RELIABILITY ENGINEERING & SYSTEM SAFETY

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Dear Jack:

Enclosed is a manuscript that I would like you to review. Please complete your review *within three weeks.* If you are unable to do so, please send it back as soon as possible.

The journal publishes original research papers, review articles, industrial case studies, and technical notes (the latter may report on work yet to be completed, or may extend or refine results that are already published). *An important aim is to achieve a balance between academic material and practical applications.* In your review, please address the following questions:

1. Is the paper technically accurate? Are its conclusions justified?
2. Does it give proper credit to prior published work? If not, include the omitted citations.
3. Are title and abstract adequate to the content of the paper?
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5. Should it be
   a) accepted with minor revisions at the discretion of the Editor?
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Your identity will not be revealed to the authors. *If possible, please send me your comments via e-mail.* Thanks for your help.

Sincerely,

George

George Apostolakis, *Editor-in-Chief*

From: John Sorensen
To: Apostolakis, George
Date: 4/11/01 2:33PM
Subject: Organizational Risk Indicators by K. Oien

George:

This is an interesting paper, primarily because it lays out a complete path for identifying organizational risk indicators and relating them to predictions of risk. Having said that, there are a number of steps in the process where I am not technically qualified to pass judgement on the validity of what is proposed. What the author says seems reasonable, but I can't tell if it is true.

The author argues that organizational performance indicators that reflect risk can be defined, and that they can be used to predict and control future risk levels. He makes his illustration tractable by confining his risk metric to a single parameter, frequency of leaks, and confining his selection of organizational factors to those factors that have a plausible relationship to frequency of leaks.

The value of the paper is that it displays, and suggests methods for, all of the steps required to relate organizational factors to safety performance and to relate safety performance to performance indicators. Individual steps or elements in the author's methodology could be challenged without invalidating the overall process. He has provided an example of possible leading organizational performance indicators, something that so far the NRC staff has not done for nuclear power plants. I think the paper falls short of demonstrating that the chosen performance indicators are capable of predicting changes in risk or even (more directly) leak frequency. Application of the methodology over a reasonable time period with proper data collection, both on the performance indicators and on leak frequency, could show such a capability. Its also possible that performance data would not support the postulated correlation, and that changes would have to made to the model(s) or to the performance indicators.

You may recall that in my draft (long) paper on safety culture and in the presentations I made to the Human Factors Subcommittee and in the January 2000 planning retreat, I presented an activity diagram identifying the steps required to relate safety culture to safety of operations and, ultimately, to suitable performance indicators. In my remarks I observed that all of the papers I reviewed dealt with only a few of the required activities, and none dealt effectively with suitable performance indicators. I believe Oien's paper addresses all of the required activities, and suggests a plausible method of carrying out each one.

I do not feel competent to pass judgement on the validity of some of his suggested methods. I have neither the required statistical knowledge nor the probabilistic risk assessment skills. To the uninitiated, Section 5 (Development of a quantitative methodology for assessing the effect on risk) is impossible to judge, and subsection 5.3 (Weighting process) is almost surreal. For example, to quote from the paper, p. 28, line 2, "We use a Hidden Markov Model (HMM) to estimate the ('hidden') states of the organizational factors based on the ('observed') number of contributions to leaks from each organizational factor." I have no idea whether a Hidden Markov Model is appropriate here, or even what a Hidden Markov Model is. Someone with the requisite statistical and PRA competence should also look at this paper.

The one element that strikes me as most questionable relates to the validation of the model by comparing past organizational performance to observed leak rates. The problem is that the chosen performance indicators have not been measured during the time periods where the leak rates have been observed. This difficulty is resolved by estimating the performance indicators after the fact. The author claims this has little impact on the validity of the process, but it seems a bit circular to me. In Bayesian fashion he points out the future updates will tend to wash out the original estimates. (See the discussion beginning with the last paragraph on page 29.)

I see the paper's accomplishment as presenting a rare picture of the entire problem of relating

organizational factors to suitable safety performance indicators. The paper falls short, in my view, of establishing the validity of the performance indicators proposed, and therefore the overall validity of the proposed process remains to be demonstrated. The author acknowledges in his conclusions, "What is needed now is first of all a real case implementation." (Page 44, Section 7.7, Further work.)

Specific comments for your consideration:

I would suggest adding a qualifying phrase "when validated" to the last sentence of the abstract: "Risk indicators, when validated, will aid in ... ."

There is a mention of NOMAC and WPAM on page 7, to the effect that "NOMAC" was "later to become the WPAM method." My understanding of the relationship is a little different, but you would know the correct choice of words there.

The list of references includes a reasonable sample of the literature on NRC sponsored work.

I hope this is helpful.

Jack

Notes on Oien Paper

Paper raises issue of "prediction" impact of organizational factors on risk, and using such predictions to reduce risk.

Ref [19], "Indicators to Monitor NPP Operational Safety Performance, IAEA-J4-CT-2883, Draft 15, January 1999, IAEA, Vienna " ...but even these latter quantitative tools have rarely been linked to risk assessment. They usually just assume an impact on safety."

"In this paper we describe the development of organizational risk indicators that can be used as a tool for frequent control of risk." (Page 2)

Elements: organizational model
organizational risk indicators
quantification methodology

"There is no single field of research that covers both quantitative impact of organizational factors on risk and measuring the quality of the organizational factors utilizing indicator measurements." p. 6

One problem is what to correlate wtih when accidents are rare events. p. 6

Referenced NUREG/CR
3215, Osborn (x)
3737, Olson (x)
4378, Olson (x)
5241, Olson (x)
5437, Marcus (x)
5610 Wreathall (not issued, according to distribution center).
5538, Haber (x)

Is it true that "NOMAC" was "later to become the WPAM-method"? My reading of the history is a little different. I suggest an appropriate edit here. (p. 7)

Mintzberg is common reference for organizational frameworks. (p. 8)

"Safety indicator research" is cited as Olson (NUREG/CR 3737 & 5241) and Lehtinin [18] (Finnish paper).

Paper equates Bayesian networks and influence diagrams. Is this correct?

Section 5 is a complete mystery to me.

The "base value of the leak frequency" is taken as the value in the last updated QRA.

The description of the weighting process is almost surreal. Use of a statistical model to estimate former states (rather than having measured them) severely undercuts validation of the model and methodology. The example in section 5.6 does nothing to allay my concern. Perhaps I lack the statistical competence to understand the process.

Organizational Risk Indicators

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Abstract

Organizational risk indicators are proposed as a tool for risk control during operation of offshore installations, as a complement to QRA-based indicators. An organizational factor framework is developed based on a review of existing organizational factor frameworks, research on safety performance indicators, and previous work on QRA-based indicators. The results comprise a qualitative organizational model, proposed organizational risk indicators, and a quantification methodology for assessing the impact of the organization on risk. The risk indicators will aid in a frequent control of the risk in the periods between the updating of the quantitative risk assessments.

Keywords: Organizational factors; Organizational risk indicators; QRA-based indicators; Quantitative Risk Assessment (QRA); Risk control

1. Introduction

The importance of management and organizational factors on the risk of major accidents in high-hazard industries has been demonstrated through accident investigations in the last couple of decades. These include Three Mile Island (Perrow [1]), Bhopal (Shrivastava [2]), Challenger (Winsor [3]), Chernobyl (Reason [4]), Piper Alpha (Paté-Cornell [5]) and Zeebrügge (Rasmussen [6]), to mention a few. All of these represent qualitative retrospective hindsight. What about predicting the impact of organizational factors on risk in advance, and use this insight proactively to avoid or reduce the risk of new disasters? Risk prediction has, so far, mainly covered technical failures and human errors, but some research efforts during the last decade

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have concentrated on including organizational aspects explicitly (e.g., Murphy & Paté-Cornell [7]; Embrey [8]; Davoudian et al. [9-10]; Mosleh et al. [11]; Papazoglou & Aneziris [12]). These efforts can be seen as extensions of the quantitative risk assessments (QRAs), and performed as part of, or as add-on to the QRA. However, these QRAs are updated rather infrequently, and in the meantime parameters and assumptions in the QRA change, which means that the value of the QRA as a risk control tool diminishes. Other tools like living QRAs and risk monitors have been developed to better cope with the challenge of continuous risk control (see e.g., Johansson & Holmberg [13]; Kafka [14]; IAEA [15]). During operation, not only technical and human performance change, but also the performance of the organization itself may change, e.g., quality of procedures, training, etc. The safety performance of organizations has been attempted measured both qualitatively with so-called safety audit methods (e.g., Bird & Germain [16]; Wagenaar et al. [17]) and quantitatively by establishing 'safety indicators' (e.g., Lehtinen [18]; IAEA [19]), but even these latter quantitative tools have rarely been linked to a risk assessment. They usually just assume an impact on safety.

In this paper we describe the development of organizational risk indicators that can be used as a tool for frequent control of risk. The methodology resembles those organizational factor frameworks that have been developed to explicitly include organizational factors in the risk assessments. One difference is that the frequent measurement of the quality of the organization (in our methodology) builds on 'programmatic' or 'indirect' performance indicator research.

The organization we are analyzing is an organization that operates and maintains an offshore installation, and the analysis is based on an existing QRA, specific for the installation ('the sociotechnical system') in question.

We have made a literature review (Øien [20]) and analyzed the existing organizational factor frameworks according to a common decomposition structure (Øien & Sklet [21]; Øien [20]). Based on this analysis and our requirements and preferences for each element of the framework, we have synthesized a new organizational factor framework denoted organizational risk influence model (ORIM). This includes a link to the 'technical' risk model in the QRA that is based on our previous work (Øien [22]).

The principal result of our research is the development of an organizational factor framework from which organizational risk indicators can be established and used for

the purpose of risk control during operation of offshore installations. The framework includes: (1) an organizational model, (2) organizational risk indicators, and (3) a quantification methodology. The organizational model may also be used as a qualitative tool for establishing root causes of incidents and accidents, independent on any quantification of impact on risk.

The use of organizational risk indicators in addition to direct risk indicators provides a tool for risk control during operation of offshore installations, in the periods between the updating of the risk assessments. The tool covers a reasonably large portion of the total risk.

In Section 2 we have described the research approach, linking this work to previous work and analyzing existing research. Section 3 describes the development of a new organizational framework including the development of an organizational model and organizational risk indicators. Section 4 presents some intermediate qualitative results, that is, the organizational model and the proposed organizational risk indicators. Section 5 covers the development of the quantification methodology, and Section 6 summarizes the results. The results are then discussed in Section 7 ending with the conclusions.

2. Research approach

2.1 Link to previous work

The work presented in this paper builds on previous work that we have carried out on the development of technical risk indicators, based on a risk assessment of a sociotechnical system (Øien [22]). In order to explain our research approach we need to view this in light of our 'point of departure'. Thus we will briefly describe the status of our previous work, with which this research on organizational factors fits in.

