first be used to evaluate if the job is safe to perform by itself, and thereafter PR may be used to verify that the job does not interact with other simultaneous tasks to give unacceptable risk peaks or conflicts in the risk level.

The main conclusion is that different risk measures are needed for different planning decision types. Average risk is suited only for long-term or strategic decisions while APR and PR provide relevant contextual information to support operational decisions.

3 Risk analysis to Support Operations

The concepts of a living QRA and Risk Monitors are well-known in the nuclear industry and dates to 1988 when the “maintenance rule” was introduced by the regulatory authorities. This regulation stated that every licensee *shall assess and manage the increase in risk that may result from the proposed maintenance activities.* This gave birth to the first Risk Monitor that was used in the UK (Puglia & Atefi 1995; Majdara & Nematollahi 2008; NEA 2005). Another example of a risk monitor is RiskWatcher (Risk Spectrum 2017)

In the oil and gas industry, risk management in operations has traditionally been based on largely qualitative risk information. In recent years, we can identify three different paths that are aimed at establishing a better quantitative basis for managing risk in operations. These partly overlap:

- Updating the quantitative risk analysis – the objective is to calculate an updated average risk level on a frequent basis, whenever significant modifications are made, or at least as often as required for decision-making. In principle, detailed risk models and simulations that include process data, e.g. temperature, pressure etc. are used for the calculation. An update of this nature usually requires a few months.

- Area risk charts – to simplify the detailed and often lengthy quantitative risk analyses, area risk charts have been used as an attempt to present concise and relevant information to operations. This document summarises results from the quantitative risk analysis area-wise and presents them in a more readable and easy to interpret format. It provides operations with an overview of the average risk in an area and the main risk contributors.
- Barrier management – this has been very much in focus in the offshore oil and gas industry in Norway the last few years, largely due to attention on this topic from the Petroleum Safety Authority of Norway (PSAN) (PSAN 2013). The basis for this is the energy-barrier principle (Gibson 1961, Haddon 1980) that focuses on the individual real-time status of barriers only. The approach tends to give focus on the individual barriers, but not the risk picture in total (Hayes 2013).

In other developments in the process industry, the term Dynamic Risk Analysis has been more commonly used. One of the first attempts at developing a dynamic risk analysis was by Meel et al (2007). This was based on statistical analysis of incident data and loss statistics. The results are updated accident probabilities and risk estimates for a specific plant. However, there is no detailed underlying risk model and the approach is not able to predict future risk levels based on changes in plant status or activities, only based on experience.

Kalantarnia et al (2009) developed a method based on QRA, building on the work by Meel and Seider (2006). Bayesian updating based on experience data was used also in this case, but the accident scenarios were modelled using event trees and fault trees. This has formed the basis for most of the work done later. Further developments have been done by introducing Hierarchical Bayesian Analysis (Yang et al 2013, Khakzad et al 2014), predictive accident modelling (Rathnayaka et al 2011) and Dynamic Operational Risk Assessment (Yang and Mannan 2010a, 2010b).

Paltrinieri & Khan (2016) provide a comprehensive overview of recent developments in dynamic risk analysis. In summary, recent developments may be summarised in two main categories:

- The basis for the analysis is accident models, usually taken from existing QRAs. This implies that activities in operations are modelled explicitly to a very limited extent.
- The updated risk picture is provided by using either precursor data or other experience data from the plant or by using indicators that predict future states of the system.

The method described in the following is based on the use of indicators that predict future states and connecting these indicators into explicit risk-modelling of all the risk-inducing activities that are taking place in the plant. In addition, information from the existing QRAs is also being used, including barrier management solutions and activity/work planning solutions to monitor the real-time risk on an oil and gas facility.

4 Dynamic Risk Modelling

4.1 Modelling Objective

Identification and clear understanding of decision context and the associated decisions are critical before any risk model is developed. The need for a dynamic risk model arises when risk changes frequently, as a function of changing operational conditions as discussed in Section 2.2. For petrochemical facilities, the primary focus is the risk of a major accident from process upsets. This is the relevant risk scenario that is chosen for the risk model presented in this paper. Other scenarios that may also be relevant to study is the risk of blowouts due to well kicks during drilling operations, the risk of ship impact/collision from visiting/passing vessels etc.

As activities are executed, or failures occur during operations, the risk levels change. This may be understood by looking at the barrier representation in Figure 4.1. Several pre-designed layers of protection or barriers prevent the uncontrolled progression of a leak scenario. These include technical, operational as well as organisational elements that either individually or collectively reduce the possibility for a specific incident to occur. It is the changing status and condition of these barriers due to impairments and/or ongoing activities that define the changing (transient) risk level at a facility.

These impairments and deviations occur during daily operations. Risk information needed to support decisions here includes the APR and PR as introduced in Section 2.3.

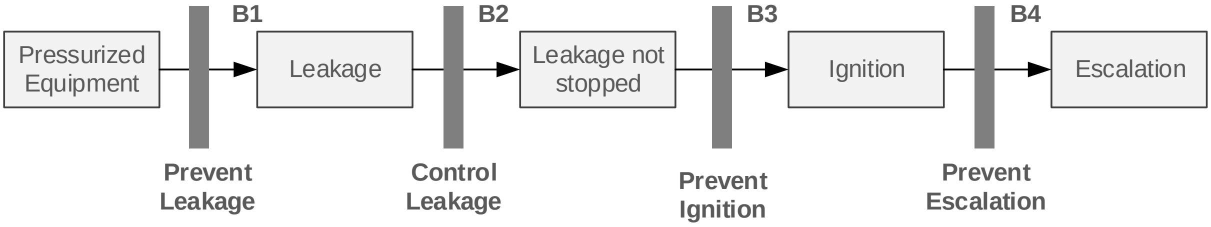

Figure 4.1 Barrier representation of the undesirable event sequence

4.2 Basic Unit in the Modelling Framework

The basic unit of the modelling framework are "*risk increasing tasks*" (referred to as A1 tasks) and "*risk increasing conditions*" (referred to as A2 conditions). These are the lowest unit or level in the risk model. A1 risk increasing tasks are tasks that introduce a hazard that might affect the integrity of a barrier and A2 risk increasing conditions are factors that directly impair or weaken a barrier system/element. In the first case there is a probability of impairment, in the second case there is certainty. Table 4.1 lists some examples of category A1 and A2 factors.

Table 4.1 Generic List of Tasks (selected examples) and the corresponding affected barrier function

Task		**Influencing Factors**	**Barrier Function**
A1	Work on HC-systems	Competence Isolation Plan Time Pressure	Prevent Release
A1	Heavy lifting over HC-systems	Lifting Equipment Competence Time Pressure	Prevent Release
A1	Hot Work (Class A and B)	Habitat Competence Time Pressure	Prevent Ignition
A2	Process Safety Valve Impairment	Degree of Impairment Compensatory Measures	Prevent Release
A2	Gas Detection Impairment	Degree of Impairment Compensatory Measures	Control Release
A2	Fire Detector Impairment	Degree of Impairment Compensatory Measures	Prevent Escalation
A2	Use of Electrical Equipment	Degree of Impairment Compensatory Measures	Prevent Ignition

The complete list of A1 tasks or A2 conditions depends on the risk picture and aspects that cause the changing risk picture. Based on this, we can establish a generic list of typical activities that directly or indirectly affect the risk level. This is the starting point for the risk model.

Moving one step further, the nature or extent to which the different tasks or conditions may cause changes in risk is described through influencing factors. For example, if a process safety valve has adequate redundancy while a recertification task is performed, this is not a complete weakening of the process safety barrier. In order to reflect these aspects, each A1 task and A2 condition has a set of influencing factors that help describe the activity in better detail. Table 4.1 lists some examples of influencing factors.

In addition to the dynamic aspects (activities A1 and A2) that change the risk level, decision makers also need information about the general technical integrity and design of barriers in the area these activities occur. For instance, a barrier impairment in an area with design limitations or weakened technical integrity may be more critical than the same barrier impairment in another area with robust design and redundancy. Activity Performance Risk and Period Risk are therefore also a function of the technical integrity and design of barriers. Type B and C factors model these aspects. Type B factors relate to the technical integrity of equipment and Type C factors relate to design deficiencies in barriers. An example of a Type B factor is equipment degradation due to age or fatigue, while an example of a Type C factor is limitations in gas detector coverage, inadequate firewater capacity etc.

To summarise, Figure 4.2 illustrates how all these varied factors come together to describe the changing risk picture. For the chosen modelling objective, a representative set of A1 tasks and A2 conditions must first be defined based on the barrier grid (Figure 4.1). Type B and C factors then come together to describe the complete risk picture.