In Øien [22] we stated the research topic as a problem, i.e., "how to control the risk of an offshore petroleum installation, i.e., change in risk with time". We developed a general methodology for the establishment of risk indicators that can be used as a tool for risk control during operation of offshore petroleum installations. The general methodology is an eight-step procedure that includes a screening process as follows:

1. Selection of categories of accidental events
2. Identification of risk influencing factors (RIFs)
3. Assessment of potential change in RIFs
4. Assessment of effect of change on risk
5. Selection of significant RIFs
6. Initial selection of risk indicators
7. Testing and final selection of risk indicators
8. Establishment of application routines

A specific feature of this methodology is that the selection of RIFs (step 5) is based on sensitivity analyses (step 4) using expert judgments (step 3) of the range of the parameters (representing the RIFs in the risk model). Thus the approach is risk-based, and it is based on realistic changes (not theoretical changes) in the parameters/RIFs. Step 5 represents a screening of the most important parameters in the risk model, for which we assign indicators (measurable variables).

The testing of selected indicators in a pilot project showed that the 'number of leaks during a specified time period', was inappropriate as an indicator for the RIF 'process leak' due to the very limited number of leaks per period. The conclusion was that it was necessary to search for the causes of leaks and to establish indirect 'organizational' type of indicators. In discussing the need for further work we stated that "the goal is to identify organizational risk indicators that complement the QRA-based indicators". The result of this is what we will present in this paper. A conceptual model of this 'point of departure' is illustrated in Fig. 1.

A sociotechnical system (an offshore petroleum installation - OPI) is modeled in the QRA thus obtaining a risk estimate, i.e., a measure of risk. From the risk model we have identified the most important RIFs (through their corresponding parameters in the risk model). The change in these parameters/factors over time is measured through the assignment of indicators. In some cases these indicators are more or less direct measures of the corresponding factors (e.g., 'number of hot work permits class A and B' for the RIF 'hot work'). In other cases we need to use a somewhat more indirect measure (e.g., 'number of all failures in electrical equipment' for the RIF 'ignition due to (critical) failure in electrical equipment'). In the pilot study four out of nine risk indicators were direct, whereas the other five were indirect risk indicators. Together they constitute the QRA-based indicators. One of the indirect risk indicators

was 'the number of all leaks', however it turned out that even if we included the leak category 'small' (which is too small to be included in the QRA) the number of leaks per period were still too low.

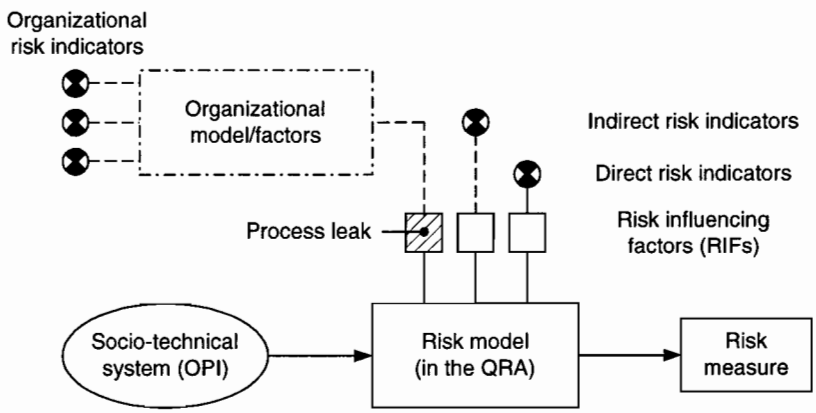

Fig. 1. Conceptual model of the starting point for the development of organizational risk indicators.

For the parameter 'leak frequency', and only for this parameter, we aim at establishing organizational risk indicators as substitute for the (inadequate) QRA-based indicator. This will be accomplished by developing an organizational model or set of factors, providing the link between the organizational risk indicators and the 'leak frequency'. In addition we need a quantification methodology in order to assess the quantitative impact on risk due to changes in the organizational risk indicator measurements.

The other important parameters in the risk model are controlled through the QRA-based indicators. Thus we have a risk control perspective in our development. We only search for organizational root causes where this is needed from a risk control 'point of view'. The impact of organizational changes on all parameters except for the leak frequency will be captured implicitly through the QRA-based indicators. Obviously then, we do not cover explicitly the total impact due to change in one specific organizational factor, since some of the effect are implicit. As we will discuss later, this has some resemblance to a method called SAM (System Action Management), which also concentrates on a specific part of the risk model, thus not covering the overall risk of a complex sociotechnical system (Murphy & Paté-Cornell [7]).

2.2 *Literature review*

There is no single field of research that covers both quantitative impact of organizational factors on risk and measuring of the quality of the organizational factors utilizing indicator measurements. By and large this has been carried out as two separate research areas.

Research on organizational indicators has been carried out mainly by social scientists. This field of research grew out of the research on root causes of major accidents and the realization that technical failure and human error were not the ultimate answer to every incident and accident. The search for the origins of major accidents led the research into the area of management and organization. "The cause of the accident was human error", was no longer regarded a sufficient answer. "Human error", so what? Why did this error occur? Why was this enough to cause a disaster? Today, almost any major accident may be termed an 'organizational accident', as Reason puts it (Reason [23]), indicating that the person 'pulling the trigger' is influenced by the organization and that even given an initiating event the organization should have defenses against a 'single/(silly) mistake'.

This line of research is retrospective; it is hindsight. How can you turn this hindsight into proactive predictive knowledge? One direction to this was the development of ways of assessing the 'quality' of the organization and assessing the impact of such a 'quality' on safety, without any connection to a risk model of the sociotechnical system in question. This can in turn be split in two mainstreams, one being 'safety audit' qualitative type of assessments, and the other being 'organizational indicator' quantitative type of assessments. In both cases the impact on safety is either assumed or attempted substantiated through, e.g., correlation analyses. However, one problem is what to correlate with when accidents are rare events.

Of these two mainstreams the research on 'organizational indicators'[1] is of most interest for us, since frequent risk control requires a reasonable 'speedy' evaluation of the state of the organization. After having realized the important role of organization and management in accidents, the US Nuclear Regulatory Commission initiated a series of research project on safety performance indicators, starting in the early '80s. Some of these projects focused on the safety performance of the management and the

[1] The term 'organizational indicators' is rarely used in the literature, instead terms like 'programmatic performance indicators' and 'indirect performance indicators' have been used.

organization (e.g., Osborn et al. [24]; Olson et al. [25-27]; Marcus et al. [28]; Wreathall et al. [29]). This line of research continued both inside and outside the US (e.g., Johansson & Holmberg [13]; Lehtinen [18]; IAEA [19]).

In the early '90s the second line of research that is of great interest for us started, that is, the research on the effect of organizational factors on risk. One of the projects that represents a transition from the 'safety performance of organization and management' research to the research on organizational factors effect on risk was the development of what is called NOMAC (Nuclear Organization and Management Analysis Concept, Haber et al. [30]). Although this effort originates from social science and organizational theory (e.g., Mintzberg [31]) and is a top-down approach, it included an attempt to quantify the effect of organization and management on risk. This part was subcontracted to a group of natural scientist at UCLA[2] for which the research on quantitative risk assessments is one important domain. This initial NOMAC-work was later to become the WPAM-method (Work Process Analysis Model, Davoudian et al. [9-10]).

Other organizational factor frameworks include SAM (System Action Management, Murphy & Paté-Cornell [7]; Paté-Cornell [32]); MACHINE (Model of Accident Causation using Hierarchical Influence Network, Embrey [8]); ISM (Integrated Safety Model, Wreathall et al. [29]); ω-factor (Mosleh et al. [11]); I-RISK (Integrated Risk, Oh et al. [33]). Most of these frameworks are bottom-up approaches starting from the technical system and ending with the organization. It is also rather natural science dominated. However, in the I-RISK development a blend of scientists made up the research team, some covering the organizational aspects and others covering the technical/QRA aspects, working both top-down and bottom-up at the same time. For a detailed review of this literature see e.g., Øien [20] and Vaquero et al. [34].

2.3 Analysis of existing frameworks

The detailed review (Øien [20]) covered the following organizational factor frameworks:

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[2] UCLA – University of California Los Angeles.

- SAM (System Action Management)
- MACHINE (Model of Accident Causation using Hierarchical Influence Network)
- ISM (Integrated Safety Model)
- ω-factor model
- WPAM (Work Process Analysis Model)
- I-RISK (Integrated Risk)

All these organizational factor frameworks describe the organization either by a list of factors or by some model (e.g., hierarchical) which affects the performance of 'front-line' personnel. This influence is established through an assessment of the 'quality' of the organizational factors (which may be denoted the 'rating process') and the effect of the organizational factors on personnel performance or some intermediate factors (which may be denoted the 'weighting process'). The total influence is obtained by aggregating (propagating) the effect through all levels in the model. The way this is carried out depends on the modeling technique selected. Next this effect has to be linked to the risk model and this will often require some adaptation of the risk model, preparing it for the inclusion of the effect of the organizational factors. Finally the risk estimate is recalculated. The different elements of the frameworks may thus be categorized as follows:

1. Organizational model/factors
2. Rating of organizational factors
3. Weighting of organizational factors
4. Propagation method/algorithm
5. Modeling technique
6. Link to risk model
7. Adaptation of risk model
8. Re-quantification of risk

Based on our 'point of departure' for analyzing the impact of organizational factors, we were particularly interested in the first five elements. The three last elements are in our case determined by our previous work. That is, the leak frequency can be seen as the link to the risk model (element 6) being one of the most important parameters

found by sensitivity analysis (element 7) from which the relative change in risk can be estimated (element 8).

The analysis revealed that the amount of similarities between the different frameworks with respect to the organizational model or set of factors is rather limited. This is no big surprise since even for pure classifications of organizational factors there are significant differences (Wilpert [35]). One of few commonalties, at least between some of the frameworks, is the reference to research on management and organization carried out by Mintzberg (e.g., Mintzberg [31]).

Rating of organizational factors means to assess the quality or 'goodness' of the factors. It is a measure of the 'state' of a given factor. The rating process in the six frameworks analyzed is mainly based on some kind of expert judgments or the use of qualitative tools similar to safety audit tools. Interestingly, none of the frameworks have attempted to use indicators (measurable variables) for the purpose of measuring the 'quality' of the organizational factors.

Weighting of organizational factors implies an assessment of the effect/strength/ impact that the organizational factors have on risk directly or indirectly through intermediate factors or parameters in the risk model. All of the frameworks suggest using expert judgment also for the assignment of weights, with the exception of the ω-factor method that propose a data-driven approach as an alternative to the use of experts.

After having assigned individual rates and weights they are combined and aggregated in order to reflect the total effect on risk or a parameter in the risk model. If the organizational model constitutes several layers of factors, the effect is propagated through the model. The propagation method or algorithm is the way in which the rates and the weights are combined and aggregated. There are two main methods of propagation used in the existing organizational factor frameworks. One is the 'simple sum of products' method in which each individual rate and weight are multiplied and then added. In this case the rates are assigned only for the present states of the organizational factors, and the weights are given for these present states. The other is 'according to the influence diagram technique', which means that every possible combination of states of the organizational factors must be given a rate (unconditional joint probability) and a weight (conditional probability) that are multiplied and summarized. (This is described in more detail in Section 5.)

The modeling techniques differ between the frameworks, however, three of the six frameworks use the same modeling technique, which is influence diagrams (or rather Bayesian networks).

The effect of organizational influences goes through parameters in the risk model (or technical system model) in all of the analyzed frameworks. In some cases important parameters are identified and selected, whereas in other cases adapted generic parameters are used in order to capture a significant portion of the total risk. For those methods having the objective to recalculate the total risk due to the influence of organizational factors, there is apparently realized a need for some sort of reduction process with respect to the risk model. Considering each and every specific parameter would be an overwhelming task, thus they are either grouped in some manner or the focus is on the most important parameters. These parameters are recalculated and new risk figures obtained reflecting an explicit inclusion of the effect of organizational factors.

3. Development of a new framework (ORIM)

The development of a new framework suited for our purpose is based on an element-by-element evaluation of the existing frameworks compared to our requirements and preferences. The framework has to be fit for our purpose and the context for which it will be applied. This implies that the organizational factor framework has to be adapted to our previous work on risk indicators, which in turn means that the handling of the elements 6, 7 and 8 is predetermined as described in the previous section.

3.1 Organizational model development

There are both theoretical and practical concerns regarding an adequate organizational model. On the theoretical side the model should preferably be:

1. Theoretically founded, i.e., having a sound basis from organization theory, management theory, safety management theory, etc.

2. Structured, i.e., consist of a network of relations, not just a classification of factors.
3. Substantiated through incident and accident data. Alternatively, the factors/model may be validated based on comparison of high and low accident companies or based on studies of high reliability organizations.

On the practical side the model must be comprehensible and usable both qualitatively and quantitatively.

The existing organizational factor frameworks have based their organizational models partly on theory, causal analyses of accidents and incidents, or observations of a specific organization (or some combination of these). Also the purpose of the frameworks influence the modeling of the organization. In our case the purpose is to control risk during operation, and in particular contribute to proper risk surveillance. The possible need for risk-reducing measures to control risk may be the result of the surveillance, however, risk-reducing measures is not the main focus of our work. The SAM framework (Murphy & Paté-Cornell [7]) emphasizes the value of organizational risk-reducing measures as alternatives to technical measures, thus focusing on identifying the most adequate risk-reducing measures. Despite the difference in purpose, SAM is the existing organizational framework having the greatest resemblance to the approach that we have chosen. However, whereas SAM usually focuses on the part of a sociotechnical system known to be in need of remedial actions, we focus on the most important risk factors with respect to potential change (and *potential* need of remedial actions). It need not be any unacceptable problems in the organization at present, and the change can equally well be in a positive direction.

Since we only cover a limited part of the risk model, that is, one specific parameter (the leak frequency), we are in a better position to develop a specific organizational model. We can base our model specifically on leak events instead of general accident data. In addition, we can benefit from observations of the specific organization in question, as does the SAM framework and also emphasized by Galbraith [36]. The model is to a lesser degree influenced by general organization theory, at least directly. Indirectly it is influenced by work of Olson et al. [27].

Different leak event reporting systems (being part of a more general accident and incident reporting and investigation system) and different generic leak event data sources utilize to a large degree dissimilar causal categories. It is also large

differences in how far back in the causal chain the investigations and data sources reach. Based on a review of generic leak event data-sources (e.g., OREDA [37]; E&P Forum [38]; HSE [39]), and the specific accident and incident reporting system for the pilot organization (Synergi [40]), we selected the following causal categories to constitute the causal link between the organizational factors and the leak frequency:

1. The parameter (failure mode)
2. The component/equipment
3. The main functions performed by front-line personnel
4. The programs supporting the front-line personnel, and organized by operational management

This provides the structure (the levels) of the organizational model. In order to substantiate the model through a qualitative analysis of the existing leak data, we needed to find information of these categories in the specific accident and incident reporting system used by the organization in question. Their accident and incident reporting system is termed Synergi (Grundt [41]; Synergi [40]). It is based on the loss causation model known as the ILCI-model (International Loss Control Institute model), which is the accident model used in the International Safety Rating System (ISRS), (Bird & Germain [16]). The ILCI-model consists of other causal categories than those listed above, which means that some of the information must be found in the free-text in the leak event reports. This applies in particular for the second and third causal categories.

Since we start with the leak itself (focusing on the leak frequency parameter) we need to sort out those event reports comprising leak events. This is facilitated using the Synergi software.

The second category (component/equipment) is classified according to (or closely resembles) the Norwegian Oil Industry Association's classification (Petcon [42]) as follows:

- Valves
- Flanges and joints
- Pipes

- Instrumentation and piping
- Other

The third category comprises the main functions performed by the front-line personnel for which there are potential for causing a leak. The main functions (for the pilot installation) may be divided in:

- Process operation
- Corrective maintenance
- Preventive maintenance (including inspection)
- Well operation (workover)

The advantage of the ILCI-model as a basis for the accident reporting system is that it forces the investigators to consider remote organizational type of factors as potential contributors to the accidents and incidents.[3] Even if we did not find the original structure of the ILCI-model to be adequate for our purpose (focusing specifically on leaks) the information is there, at least to some extent, and we can restructure the original model or develop our own classification of the forth category.

The classification of the forth and most remote category of causal factors is based on, e.g., an analysis of leak event reports and a restructuring of the two most remote causal categories in the ILCI-model (that is, 'basic causes' and 'lack of control'). In addition, we have drawn on ideas from a model presented by Olsen et al. [27].

The organizational factors included in our model are only those that may contribute to leaks, which are much less than the total number of factors included in the loss causation model. In addition we only capture those factors that can be linked to specific events within reasonable use of resources. Thus we do not capture the most remote type of organizational factors explicitly, such as 'management commitment to safety'.

Furthermore the organizational model is not meant to capture every hypothetical leak event. It is a balance between a theoretical, complete model and a practical,

[3] We analyzed three leak events that had been rather thoroughly investigated and documented. The technique we used was the STEP-method (Sequentially Timed Event Plotting), (Hendrick & Benner [43]). These analyses showed us that it was not possible by a second hand analysis to reach to the 'lack of control' factors in the ILCI-model. Thus it is essential that the inclusion of organizational factors is part of the scope of the initial investigation.

usable model. Thus, factors that are rarely involved (e.g., only once in three years) are not included in the model, but the model should be kept updated with respect to contributing factors since this may change with time.

The causal analysis of previous leak events formed the basis for the identification of the following important contributing factors to leaks:

- Individual factor (attention/concentration, etc.)
- Training/competence
- Procedures, job safety analysis (JSA), guidelines, instructions
- Planning, coordination, organization, control
- Design
- Preventive maintenance (PM-) program/inspection

These factors may be divided into three subsets. The first is the 'individual factor', covering a variety of reasons for slips and lapses. The specific reasons (e.g., inattention, lack of motivation, etc.), including the underlying explanations for these reasons (e.g., recent divorce, argue with a colleague, etc.) are difficult to reveal and are normally not included in leak event reports, not even if a thorough investigation has been carried out. It is to a large extent influenced by the individuals themselves, and can only to a limited extent be prevented by management. Nevertheless, it is important to include this factor for two reasons. First it represents the only 'causative' factor in many leak events, meaning that other influencing factors did not 'cause', but 'failed to prevent' this slip or lapse to result in a leak. These other influencing factors may be seen as barriers, but in many cases the failures of barriers alone cannot cause a leak. Second, it is important to discover any trend in this factor, because a negative trend in this factor has to be remedied by other types of measures (e.g., motivational measures) than those organizational risk-reducing measures derived from the other influencing factors.[4]

The second subset of factors is 'training/competence', 'procedures, JSA, guidelines, instructions', and 'planning, coordination, organization, control'. These three factors (or factor groups) represent some of the main responsibilities of the operational management. They constitute the preparation/support functions that need to be in

[4] A third reason is 'psychological'. It feels unjust for a supervisor if he/she is the only one to get 'the

place so that the front-line personnel can carry out their jobs properly. The key individuals in the management of these factors are the supervisors. Their role and importance with respect to safety has been investigated by, e.g., Mearns et al. [44].

The third subset of factors is 'design' and 'PM-program/inspection'. These factors are in the case of offshore petroleum installations to a large degree managed from the onshore organization, and may be viewed as 'constraints' for the operation and management of the installations (both for the operational management and the front-line personnel). The operational management can influence these factors but normally only by way of the onshore organization.

The resulting organizational model is presented in Section 4.1.

3.2 Evaluation of the quality of organizational factors

One of the first steps in our endeavor to quantify the effect of organizational factors on risk is to evaluate the 'quality' of the organizational factors at a given point in time. This evaluation is what we have denoted the rating process and it implies measuring the 'state' of each organizational factor. In existing frameworks this rating is mainly based on some kind of expert judgments or the use of qualitative tools similar to safety audit tools. In most cases there is not paid much attention to this part of the frameworks, and it is usually an 'once and for all' evaluation, thus it is not meant to be carried out repeatedly. This is where our approach is rather different from the existing frameworks since we develop this framework to be applied for risk control purposes, which means that we will repeat the rating process frequently (typically each quarter of the year).

Due to our focus on risk control, we also need to distinguish between fairly incremental changes in the states of the organizational factors. It is not sufficient to distinguish between say "good" and "bad" states. On the other hand it must be possible to distinguish between the different states in a credible way, which means that it is limits to how fine-graded the scale can be. Also, a large number of states will make the quantification process rather comprehensive. Based on an overall evaluation of the grading we decided to start out with a five-graded scale.

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blame' when he/she knows that, e.g., an operator has made a 'big mistake'.

Instead of making use of safety audit type of techniques, which are typically rather time-consuming, we have paid more attention to the literature on safety indicators, and in particular those that measure the remote organizational factors, denoted for instance 'programmatic performance indicators'. The utilization of indicators will facilitate our demand for a 'speedy' evaluation and will also provide quantitative statements of the states of the organizational factors. The indicator values are based on registrations of observable variables carried out during a predefined time period. These values must then be transformed to a 'state' for each of the organizational factors. Thus, we only rely on observations/registrations and not on interviews, questionnaires, etc., which are much more time-consuming. However, this puts high demands on the validity of the chosen indicators, both individually and in terms of the total coverage.

Based on a review of literature covering safety indicator research (e.g., Olsen et al. [25, 27]; Lehtinen [18]) and the review of pertinent projects (e.g., Statoil [45]) a preliminary list of potential organizational risk indicators was established. Only those indicators that could be linked to the organizational factors described in the previous section were selected for this preliminary list. In some cases the identified indicators had to be adapted, and also some of the indicators in the preliminary list were transformed from proposals of risk-reducing measures (e.g., the recommendation of a specific course was translated to 'the proportion of the personnel who had taken this course').

This preliminary list was scrutinized in several workshops by the analyzing team and an Offshore Installation Manager, but the present list of organizational risk indicators may still be regarded as a proposal. Prior to, or as a part of an implementation, the offshore personnel on the installation in question have to take part in an evaluation of the proposed indicators. The list of indicators is presented in Section 4.2.