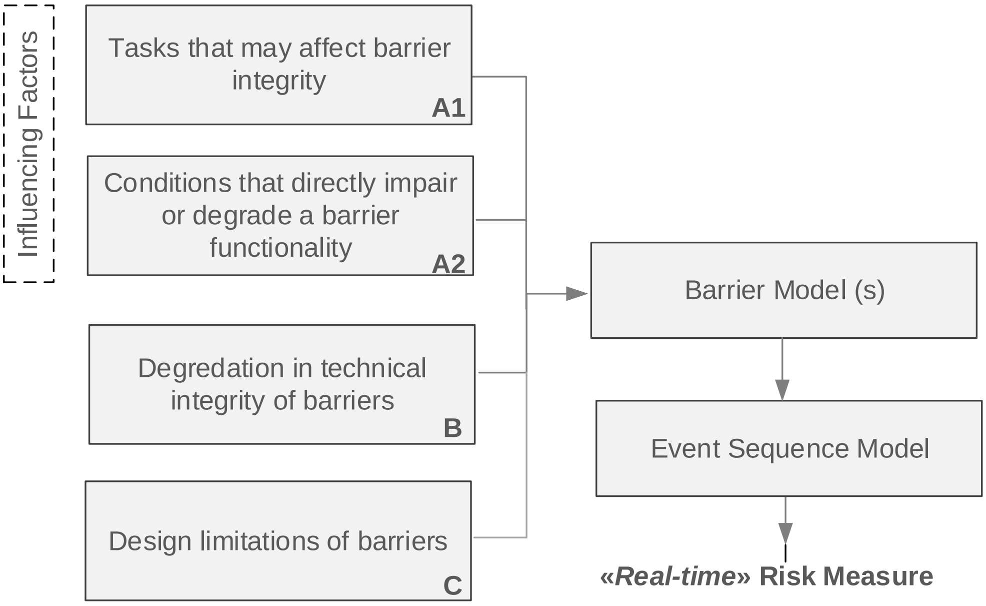

Figure 4.2 Outline of the risk model

4.3 The Risk Model

As mentioned in Section 3, the risk model developed is initially a simplification of the detailed risk models used in the quantitative risk analysis. In other words, the risk model is modified so as to use only relevant information about technical system configuration and design from the QRA (e.g. B and C factors). In addition, the dynamic aspects of A1 tasks and A2 conditions are also included directly in the risk model. The established risk model is quantifiable and provides decision makers with risk measures like APR and PR discussed earlier.

The risk model is based on a traditional set-up of event and fault trees. While event trees model the event-sequence illustrated through the barrier grid in Figure 4.1, fault trees model failure scenarios for the pivotal events in the event tree. The end frequencies from the event tree provide a risk measure. The basic events in the fault trees are the Type A1, A2, B and C factors. See Section 4.4 that provides concrete examples of how input is provided to these different factors.

The effect of the influencing factors on the A1 and A2 basic events are modelled through influence diagrams. The model structure and quantification approach is inspired from the Hybrid Causal Logic (Røed et al., 2009) and Risk_OMT (Vinnem et al., 2012) methods, where Bayesian Belief Networks (BBNs) integrate with the traditional event and fault tree quantification. Figure 1.3 illustrates this generic model setup.

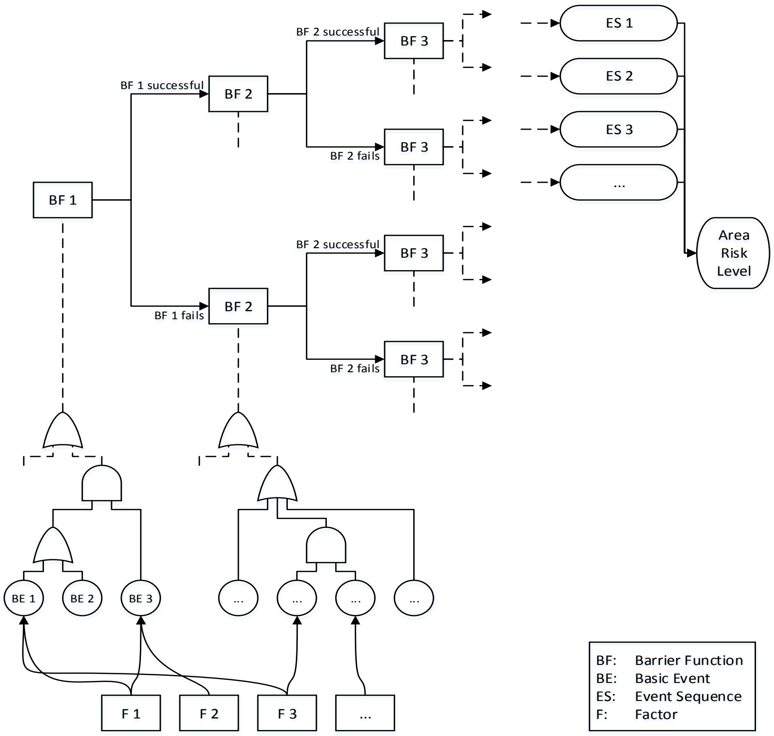

Figure 4.3 Generic model setup – combination of event tree, fault trees and influence diagrams

4.4. Model Calibration

This section gives some concrete examples on how the risk model is calibrated with information from the design risk analysis and other suitable data sources.