3.3 Outline of a quantification methodology

Three of the six existing organizational factor frameworks use influence diagrams as modeling technique, and we have also chosen to use influence diagrams (or Bayesian networks). Apart from the fact that several other frameworks within this

field of research build their quantification on the use of influence diagrams there are specific advantages with this technique. It provides an intuitive representation of the causal relationships linking the organizational factors to the quantitative risk model. This intuitive representation is essential when communicating with domain experts. The relations as well as the states may be represented probabilistically, and there is no limitation on the number of states (that is, we are not restricted to binary representation). Interaction between factors can be explicitly taken into account, e.g., the effect of 'bad' training and 'bad' procedures at the same time may be worse than the added individual effects of these factors being in a 'bad' state. Influence diagrams have a sound mathematical basis in Bayesian probability theory, and are previously introduced in the safety and reliability literature (see e.g., Barlow [46-47]; Moosung & Apostolakis [48]; Hong & Apostolakis [49]). Influence diagrams are also supported by different software tools (e.g., HUGIN [50]; Netica [51]).

A major challenge using influence diagrams is the assignment of weights (i.e., the strength of the causal relations) to every possible combination of states of the organizational factors. The benefits are that it explicitly takes any interplay between factors into account, and the weights are predetermined assuming the different combinations of states, so there is no need for reassigning weights as a result of changes in the states. However, the number of weights that have to be assigned is rather large even for moderately complex models.

The propagation of the rates (i.e., the assessed states of the organizational factors) and the weights are an inherent part of the influence diagram technique, and are no longer a problem even for large models. It has recently been solved by the development of 'clever' algorithms (see, e.g., Jensen [52]). What really constitutes the practical challenge is the assignment of weights, that is the conditional probabilities given all possible combinations of states. Usually some kind of expert judgment procedure is proposed in order to establish these weights, but also data-driven approaches have been suggested (Mosleh & Goldfeiz [53]). In our case we decided to pursue both approaches, but we will focus on the data-driven approach in this paper.

3.4 Synthesis of the approach chosen for the development of a new organizational framework

If we compare our approach to the development of an organizational factor framework for the quantification of organizational factors' effect on risk, with other existing frameworks, we can use the common decomposition structure comprising eight elements, which was presented in Section 2.3. The approach chosen for the development of ORIM is illustrated in Table 1 for each of the eight elements.

Table 1

Approach chosen for the development of ORIM

Element		ORIM approach
1	Organizational model/factors	Specific model based on causal analysis of leak events
2	Rating of organizational factors	Indicators to assess the states. Five anchored states.
3	Weighting of organizational factors	Data-driven and expert-based
4	Propagation method/algorithm	According to the influence diagram technique
5	Modeling technique	Influence diagram (Bayesian network)
6	Link to risk model	Leak frequency
7	Adaptation of risk model	Screening of parameters using sensitivity analysis
8	Re-quantification of risk	Relative change in risk

Before we proceed with the development of the quantitative part of ORIM we will present intermediate qualitative results comprising the organizational model and the organizational risk indicators.

4. Intermediate qualitative results

4.1 Organizational model

The organizational model (the 'leak model') is illustrated in Fig. 2. Each of the four categories of causes, including the leak itself, represents one level in the model. On the forth level, which we denote 'organizational factors', we have differentiated somewhat between the three subsets of factors. They are displaced relative to each other in order to underline their different 'nature'. In addition we have used dashed

lines for the 'individual factor' since this factor is not an actual organizational factor. It includes inherent features of the individuals.

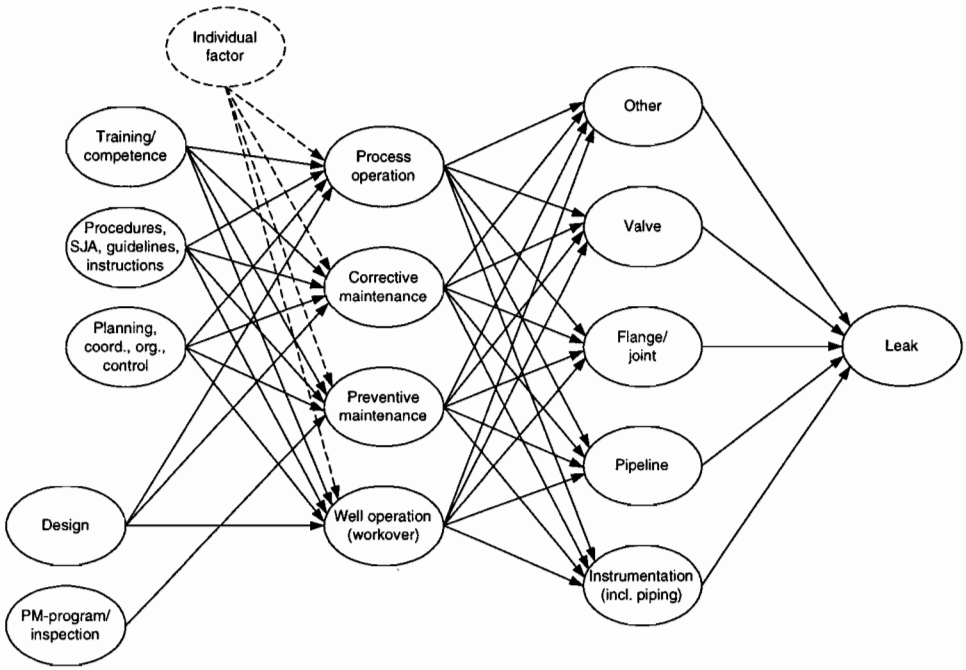

Fig. 2. The organizational model (the 'leak model').

The organizational model is illustrated using influence diagram (or Bayesian network), and all possible connections/relations are included (represented by arrows), i.e., we have not included only those relations being identified based on the analysis of existing leak reports.

As we have emphasized previously this model has to fulfil the requirements of both being reasonable complete and the same time practically usable, which means to balance two conflicting requirements. And above all, it has to fit our purpose. In addition to point out the most important organizational factors influencing the leak frequency and the most important relations (and 'pathways'), it shall also provide the basis for a quantification of the effect on risk, due to changes in the organizational factors. The organizational factors are briefly defined in Table 2.

Table 2

Definitions of the organizational factors

Organizational Factor	Definition/explanation
Individual factor	Individual factor refers to slips and lapses. It is sometimes the only 'true' cause of leak events whereas other influences fail to prevent leaks from occurring given an initial slip. It is used as a 'knob' to attach 'blunders'.
Training/competence	Training/competence refers to the training and competence that are necessary for the operating personnel to carry out their jobs without causing any leaks. This covers both general system knowledge and specific skills required for operational and maintenance tasks.
Procedures, JSA, guidelines, instructions	Procedures, JSA, guidelines, instructions refers to all written and oral information describing how to perform the operational and maintenance tasks in a correct and safe manner. The main emphasis is on the task information necessary to avoid the occurrence of leaks.
Planning, coordination, organization, control	Planning, coordination, organization, control refers to the preparations being necessary to avoid leaks during the execution of operational and maintenance tasks. This is a main responsibility of the supervisors.
Design	Design refers to the physical construction and assembly of process and other equipment. The design must be such that the installation can be operated and maintained without causing leaks.
PM-program/ inspection	PM-program/inspection refers to the programs (activities and intervals) including inspection that are carried out to prevent failures and potential leak consequences of such failures.

4.2 Organizational risk indicators

Changes in the states of the organizational factors are measured through the use of indicators. Proposals for such organizational risk indicators for a particular installation is presented in Table 3. The 'individual factor' is not included. The reason for this is explained in Section 5.1 in connection with the quantitative model.

It should be emphasized that the proposed indicators do not represent an exhaustive evaluation, and the number of indicators per factor is arbitrary. Additional evaluations are needed as part of or as a preparation for implementation. However, this list of organizational risk indicators has been used as a 'test-basis' for the development of a quantification methodology.

Table 3

Organizational risk indicators proposed for the pilot installation

Organizational Factor		Organizational Risk Indicator	
OF1	Training/ competence	ORI11	Proportion of process technicians having formal system training
		ORI12	Average no. of areas in which the process technicians are trained
		ORI13	Proportion of instrument technicians attended joint/valves courses
		ORI14	Proportion of mechanics attended courses in flange mounting
		ORI15	Proportion of mechanics attended courses in gaskets and seals
		ORI16	Average no. of years experience on this installation for rel. pers.
		ORI17	Average no. of years of experience in total for relevant personnel
		ORI18	Proportion of relevant personnel pursuing vocational development
OF2	Procedures etc	ORI21	Proportion of relevant personnel having received JSA training
		ORI22	Proportion of relevant personnel having performed JSA last year
		ORI23	No. of JSAs carried out last quarter of the year
		ORI24	No. of controls of JSA preparation and application
OF3	Planning etc	ORI31	Proportion of critical jobs being checked
		ORI32	Proportion of work orders signed at workplace
OF4	Design	ORI41	No. of design related leaks and leak attempts
OF5	PM-program/ inspection	ORI51	No. of hours inspection of leak exposed equipment
		ORI52	No. of corr. maintenance work orders on leak exposed equipment

Organizational Risk Indicator ORI11, -13, -14, -21, -22 and -24 are adapted from Statoil [45], ORI16 and -17 are adapted from Olson et al. [27], and the remaining indicators are developed in the Indicator project (Øien & Sklet [21]).

5. Development of a quantitative methodology for assessing the effect on risk

As stated in Section 3.3 we have chosen influence diagrams, or Bayesian network,[5] as modeling technique. We gave a brief qualitative introduction to Bayesian network, and described the organizational model qualitatively using this technique in Fig. 2.

In this section we describe a quantitative methodology for assessing the effect on risk of changes in the organizational factors. We limit the explicit assessment of the organizational factors to the leak frequency parameter in the risk model. This means that we estimate the leak frequency, λ, of an installation as a 'function' of the states of

[5] From now on we will use the term Bayesian network. In parts of the literature (e.g., Jensen [52]) the term influence diagram is used when decision nodes and utility nodes are included in the network.

the organizational factors. However, we also take the actual observed leaks into account when the new expected leak frequency is estimated.

Since we cannot observe the status of the organizational factors directly, we need to identify and measure a number of indicators for the various organizational factors as presented in Table 3. Thus we need to:

- Assess the states of the organizational factors using indicators
- Determine the effect of the organizational factors and the number of observed leaks on the estimated leak frequency
- Calculate the effect of changes in the leak frequency on the total risk

First, however, we need a brief introduction to the quantitative aspects of Bayesian networks, since we not only use the Bayesian network as a qualitative modeling technique, but also for quantification.

According to Jensen [52], a Bayesian network[6] consists of the following:

- A set of variables and a set of directed edges between variables
- Each variable has a finite set of mutually exclusive states
- The variables together with the directed edges form a directed acyclic graph (DAG). (A directed graph is acyclic if there is no directed path $A_1 \rightarrow \cdots \rightarrow A_n$ such that $A_1 = A_n$.)
- To each variable A with parents $B_1, \ldots, B_n$ there is attached a conditional probability table $P(A=a \mid B_1=b_1, \ldots, B_n=b_n)$

When a variable A has no parents, the conditional probability table related to A is reduced to a set of unconditional probabilities, $P(A=a)$, that have to be specified. In our approach, we assume we can *determine* the state of an organizational factor A with 'certainty' using indicator measurements. Thus we have $P(A=a) = 1$ for one of the possible states, a, and zero for the rest of the states, for each organizational factor.

From the indicator measurements, we determine a state value for each of the organizational factors. We refer to this assessment as the *rating process*. The rating

[6] See also Barlow [47] p. 150 for a similar definition of what he denotes a probabilistic influence diagram.

values obtained by this rating process are the assessed state values of the organizational factors.

The *strengths* of the causal relations are expressed as numbers attached to the links. For each dependent variable (so-called 'children nodes' in the Bayesian network) this strength is expressed by a conditional probability table (see the last statement in the definition above). We refer to the conditional probabilities as *weights*, and the process of assessing the conditional probabilities as the *weighting process*.

In our case it may seem superfluous to assess the weights for all combinations of states of the organizational factors since we determine the states with certainty in the rating process. One reason for not only focusing on the present combination of states of the organizational factors is that we intend to repeat the rating process frequently. Different combinations of states may thus occur, and with fully specified conditional probability tables we have pre-assessed all possible weights, which means that we do not need to repeat the weighting process. The only thing we need to repeat is the new indicator measurements (and the observation of leaks in the last time period).

The rating process and the weighting process give 'input values' to the Bayesian network (state values and conditional probability tables). Knowing the states of the organizational factors, and having the conditional probability tables embedded in the Bayesian network, we can use the Bayesian network to estimate the new leak frequency. Knowing the base value of the leak frequency (e.g., the value in the last updated QRA) we can calculate the relative change in the leak frequency. Through the QRA we can calculate the effect on total risk.

Thus the quantitative methodology comprises the following steps:

1. Establish the quantitative model
2. Assess the states of the organizational factors (the rating process)
3. Assess the impact of the organizational factors (the weighting process)
4. Calculate the effect on the leak frequency
5. Calculate the effect on the risk

5.1 Quantitative model

The qualitative organizational model in Fig. 2 is the basis for developing a quantitative model. We might have used the complete model, that is all four levels, as the quantitative model, but our main goal is to control the effect of changes in the organizational factors on risk (through the leak frequency). This means that the intermediate levels in the risk model are only a means to reach from the leak frequency to the organizational factors in the qualitative evaluation of the leak events. To retain the intermediate levels in the quantitative model is only necessary to the extent that this facilitates the quantification process in general, and the assessment of weights in particular. Assessment of weights implies that each node in the model must be assigned a conditional probability table comprising the weights, which is a challenging task. Whether we attempt to use a data-driven or an expert-based weighting process, we need to evaluate the feasibility of creating these conditional probability tables in a credible way. Based on an evaluation of establishing a conditional probability table directly on the leak frequency versus a conditional probability table for each node on the intermediate levels in addition to the leak frequency, we have decided to remove the intermediate levels. This means that the quantitative organizational model links the organizational factors directly to the leak frequency, i.e., the organizational factors are the input nodes ('parents') to the leak frequency.

The leak frequency (λ) is a non-observable unknown variable that is influenced by the organizational factors ($OF1$,.., $OF5$). Thus, the organizational factors influence the leak frequency, which in turn influence the number of observed leaks (#*Obs*). This is illustrated in Fig. 3.

The 'individual factor' in the qualitative model is not included as an organizational factor in the quantitative model. It may be difficult to decide whether, for example, a slip is a triggering factor, or the leak events may be ascribed to organizational weaknesses only. Reason [23] states that "knowing precisely what went on in the minds of the people concerned at the time these errors were committed would contribute little to our understanding of how organizational accidents happen or how their occurrence could be thwarted in the future".

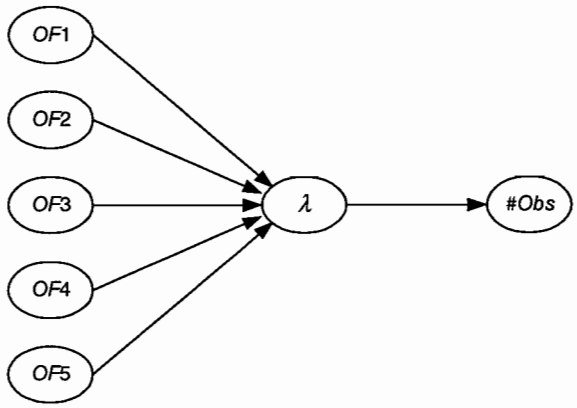

Fig. 3. Quantitative model. (*OF*1='training/competence', *OF*2='procedures, JSA, guidelines, instructions', *OF*3= 'planning, coordination, organization, control', *OF*4='design', and *OF*5='PM-program/inspection'.)

Even if an event can be ascribed to a slip as a triggering factor, this slip alone will not be enough to cause a leak. In every leak event we have analyzed, it was possible to identify one or more of the other organizational factors (other than the 'individual factor') as root causes of the event. This should imply that if the organizational factors were adequate, they would prevent a leak from occurring, even given a triggering slip. Thus we have removed the 'individual factor', and it will not influence the quantification. This is also in line with Reason [23] who states that "the issue is not why an error occurred, but how it failed to be corrected".

Next we need to adapt the measuring of the states of the organizational factors to the quantification process.

5.2 Rating process

We assume that each of the organizational factors can be in one of five mutually exclusive states according to Table 4.

The current states of the organizational factors are assessed through the rating process. The output of the rating process is the assessed rating values of the organizational factors. These rating values correspond to the state values (input values/evidence to the Bayesian network) of the organizational factors when we determine the states with certainty using indicator measurements.[7]

[7] An alternative approach, which is a more common approach when using Bayesian networks, is to assign a probability distribution to the state values of each variable instead of one specific rating value.

Table 4

Organizational factor states

Designation	State value
'Very bad'	1
'Bad'	2
'Average'	3
'Good'	4
'Very good'	5

Each organizational factor may be assessed by a number of indicators, as shown in Table 3. Assume that organizational factor no. k, OFk, may be assessed by n_k different indicators, k=1,..., 5. The measured value of indicator no. j for organizational factor no. k, $ORIkj$, is denoted m_{kj}. These indicator measurements are also rated from one to five. To define the rating values we assign so-called anchoring values to the end-points, that is, a lower value m_{kj}^L corresponding to 'very bad', and an upper value m_{kj}^U corresponding to 'very good'. Between these anchoring values we assign the rating values according to a linear scale. The rating process is illustrated in Fig. 4 (imagine it being to the left of Fig. 3).

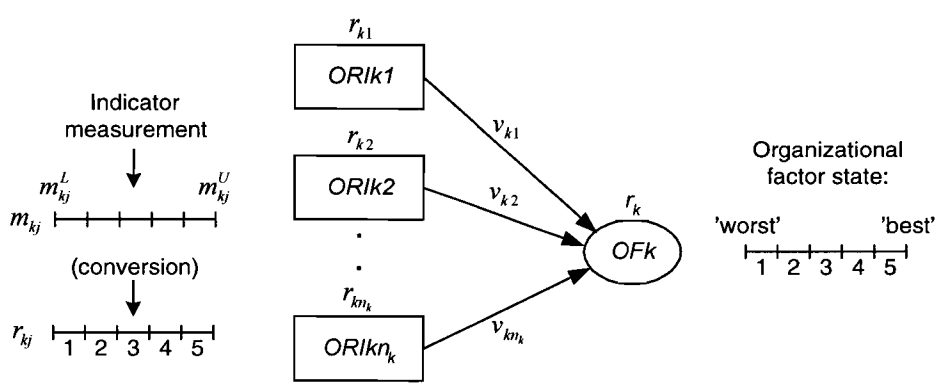

Fig. 4. Rating process.

The measured values of the indicators are converted to a rating value for each indicator and these rating values are weighted to produce a weighted average as the rating value of OFk.

r_k = the rating value of OFk

$$r_k = \sum_{j=1}^{n_k} v_{kj} \cdot r_{kj} \tag{1}$$

where $\sum_{j=1}^{n_k} v_{kj} = 1$

such that the v_{kj}'s will be a 'distribution' of the individual weights of the different indicators. These weights are assigned by expert judgments and are assumed to remain constant over time.

The rating value, r_k, of the organizational factor *OFk*, as obtained from eqn (1), is now rounded off to an integer value in $\{1,\ldots, 5\}$ by standard rounding off rules.

The indicators are measured after intervals of equal length, normally a quarter of the year. Based on these measurements, the rating values of the organizational factors are established from eqn (1). During the intervals between the indicator measurements, the rating values are assumed to remain constant.

We now know the present states of the organizational factors and the next step is to assess the impact of the organizational factors on the leak frequency. This impact is assessed for any values of the organizational factors; thus it is not related to the present states of the organizational factors.

5.3 Weighting process

In the weighting process we establish conditional probability tables for the dependent variables (that is, the 'children nodes' in the Bayesian network). From Fig. 3 we see that there are two dependent variables, that is, the leak frequency (λ) and the number of observed leaks (*#Obs*). Let us start with the leak frequency for which we use a data-driven weighting process, as illustrated in Fig. 5.

Before we describe the weighting process in some detail, we give a brief introduction and explanation of Fig. 5, starting with the outcome, i.e., the conditional probability table, and working our way backwards. We use a Cox-like regression model to establish the conditional probability table, and maximum likelihood estimation (MLE) to obtain the regression-coefficients. The covariate values (single organizational factor states and combinations of factor states) have not been measured

by indicators (or otherwise determined) at the time of the leaks and have to be estimated. We use a Hidden Markov Model (HMM) to estimate the ('hidden') states of the organizational factors based on the ('observed') number of contributions to leaks from each organizational factor. The numbers of contributions are assumed to be Poisson distributed with the expected number of contributions to leaks as parameter. For this parameter we assume a model of the relationship between the expected numbers of contributions from each organizational factor and the state of this factor. The parameters in this model are estimated based on expert judgments (utilizing information from the leak events) and Markov Chain Monte Carlo (MCMC) simulations.