Take for example hydrocarbon release due to manual intervention. The corresponding basic event in the fault tree is, "*A1: Leak introduced from manual intervention on normally pressurized hydrocarbon equipment*". The leak probability associated with performing this activity is based on the total annual leak frequency for the facility, $f_{Total\ (QRA)}$. This is information that is readily available from the QRA.

The average portion of leaks from $f_{Total\ (QRA)}$ that are caused by manual intervention is extracted from this using $\frac{n_{A\ (LD)}}{n_{Total\ (LD)}}$, where LD refers to historical data from a leakage statistics database (E.g. RNNP,2017). Note that $n_{A\ (LD)}$ is the number of leaks due to manual intervention, and $n_{Total\ (LD)}$is the total number of recorded leaks in general.

This number is in turn divided by a facility's annual number of work orders for work on normally pressurized equipment, i.e. $N_{Annual\ WOs}$ (can be obtained from counting the number of work orders from previous years on the facility, alternatively by estimations in the QRA). This gives the average leak probability per executed work order which may be used directly in the risk model.

$$p_{A,\ per\ WO} = \frac{f_{Total\ (QRA)} \times \frac{n_{A\ (LD)}}{n_{Total\ (LD)}}}{N_{Annual\ WOs}}$$

This p_A is further adjusted based on the nature of the hydrocarbon work, e.g. factors such as operator competence, time pressure, supervision, isolation plan availability etc. This adjustment is made through an influence diagram setup.

The above is just one example of how QRA input parameters are adjusted to make them useable in a dynamic real-time risk model. Similar types of input data adjustments need to be made on a variety of other QRA input parameters as well for the different barrier functions (e.g. probability of ignition from hot work A, probability of escalation, probability of gas detection etc.)

4.5 Relevant Data Sources for Real-time Updating

The likelihood of Type A1, A2 and B basic events change frequently as a function of the nature of work being executed and the status of barriers at a given point in time. A number of different data sources provide updated information in the form of influencing factors. Type C design deficiencies are inherent deficiencies that exist due to the nature/choice of design and these factors are static in the model.

Table 4.2 Examples of input sources to the different basic elements in the risk model

A1 Tasks that may affect barrier integrity	**Examples**
Maintenance management system	Notifications Work Permits Work Orders
A2 Conditions that directly affect barrier functionality	
Deviations recorded in the Control System	Overrides, Trips
Other Barrier breaches or deviations	Condition alarms/Fault alarms/Dangerous Undetected Failures etc.
B Degradation in technical integrity of barriers	
Slow degradation mechanisms	Overdue PM on safety critical systems

Table 4.2 provides examples of input sources that may be used for A1, A2 and B basic events. The increasingly widespread use of computerised solutions in process industries means that the amount of available data is often huge and increasing. Unfortunately, the data often exists across different systems in a variety of formats.

Particular decision types need to be supported by relevant risk information. In this context, operational decisions require APR and PR to provide decision makers with an understanding of the individual as well as the collective contribution of planned activities to the risk. Section **Error! Reference source not found.** illustrates how these measures may be obtained from the risk model through an illustrative example.

5 Risk Model Applied to Activity Planning

5.1 Example 1 – Risk Profile APR and PR

Maintenance and work planning for oil and gas facilities usually follows a centralised work order and work permit planning system (Sarshar et al., 2015). Consider a work order involving removal of a pressure safety valve from a pressurised hydrocarbon segment - installing a blind flange, followed by re-pressurizing the system and putting it back in operation. This can be broken down into tasks that are executed in the following order.

Table 5.1 Sequence of planned tasks and affected barrier function(s)

ID	Task	(Potentially) Affected Barrier Function	From (Hour)	To (Hour)
1	Erect Scaffolding	BF4: Affect drag pressures from possible explosion BF3: Affect ventilation in the area	1	7
2	Isolate Hydrocarbon Segment	BF1: Leakage during isolation of HC segment	2	3
3	Remove PSV and Install Blind Flange	BF1: Leakage while performing work on HC segment	3	6
4	Reinstate Hydrocarbon Segment	BF1: Leakage introduced while reinstating HC segment	6	9
5	Remove Scaffolding	NA: Reversal of effects from ID 1	12	12

The Gantt diagram in Figure 5.1 illustrates the flow of tasks for the work activity. Moving from task to task, the risk level varies. Feeding this as input to the risk model, a risk profile is generated as shown in Figure 5.2. Note that this example assumes that no other work orders exist simultaneously. The risk measure (y-axis) is removed. Choice of risk measure is discussed in Section 6.2.

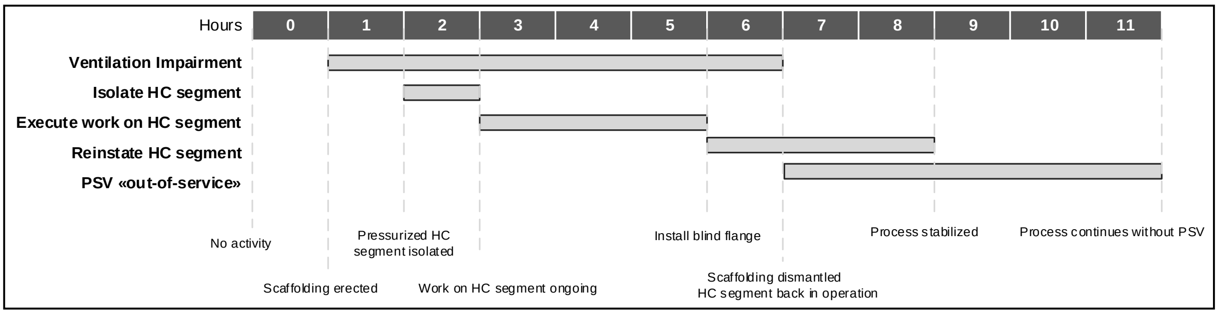

Figure 5.1 Gantt diagram showing workflow for the different tasks involved in the chosen work package

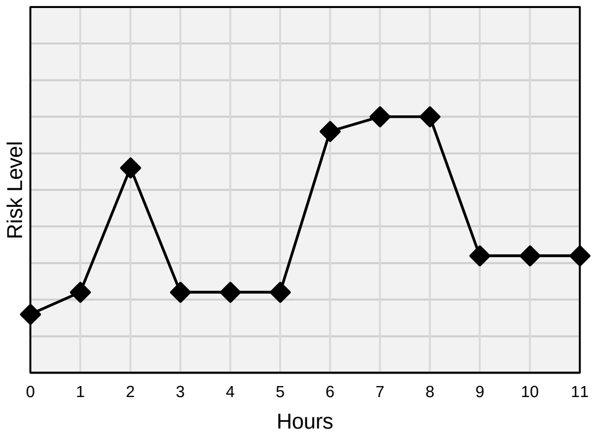

Figure 5.2 Risk profile for the chosen work order

The risk level at *t=0* represents the average risk for the relevant area considering no work activities or barrier impairments exist. At *t=1* a small increase in the risk level is seen due to a minor change in ventilation patterns due to the introduction of the scaffolding. The construction of scaffolding in the area affects how released gas is dispersed, thereby affecting the probability of ignition in the area and increasing the risk level. At *t=2* the first high peak is observed while the hydrocarbon segment is being prepared for intervention (i.e. depressurized and isolated). During intervention (i.e. removal of the PSV and installation of the blind flange) from *t=3 to 5*, the risk level drops because at this time the segment is completely depressurized, isolated and thereby empty of hydrocarbons. At *t=6* the risk level again increases when the segment is re-pressurized and put back in operation. This happens because errors might be introduced during the work execution, leak testing or final control activities. The risk level remains high for a couple of hours (*t=7 to 8*) until the process has stabilised. Thereafter, from *t=9* and onwards, the risk level drops to a level slightly higher than at *t=0* (since now a single PSV is removed and out-of-service).

The risk profile seen in Figure 5.2 is a combined expression of both activity performance risk (APR) as well as period risk (PR) to the decision maker. Since this example assumes no simultaneous work orders, each point in the graph is a representation of APR (given no other simultaneous activities). The area under the curve is an expression for the total risk seen over the eleven hour period. Mathematically, $PR = \sum_{t=1}^{11}(R_t - R_{basic})$ where

- R_t is the risk at time t
- R_{basic} is the basic risk assuming no activities or barrier impairments (in this example $R_{basic} = R_0$).

An understanding of the changing risk profile in operations is of importance to optimise work scheduling and avoid peaks in the risk levels. For example, if a hot work B activity, such as grinding of a metal surface had to be performed in this area of the facility at the same time, the risk profile would be quite different if the activity was performed at *t=4* versus at *t=6* (shown as option 1 versus option 2 respectively in Figure 5.3).

Visualising the different options of performing an activity at different points in time is another way to visually communicate both aspects of APR as well as PR to the decision maker. In this example, the peaks in Option 1 and Option 2 illustrate the APR given an existing period risk profile. This combined visualisation showing the altered risk profile allows the decision maker to visualise at once and simultaneity effects that might require rescheduling of certain work tasks.