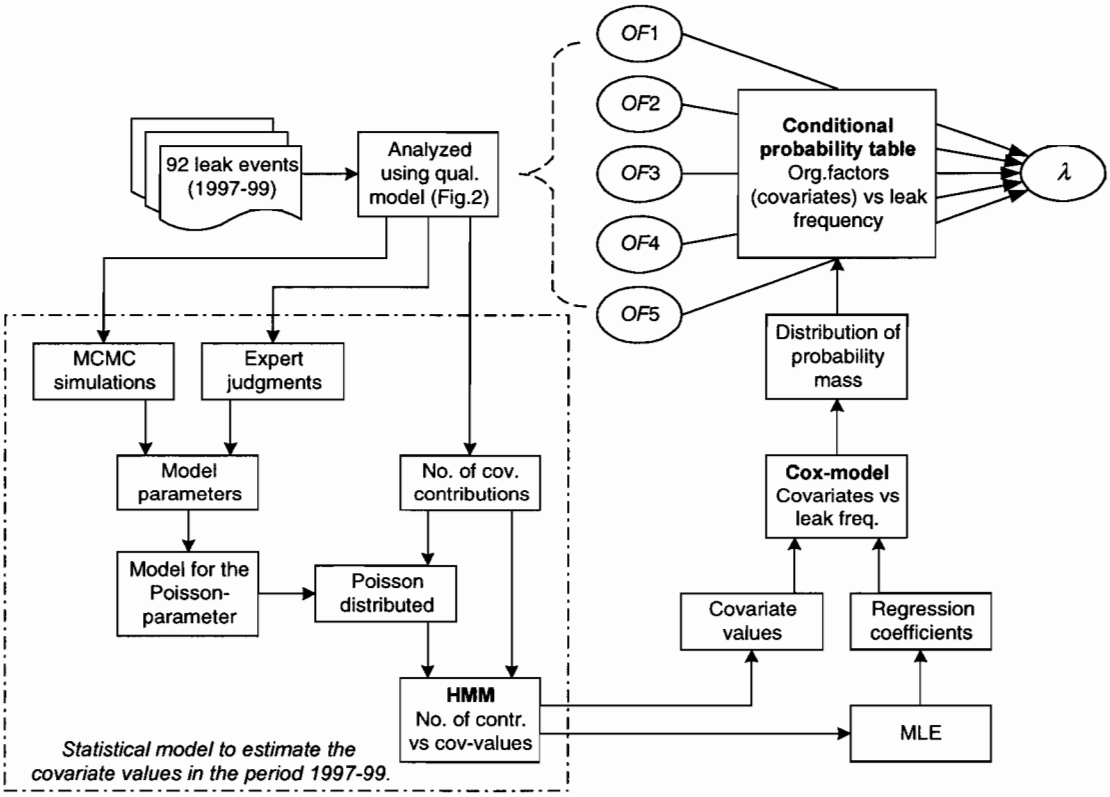

Fig. 5. Overview of the data-driven weighting process for the leak frequency.

For the leak frequency we assume for simplicity five discrete states as described in Table 5.

The state value is a 'representative' value for the corresponding leak frequency range, and is the value used in the calculations. The total range of the leak frequency is based on 20 experienced process leaks on the pilot installation in the time period 1997-99. In this period the average leak frequency per quarter of the year was 1.7. A

leak frequency higher than about eight per quarter of the year is considered highly unlikely.

Table 5
Leak frequency 'states'

Designation	Leak frequency range[a]	State value[a]
'Very low'	0-0.2	0.1
'Low'	0.2-2	1
'Average'	2-4	3
'High'	4-6	5
'Very high'	≥6	7

[a] Leaks per quarter of the year

A total of 92 leak events from three installations (including the pilot installation) in the same oil field have been analyzed. In this analysis the three installations have been considered 'equivalent'. The analysis was based on the qualitative organizational model in Fig. 2. We have assessed which of the organizational factors (one or more) that have been involved in each of the 92 leaks. From Fig. 3 we have $\lambda = \lambda(OF1, OF2, OF3, OF4, OF5)$, but the states of the organizational factors may change with time, thus the leak frequency is assumed to be time dependent, that is

$$\lambda(t) = \lambda(OF1(t), OF2(t), OF3(t), OF4(t), OF5(t)) = \lambda(\boldsymbol{OF}(t)) \tag{2}$$

In eqn (2), we assume that $\lambda(t)$ will change only after each time period, and will remain constant during the periods (t_i, t_j). $\lambda(t)$ will hence be a step function. For simplicity we use t as time period number t in the following.

The analysis of the 92 leak events revealed which factors contributed to the leaks. However, as mentioned, we did not know the states of the organizational factors at the time of the leak events. We considered it to be practically impossible to assess what the states of the organizational factors had been at the time of the leak events based on expert judgments. Instead we estimated the former states based on a statistical model (Hidden Markov Model, see, e.g., Rabiner & Juang [54]). The leak event data were sorted according to the number of times each organizational factor had contributed to a leak (per period). We assumed that the states of the organizational factors changed

'smoothly', and that the state value of $OFk(t)$ with a certain probability (estimated by the leak data) would be equal to $OFk(t\text{-}1)$, that is, the state value at the previous period, or possibly changed one level. Thus, we assumed that the state value could not change two or more levels from one time period to the next.

The state of an organizational factor in a given time period, $OFk(t)$, determines the probability distribution of the number of times, $N_k(t)$, the factor will contribute to a leak in this period. We use a Poisson distribution, with parameter $\mu_k(t)$, for the number of contributions to leaks of factor OFk in the time period t, that is

$$P(N_k(t)=n)=\frac{\mu_k(t)^n}{n!}e^{-\mu_k(t)} \tag{3}$$

We assume the following model for the expected number of contributions of factor OFk in the time period t, (that is, the parameter $\mu_k(t)$ in the Poisson distribution):

$$\mu_k(t)=\mu_k^{\,0}-\alpha_k\cdot OFk(t) \tag{4}$$

where $\mu_k^{\,0}$ and α_k are unknown positive constants. These are estimated based on a rather complex procedure of combining the following expert judgments:

1. The average state of factor OFk in the total time period of the registered leaks
2. The effect on the number of contributions assuming that the state of factor OFk is changed from the worst possible state to the best possible state

with Markov Chain Monte Carlo simulations (see, e.g., Gilks et al. [55]).

The first judgment was carried out in a workshop with an Oil Installation Manager, and resulted in the following combination of states for the five organizational factors; 3-4-2-3-2, i.e., $OF1$ being in average in state '3', $OF2$ in stage '4', etc.

The second judgment was based on an in-depth evaluation of the 20 leak events that had occurred on the pilot installation. For each factor the number of contributions was known for the average state (e.g., four contributions by factor $OF1$ with average state equal '3'), and then assessed for the worst and the best states by anticipating the factor being in respectively state '1' and state '5'. Based on these assessments we

estimated the states of the organizational factors in each of the twelve three-month periods from 1997-99 as illustrated in Fig. 6. Here we use the exact values, not rounded off values.

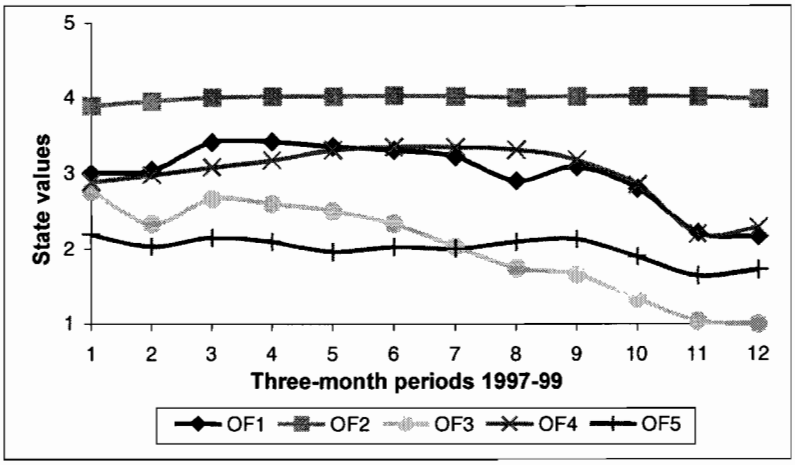

Fig. 6. Estimated states of the organizational factors

Based on the estimated states of the organizational factors, we use the analogy to proportional hazards models (to estimate the effect of the organizational factors on the leak frequency) and split the leak frequency in a baseline frequency λ_0, and an organizational factors' dependent frequency, as

$$\lambda(z(t)) = \lambda_0 \cdot h(z(t)) \tag{5}$$

where $z(t)=z_1(t), z_2(t),\ldots, z_m(t)$ is a covariate vector consisting of single organizational factor states and/or combinations of factor states (i.e., interactions between factors). In the following analysis we have only looked at the state values (r_j) of each single organizational factor (i.e., $z_1(t),\ldots, z_5(t)$), and the combined effects of combinations of two organizational factors, e.g., $z_r=r_i \cdot r_j$, (i.e., $z_6(t),\ldots, z_{15}(t)$). Combined effects of more than two organizational factors and more advanced combinations are not considered in this paper, although there is nothing in the methodology that prevents such an analysis.[8]

We now make use of the analogy to the Cox version of proportional hazards models (see, e.g., Ansell & Phillips [56]), and obtain:

[8] In the analyses of leak events there were very few cases of three factors being attributed to the same leak, and there were never more than three factors attributed to the same leak.

$$\log \lambda(z(t)) = \log \lambda_0 + \sum_{i=1}^{m} \gamma_i \cdot z_i(t) \tag{6}$$

where γ_i, i=1, 2, ... denote the regression coefficients and $z_i(t)$ is the transformed value of the covariate, i.e., the covariate level at time t subtracting the base level.

The regression coefficients, γ_i, may now be estimated by maximum likelihood estimation (see, e.g., Cox [57]). We make the assumption that the system is coherent meaning that the change of state of an organizational factor from state i to i+1 (i.e., changing to a better state) never can increase the leak frequency. The reason for this assumption of coherence is that the numerical optimization in this case gives many local maximas, and in order to reduce the number of local maximas we disregard the non-coherent solutions.

The estimation process (Øien & Sklet [58]) resulted in regression coefficients as presented in Table 6.

Table 6
Estimated regression coefficients

OFs	1	2	3	4	5	1&2	1&3	1&4	1&5	2&3	2&4	2&5	3&4	3&5	4&5
γ_i	γ_1	γ_2	γ_3	γ_4	γ_5	γ_6	γ_7	γ_8	γ_9	γ_{10}	γ_{11}	γ_{12}	γ_{13}	γ_{14}	γ_{15}
	-0.18	-0.16	-0.27	-0.16	-0.22	0.00	-0.02	0.00	-0.01	0.01	-0.01	0.01	0.03	-0.03	-0.02

The conditional probability table for the leak frequency can be established based on the regression-coefficients. From eqn (6) we obtain the expected leak frequency given a specified set of organizational factor states. The probability mass producing the expected leak frequency (for each combination of organizational factor states) is distributed over the possible leak frequency states (see Table 5) such that we attain a correct expectation and a 'suitable' variance. Each single distributed value represents a weight (i.e., a conditional probability). Table 7 illustrates a part of the conditional probability table, that is, 30 of altogether 15625 weights.

As an example we have a conditional probability of 0.648 of having a leak frequency state λ=1, given an organizational factor state combination of 3-4-2-3-2 (from *OF*1 to *OF*5).

We have now established the conditional probability table for one of the two dependent variables in the model (see Fig. 3). The second dependent variable for which we need to establish a conditional probability table is the number of observed leaks (*#Obs*).

Table 7

Part of the leak frequency conditional probability table

	Organizational factor state combinations						
Leak frequency state values[a]	OF1	3	3	3	3	3	3
	OF2	4	4	4	4	4	4
	OF3	2	2	2	2	2	2
	OF4	3	3	3	3	3	4
	OF5	1	2	3	4	5	1
$\lambda = 0.1$		0.001	0.001	0.001	0.001	0.135	0.001
$\lambda = 1$		0.440	0.648	0.815	0.949	0.862	0.577
$\lambda = 3$		0.557	0.349	0.182	0.048	0.001	0.420
$\lambda = 5$		0.001	0.001	0.001	0.001	0.001	0.001
$\lambda = 7$		0.001	0.001	0.001	0.001	0.001	0.001

[a] Leaks per quarter of the year

The conditional probability table for the number of observed leaks (*#Obs*) is simply a Poisson distribution with rate λ. (We use six 'states' for the variable *#Obs*, from 0 to 5 or more observed leaks per quarter of the year.)

5.4 Effect on the leak frequency

At the end of a registration period (quarter of the year) the organizational risk indicators are used to assess (rate) the states of the organizational factors. The information about the new states, ***OF***(*t*), and the number of observed leaks, *#Obs*(*t*), during this last time period are fed into a Bayesian network software (HUGIN [50]), and the probabilities are propagated through the network giving a probability distribution for the leak frequency. From this probability distribution we can obtain the expected value of the leak frequency as

$$E(\lambda(t)|\boldsymbol{OF}(t),\#Obs(t)) = \sum_{j=1}^{5} p_j \cdot \lambda_j \tag{7}$$

where $\lambda_1,\ldots,\lambda_5$ denote the possible states of the leak frequency λ, and p_j=P($\lambda=\lambda_j$ | $\boldsymbol{OF}(t)$ and $\#Obs(t)$) for j=1,…, 5 (obtained by the Bayesian network propagation).

Thus we have now obtained a new expected value of the leak frequency based on the states of the five organizational factors (assessed by the organizational risk indicators) and the number of observed leaks during the last time period.

We have used a Cox-regression model to obtain the effect of the organizational factors on the leak frequency (i.e., the first conditional probability table), but there are two reasons why we use the Bayesian network to estimate the new expected value of the leak frequency instead of using a Cox-regression model. First, we include the information about the number of observed leaks (as shown in Fig. 3), and second, we intend to use learning by adaptation, i.e., to modify the model successively based on the information gained after each time period.

5.5 Effect on the risk

The new expected value of the leak frequency can be entered into the QRA software to obtain a new risk figure. Alternatively the effect of the leak frequency on risk can be predetermined through sensitivity analysis and the relative change in risk obtained by

$$\frac{\Delta R(0,t)}{R(0)} = K_\lambda \cdot \left(\frac{E(\lambda(t)|\boldsymbol{OF}(t),\#Obs(t))}{E(\lambda)_0} - 1 \right) \tag{8}$$

where $\Delta R(0,t)$ is the absolute change in risk from t_0 (i.e., $R(0)$ as estimated in the last updated QRA), to the last time period t (i.e., $R(t)$). K_λ is the normalized sensitivity factor for the leak frequency parameter (Øien [22]), and $E(\lambda)_0$ is the expected value of the leak frequency used in the last updated QRA.

5.6 Example

We use the 20 leaks during the time period 1997-99 as the basis, thus obtaining a (basis) expected leak frequency equal to 1.7 leaks per quarter of the year (also corresponding to a combination of organizational factor states of 3-4-2-3-2, i.e., the average states during that three-year time period). We assume that this expected value corresponds to the expected value used in the last updated QRA, $E(\lambda)_0$. We assume this correspondence because the leak frequency in the QRA does not include the smallest category of leaks, thus we cannot obtain $E(\lambda)_0$ directly from the QRA.

The normalized sensitivity factor expresses the relative change in risk compared to the change in leak frequency. This factor has been estimated in Øien [22] giving K_λ=0.464. Inserted into eqn (8) we now obtain

$$\frac{\Delta R(0,t)}{R(0)} = 0.278 \cdot E(\lambda(t) | \boldsymbol{OF}(t), \#Obs(t)) - 0.464 \tag{9}$$

and the only value we need is the new expected leak frequency given the states of the organizational factors and the number of observed leaks during the last time period.

Assume that we have received the indicator measurements for a given quarter of the year. These measurements are translated to individual rating values for each indicator, which in turn is entered into eqn (1) together with the assigned individual indicator weights. We now obtain the ratings for each organizational factor. Assume that the combination of states assessed is 3-3-3-4-3. Assume also that we have observed three leaks during this last quarter of the year. From the conditional probability tables developed for the pilot installation we obtain the probability distribution of the leak frequency. Inserting the weights (p_j's) in eqn (7) we obtain

$$E(\lambda(t) | \boldsymbol{OF}(t), \#Obs(t)) = \sum_{j=1}^{5} p_j \cdot \lambda_j = 1.056$$

The change in risk is obtained from eqn (9)

$$\frac{\Delta R(0,t)}{R(0)} = 0.278 \cdot E(\lambda(t) | \boldsymbol{OF}(t), \#Obs(t)) - 0.464 = -0.170$$

that is, a 17% risk reduction. This may seem as a surprise since we have observed three leaks, compared to the original expected value of 1.7 leaks per period. There are two reasons for this seemingly surprising result. First, we observe that the state of three of the organizational factors have improved, whereas only one has deteriorated (combination of states changing from 3-4-2-3-2 to 3-3-3-4-3). This reduces the expected value of the leak frequency. Second, the observation of three leaks will tend to increase the expected value of the leak frequency, but the number of observed leaks are Poisson distributed, and with a parameter $\lambda \approx 1$, the probability of observing three or more leaks is only about nine percent. The observation of (as many as) three leaks can thus be seen as random, such that the states of the organizational factors have greater influence on the expected leak frequency than the observed number of leaks.

5.7 Overview of the quantification process

Fig. 7 illustrates the quantitative part in relation to our starting point for the development of organizational risk indicators (as depicted in Fig. 1).

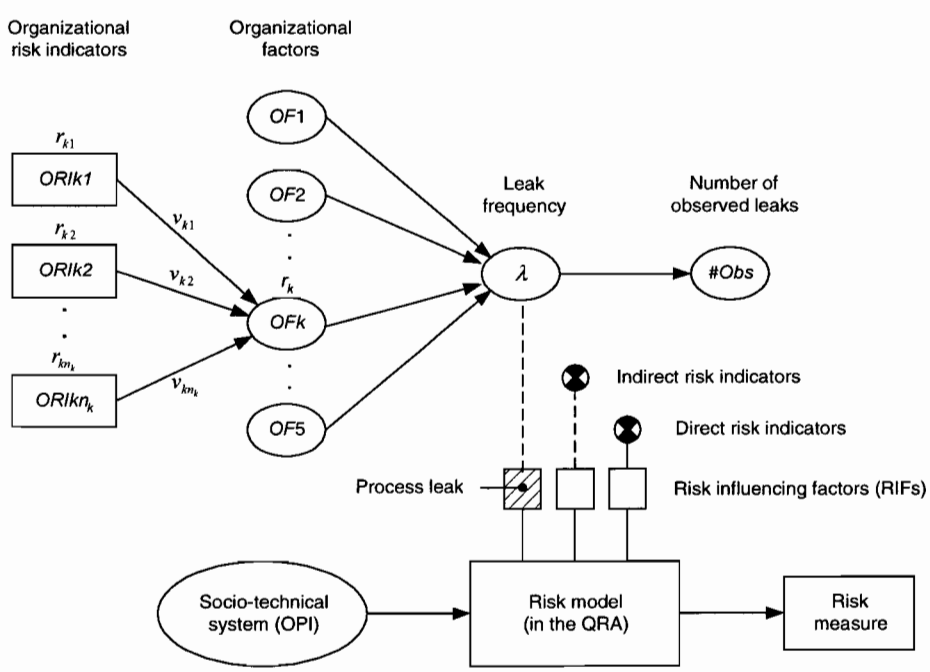

Fig. 7. Overview of the quantification process.

For the risk influencing factor 'process leak' and the corresponding parameter 'leak frequency' we do not only measure the number of observed leaks during each time period, but also the states of the organizational factors being most important with respect to leaks. The organizational risk indicators are used in order to determine the states of the organizational factors.

Knowing the states of the organizational factors and the number of observed leaks in the last time period we use the Bayesian network software to calculate the new leak frequency. The effect of change in the leak frequency (compared to the value of the leak frequency valid for the last updated QRA) is calculated using the QRA (or the result of previously performed sensitivity analyses), thus obtaining the change in total risk.

The effect of other changes than the leak frequency is captured through the direct and indirect risk indicators.

6. Results

Fig. 8 is an attempt to provide a 'big picture' of what this work has resulted in.

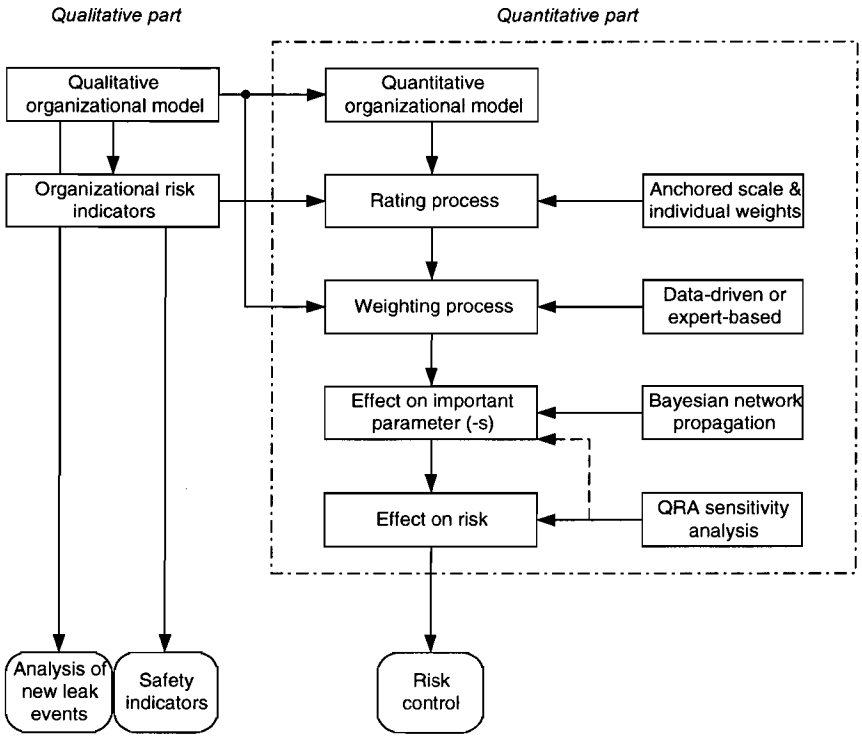

Fig. 8. Overview of the outcome of the work.

The qualitative organizational model and the organizational risk indicators were presented as intermediate results in Section 4. In addition to constitute inputs to the quantitative methodology these results may also be used as is. The organizational model may be used as a tool to analyze new leak events, thus determining which organizational factors have contributed to each new leak. The organizational risk indicators may be used without quantifying the effect of changes in the indicator measurements. We then prefer referring to them as safety indicators (only assuming an influence on safety).

The third result is the quantification methodology. It starts with the establishment of a quantitative organizational model based on the qualitative organizational model. Next the states of the organizational factors are assessed in the rating process using the organizational risk indicators as the measuring tool together with anchored rating scales. There is also an opportunity to assign individual weights for the indicators within the same organizational factor.