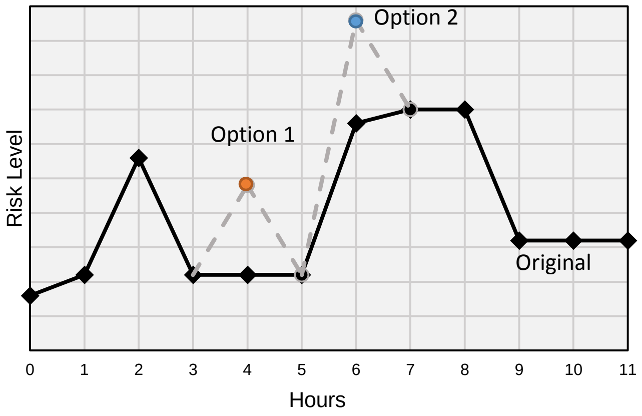

Figure 5.3 Alternative risk profiles assuming hot work B at *t=4* and *t=6*

A better knowledge of the instantaneous risk profile through the risk model can help in optimising work in time and risk, avoiding undesired peaks in risk levels during operations.

5.2 Example 2 – Marginal Risk Contribution (MRC)

When there are more than two or three such work orders being planned, making decisions based on visualising the APR/PR through a set of risk profiles is tedious. In a work planning meeting, many work operations are put together and optimised in time, resources and risk prior to actual execution of the work. In such a context, typical decisions that the model provides an answer to are:

- What are the top 10 work orders with the highest contributions to risk?
- Are there any unfortunate interactions between work operations that contribute to high risks?

The Marginal (work order) Risk Contribution (MRC) is a way to quantify and provide an answer to these questions. This measure detects:

- Any individual high-risk work orders
- Any work orders that exhibit any simultaneity clashes
- Long duration work orders that contribute to the risk over a long period of time

In simple words, this measure is calculated per work order. For a given work order, say work order *'i'* the risk is first calculated and summed up across the entire plan duration (e.g. 14 days). The same risk is again recalculated, this time excluding work order *'i'*. The difference between the two risk measures is the marginal work order risk.

Mathematically:

$\Delta \sum_{plan\ period} R_{WOi} = \sum_{plan\ period}^{all\ WO} R$ - $\sum_{plan\ period}^{all\ WO-WO_i} R$, where

- R is the risk measure
- WOi refers to the i^{th} work order

The example below is an illustration of a 7-day plan. Whole numbers are used for expressing the risk in the example for easy understanding of how the algorithm works. Table 5.2 shows a plan for seven days, comprising of three work orders, corresponding to eight work operations. Two work orders are performed in area unit A and one work orders is performed in area unit B.

Table 5.2 Sample work order plan over 7-days

Area	WorkOrderID	Work Operation	Day1	Day2	Day3	Day4	Day5	Day6	Day7
A	WO1	Install scaffolding	X	X	X	X			
		Isolate HC segment	X						
		Perform maintenance		X	X				
		Reinstate HC segment				X			
	WO2	Empty storage tank			X				
		Configure electric pump			X	X			
		High-pressure water spraying					X		
B	WO3	Remove passive fire protection		X	X	X	X	X	X

Figure 5.4 shows the risk profile across the two area units. The different lines in each of the graphs illustrate the baseline risk (lowermost line), the risk when all work orders are executed (highest line) and the risk when the mentioned work order is excluded (middle line).

The marginal work order risk contribution is calculated as the area between the topmost and the middle line. It is calculated as:

- MRC_{WO1}=8 (1+2+3+2)
- MRC_{WO2}=4 (2+2)
- MRC_{WO3}=2.5 (0.5+0.5+0.5+0.5+0.5)