The impact of the organizational factors given their respective states is assessed in the weighting process, which either may be data-driven or expert-based. (We have only presented the data-driven approach in this paper.) Also for the weighting process we make use of the qualitative organizational model. This time the recorded leak events are re-analyzed in order to determine which factors have contributed to these previous leak events, according to the classifications of organizational factors used in our model.

The effect on important parameters (in our case only one specific parameter, which is the leak frequency) is calculated using a Bayesian network propagation algorithm, taking both organizational factor states and the number of observed leaks into account.

Finally the effect on risk can be determined based on QRA sensitivity analysis or by entering the new leak frequency value into the QRA software, thus obtaining the new risk figure. The QRA sensitivity analyses are also used to determine which factors are most important with respect to potential change in risk (indicated with a dashed arrow in Fig. 8). This was carried out as part of previous work (Øien [22]).

The result of the quantitative part of the work is to provide input to risk control, that is, to assess quantitatively the impact of changes in organizational factor states (in addition to information about the number of observed leaks) on risk.

For the details of the quantification methodology we refer to the descriptions in Section 5.

7. Discussion

In this section we discuss the organizational model, the organizational risk indicators, the quantitative methodology for assessing the effect on risk, limitations, practical applications, theoretical implications, further work, and finally we draw some conclusions.

7.1 Organizational model – the leak model

The organizational model (presented in Fig. 2 in Section 4.1) is developed with the purpose of being a practical and usable model to analyze leak events (both previously reported and new events) and to provide the basis for a quantification methodology. Due to these foreseen applications of the model we have deliberately concentrated on capturing the most important factors and scenarios with respect to leak events. This, in addition to focusing on only one important parameter has made it possible to avoid ending up with a too complex model.

Our experience from the analyses of previously investigated and reported leak events is that the assessment of root causes of the leak events is rather superficial. One reason for this seems to be a too comprehensive classification of causes in the incident reporting forms. Another reason is that the causes are overlapping and ambiguous, which complicates the reporting and further increase the reluctance to spend time on reporting the causes thoroughly. This is supported by Haukelid [59] who states that "many of those who are reporting events do not complete the forms".

The rather simple organizational model that we have developed specifically for the leak events has been tested on six different oil installations by both the safety authorities (the Norwegian Petroleum Directorate) and the Oil Company being the owner of these six installations. Their experience based on these preliminary tests was that the model was easy to use and suitable for the assessment of causes of leak events. However, in some of the events they experienced difficulties in distinguishing between the organizational factors 'procedures, JSA, guidelines, instructions' and

'planning, coordination, organization, control' since these factors to some extent can be regarded as redundant. Adequate procedures may reduce the need for strict planning, and vice versa.

The organizational model is tailor-made not only regarding the leak events but also with respect to the particular installation used for the pilot study. The model may thus need some adaptation in order to be adequate for other installations/Oil Companies, but a review of the model on a general basis by other Oil Companies did not reveal any major inadequacies. In general it seemed to agree with the experience of other Oil Companies with respect to leak events.

Also as an input to a quantification methodology it is a potential pitfall to make the model too complex. In the SAM framework (Murphy & Paté-Cornell [7]) the organizational model is tailor-made for a specific part of a sociotechnical system, and is kept rather simple. In the WPAM development the original 20 factors were regarded as an adequate starting point, but have lately been drastically reduced (Weil & Apostolakis [60]). Also in the I-RISK project they experienced some problems during the development due to the complexity of the organizational model (Hale et al. [61]). Our model is developed with these experiences in mind and therefore deliberately kept rather simple, but like the SAM framework we do only cover a part of the total risk and consequently only a part of the organization.

A somewhat related topic is how far back in the causal chain the organizational model reaches. This will be discussed as part of the limitations in Section 7.4.

If we make a detailed comparison between our model and existing models developed for similar purposes we recognize that even if there is some resemblance with the organizational model in the SAM framework, the models are different. This is, as we have discussed previously no big surprise since even pure classifications of organizational factors differ extensively (Wilpert [35]). In addition, our model is at least to some degree installation specific, since this is regarded to provide a more credible model.

7.2 Organizational risk indicators

The organizational risk indicators comprise the tool we suggest to use for the assessment of the states of the organizational factors. They provide the ability for a

reasonably speedy rating process, which is deemed necessary in our case of a rather frequent measurement of the organization. The proposed organizational risk indicators (listed in Table 2 in Section 4.2) are only proposals and should be critically evaluated by the personnel on the installation in question, prior to or as part of an implementation. The final selected indicators should have high face validity judged by the personnel using the indicators.

The proposed risk indicators are partly based on the evaluation of existing safety performance indicators (e.g., Olson et al. [25, 27]; Lehtinen [18]), and two of the suggested indicators are adaptations of such safety performance indicators. However, in most cases the safety performance indicators are either somewhat too general or they are specifically adapted for one industry (for instance the nuclear power industry).

If the final selected indicators for some reasons are regarded as inadequate (e.g., not valid or insufficient coverage), then we may use additional subjective judgments. The operational management on the installation may complement the indicator measurements by qualitative judgments, or in the extreme case they may overrule the indicator-determined states of the organizational factors and assess them directly. Due to the use of Bayesian network there is no need to determine (with 'certainty') the states of the organizational factors. The states may be assigned a probability distribution over the allowable states.

The proposed organizational risk indicators are tailor-made for the pilot installation and are generally not deemed applicable to other installations. Like the organizational model and factors, indicators specifically adapted for the installation in question are regarded as being more credible compared to standardized indicators being applicable to a broad range of installations.

It is our intention to use the indicators as an input to the quantification process and in such a case we use the term organizational risk indicators since the impact on risk is estimated. In an alternative qualitative application of the indicators we use the term organizational safety indicators since the impact on risk is not established - there is only assumed an influence on safety.

7.3 Quantitative methodology for assessing the effect on risk

The quantitative methodology has both similarities and differences compared to existing organizational factor frameworks. The quantitative organizational model is based on the qualitative organizational model, which in principle has some resemblance to the models established using the SAM framework (Murphy & Paté-Cornell [7]). However, in the quantification process we have simplified the model leaving out the intermediate levels.

We make use of indicator measurements for the assessment of the states of the organizational factors, which is not the case for other organizational factor frameworks. Neither is the data-driven weighting process commonly used. Only the ω-factor method suggests using a data-driven approach for the assignment of weights (Mosleh & Goldfeiz [53]).

Focusing on the impact on important parameters is in principle comparable to what is done in the SAM method, and is also to some degree comparable to the approaches chosen in the WPAM method (Davoudian et al. [9-10]) and the I-RISK method (Papazoglou & Aneziris [12]). The difference compared to the two latter methods is that they do not focus on specific parameters, instead they establish generic parameters or parameter groups, in an attempt to capture 'all parameters' and thus also the total risk picture. The assessment of the effect on risk is usually carried out by way of the QRA software, and not based on a predetermined effect assessed through sensitivity analysis as we suggest. When we know the relative change in the specific parameter of interest we can readily obtain the relative change in risk (due to this specific parameter). We regard this as being an advantage when we carry out frequent assessments for the purpose of risk control. However, there is nothing that prohibits the use of the complete QRA software in establishing the effect on risk.

Based on sensitivity analyses performed on the quantification methodology we found that some of the most sensitive parts were a correct anchoring of the rating scales, and a correct assessment of one of the anchoring values used in the data-driven weighting process. This last anchoring value was the one obtained by assessing the assumed number of contributions to leaks of an organizational factor given that it was changed to the worst possible state.

The quantification methodology developed is generally applicable for any installation and may also be suitable for other industries. The organizational model

may have to be adapted or even totally redesigned, and the indicators must be tailor-made, but the principles of the methodology are still valid.

7.4 Limitations

The limitations of our work should be viewed in light of the purpose of this work. Minor limitations from our point of view may be seen as major limitations if the results are attempted used for other purposes.

We have established an organizational model covering those organizational factors that can be attributed to specific events without using extensive resources in the investigation of the root causes. One consequence of this is that we do not cover remote organizational factors explicitly. However, more remote causes including external causes are foreseen to influence risk through the organizational factors in the model. If this is the case, then we at least capture the effect of these remote factors although they are not included explicitly in the model. If the purpose is to assess the importance of factors that are only implicitly captured by our approach, then our model will provide little help.

We do not focus on risk-reducing measures. We are focusing on risk control and the ability to provide a signal or a warning if the risk develops in an unsatisfactory manner. Given that one or more of the organizational factors contributes to an unsatisfactory risk development, then we need to analyze the underlying reasons for the unsatisfactory development of these specific factors, potentially leading to the uncovering of remote organizational inadequacies. When we do know that we have a problem with an organizational factor, then the necessary resources may be released for a thorough investigation, resources that usually are not available at the time of the investigation of each single event.

We do only cover one specific parameter, the leak frequency, since we capture the effect of the organization on other parameters through direct and indirect risk indicators as illustrated in Fig. 1 in Section 2.1. This is in line with the risk control perspective. However, if we are interested in capturing the total effect on risk of one specific organizational factor explicitly, then we need to build similar models, as we have done for the leak frequency, for all the parameters or the most important ones.

7.5 Practical applications

The purpose of our work has been to develop a tool that can be used for the control of risk during operation of offshore petroleum installations. The risk indicators (direct, indirect and organizational) measure changes in important risk influencing factors, and based on these measurements we can estimate the relative change in risk. We suggest that the 'state of affair' in terms of risk be presented each quarter of the year. It does not provide any risk control per se. It merely provides the essential basis for controlling the risk, which is knowledge about the present situation. If the situation is 'unacceptable' then the identification of risk-reducing measures is the next step on the way to regain control of the risk.

In addition to this main purpose, the qualitative organizational model may be used for the analysis of root causes of leak events, whether or not the quantification methodology is employed.

7.6 Theoretical implications

If we compare our framework (ORIM) with the existing organizational factor frameworks then the main implications of our work are the following three features. First we use indicators to frequently measure the state of the organizational factors. Second we have developed and employed a data-driven weighting process, and third we have used a risk-based screening process to identify and select the most important parameters in the technical risk model.

7.7 Further work

It is a highly complex problem that we have pursued to solve. The methodology that we have developed gives in principle answers to each step, and there is no steps left out. What is needed now is first of all a real case implementation. However, the methodology is rather comprehensive and an implementation is not totally straight-forward. It requires for instance reevaluation of the assumptions and assessments made by the analysts in collaboration with the Offshore Installation Manager, and the

identification and selection of indicators.

An implementation must to a large degree be based on 'face validity' of the methodology, or be seen as part of further development of the methodology. The prediction capability can only be validated after an implementation of the methodology.

7.8 Conclusions

We have developed a methodology for the quantification of the impact of organizational factors on risk. In the present application we have focused on one specific parameter, i.e., the leak frequency, which is the most important parameter with respect to potential change in risk and for which direct indicators do not provide adequate measurements of change. The organizational root causes of leak events is captured in an organizational model and organizational risk indicators measure the change in states of the organizational factors. Together with the direct and indirect risk indicators previously developed, the organizational indicators comprise a tool for risk control covering the most important parameters in the technical risk model in terms of potential change in risk. This tool will aid in a frequent control of the risk in the periods between the updating of the quantitative risk assessments.

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