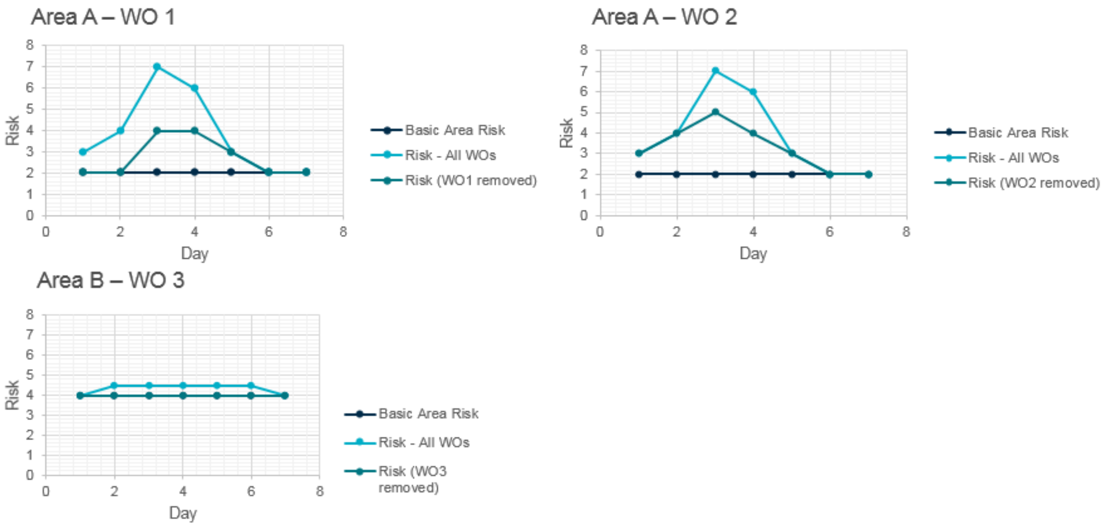

Figure 5.4 Illustration of risk profile, 7-day period

High-risk work orders within a given area may be ranked using the MRC.

For ranking work orders across different area units, the base risk in each of these areas also needs to be considered. This is because even though the MRC might be low for a work order, it may be performed in an area with a high baseline risk (e.g. performing a hot work B job in a process area vs. a utility area). Prioritisation/ranking of work orders across area units may be done using a two-dimensional plot representation as seen in Figure 5.5.

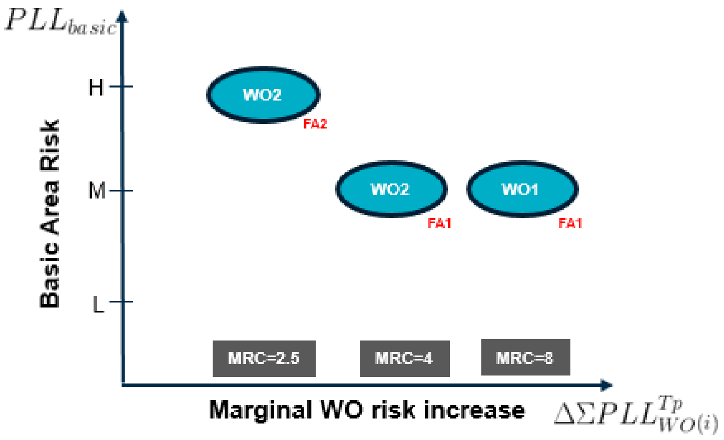

Figure 5.5 Two-dimensional representation of (marginal) work order risk across different area units

Such a plot helps differentiate between low-risk jobs performed in high-risk areas and vice-versa. Figure 5.5 illustrates that although WO2 might have a higher MRC than WO3, it may still be ranked lower than WO3 because WO3 is performed in an area with a higher baseline risk.

The MRC and it's representation in the two-dimensional plot is yet another way of expressing Period Risk (PR).

6 Discussion

6.1 Output from the Risk Model

The risk model presented in this paper provides a wide spectrum of results that may be used for different purposes. Some of these include:

- Point-in-time or instantaneous risk: Expresses the point-in-time risk at a given time instant.
- Risk profiles: Illustrates the changing risk level in time as seen using time-series plots
- Barrier status: Status of the barriers – i.e. their current condition and criticality are inherently part of the risk model and may be presented if relevant for the user.
- Importance measures (of degraded equipment): The advantage of using the event and fault trees is that proven importance measures such as Birnbaum's importance, risk reduction worth (RRW) etc. can be easily generated to aid decision makers to establish priorities for identification of risk-reducing measures.
- What-If analysis: For planning purposes, what-if analyses may be run to optimise scheduling of activities, foresee potential activity clashes and thereby prevent peaks in the risk level.

These results presented are driven by the "information need" to the decisions to be made. The method has so far been tested only on one real-life case covering two main areas of an oil and gas facility. Decision-makers involved in the model pilot-test commented that such a risk model could prove useful in the work planning meetings, to help draw attention to high-risk work packages and support optimisation of work not only based on time and resources, but also risk. This pilot test and results from the same will be described in detailed in a separate paper that is in preparation.

It is important to highlight that the development has been done in close cooperation with actual decision-makers. This means that the model and the results have been developed for plant staff and not risk analysis specialists (as is usually the case with the design QRA). Therefore, terminology within the tool and its interface are developed with operations in mind. The risk information provided enables control of the activity levels at the facility and supports maintenance processes to optimise work processes while minimising risk. Online risk management encourages a proactive approach to risk reduction by avoiding peaks in the risk level by better organising work and maintenance processes. In addition to this, the model may be used offline to study historic facility risk profiles and diagnose earlier occurred peaks in risk levels.

The manner in which risk information is presented depends on the decision maker and the decisions he/she is concerned about. For instance, an engineer planning an individual work order is concerned with the concrete activities within his/her work order, while a planner is concerned about work order coordination, i.e. avoiding that conflicting activities occur simultaneously or in overlap with each other. Therefore, while an engineer may be concerned with APR, a planner is concerned with the PR. In other words, there need to be different ways of presenting the risk to different decision makers depending on their focus areas. Not all results need to be made available to the different decision makers. Results need to be fine-tuned to suit the decision maker and his/her decision context.

6.2 Chosen Risk Measure

We commonly measure risk in terms of a statistically expected loss, calculated by multiplying frequency/probability and consequence. For strategic decisions, this is a useful measure since we can use it to minimise expected loss over a long period. For operational decisions focusing on activities, this is however not necessarily the best criterion for managing risk.

If we assume that we are about to perform a specific operation, and consider the risk before approving the start of the activity, we may then calculate e.g. a PLL-value (potential loss of life) for this operation, based on the frequency of accident and the number of fatalities should an accident occur. Mathematically: $PLL = \sum_{s=1}^{n} \Pr(s) \,.\, E(f_s)$, where

- s *is the defined/chosen "major accident" end scenarios from the event tree*
- n *is the total number of defined/chosen "major accident" end scenarios from the event tree*
- $Pr(s)$ *is the probability of occurrence of the* s^{th} *"major accident" end scenario*
- $E(f_s)$ *is the expected number of fatalities from the* s^{th} *"major accident" end scenario*

However, a more relevant criterion to use may be the probability of having an accident with a consequence that we do not want to occur, e.g. accidents with serious injuries or fatalities. This is in line with what is used in risk monitors in the nuclear industry, where the frequency of core damage is used to express the point-in-time risk.

Mathematically: $PMA = \sum_{s=1}^{n} Pr(s)$, where

- s is the defined/chosen "major accident" end scenarios from the event tree
- n is the total number of defined/chosen "major accident" end scenarios from the event tree
- $Pr(s)$ is the probability of occurrence of the s^{th} "major accident" end scenario

The selection of end events from the event tree may be altered (end events added or removed) based on the choice/tolerance of the user and their interpretation and definition of "major accident".

6.3 Acceptance Criteria

Another aspect of the quantification of risk is to what extent we accumulate risk over time. In the nuclear industry, the calculated risk is accumulated over time, to give a total for the risk that the plant has been exposed to over a year.

It may be argued that this makes little sense since risk only exists in the future. The only thing that we can measure in the past is a performance in terms of losses (fatalities, injuries or other) that we have experienced. Even if the risk is high in the coming day, we can thus argue that as long as no accidents with losses occur during that day, what risk we accept in the coming days should not be affected by this.

Instead, we need to find other ways of determining acceptance criteria. The problem then is that this cannot be done simply by taking the annual acceptance level and dividing this by 365 days. There will always be certain operations with a high risk that give short-term peaks in the risk level. How do we determine the acceptable level for a short period of time? This is an issue that needs to be further looked into.

Similar to the nuclear sector where Operational Safety Criteria (OSCs) are established (NEA, 2005) to distinguish levels of risk, similar levels need to be defined for this risk model. These levels are defined using an absolute risk level. For example, a low/moderate risk band may be defined considering the average risk from the QRA for the given area. Thereafter, the Medium/High and Unacceptable levels may be determined as multipliers on this risk level. Decisions may thereafter be based on the risk level in relation to these predefined safety criteria.

7 Conclusion

One very important reminder that we take away from this work is that risk analysis is performed to support decisions and if we don't understand the decision situations and the needs of the decision-makers, there is a good chance that we will not be able to provide useful information. This is of course not new knowledge in any way, but the work has once again highlighted the importance of understanding the context before starting the analysis.

Over the last 50 years or so, a comprehensive array of methods and tools for doing risk analysis has been developed and these have been applied to a wide range of problems and situations. It may, therefore, be easy to conclude that these are generally applicable and we may forget the basic assumptions underlying the models that we have developed.

The work undertaken in the MIRMAP project has underlined this clearly. Quantitative risk assessments have been developed to model risk for offshore oil and gas producing installations over a period of more than 30 years, and it is natural to assume that these risk models are equally applicable to the design and operational phases. However, when we study the objectives of the analysis, the context and the decisions to be made, we realise that we need to modify our models.

The model that has been described in this paper is based on "standard" or "traditional" risk analysis methods, but the content of the models and presentation of the results has been strongly flavoured by the context they are being used in. This has led to a need to develop new quantitative risk models that are quite different from the models used in QRAs for offshore installations. Clearly, they model the same accident mechanisms, but other elements of the accidents are modelled in more details compared to the QRA. In particular, there is more focus on causation and less attention given to consequence modelling. This is natural when we are in an operational setting and where avoiding accidents are the main priority, not necessarily minimising risk in the long term. Obviously, these two metrics are tied together, but they are not the same.

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