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Integrating human related errors with technical errors to determine causes behind offshore accidents

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ABSTRACT

This paper presents how to model technical and human errors and how the two error types are integrated in one common model. Human errors were modeled as an integral part of the organization's ability to handle failures, while technical errors were embedded as an integral part of the oil well drilling operation.

To reduce the number of offshore accidents there is a continuous focus on safety improvements. An improved evaluation method is therefore suggested, a method which has the potential of being run in real-time to obtain an immediate assessment of the failure. The method is based on a knowledge model of the oil-well drilling process. All concepts in the model are structured in hierarchical categories, based on well-established knowledge, combined with situation specific experiences. We have previously developed a modeling tool for technical failures during drilling. Obviously the human factor plays an important role in all accidents. However the combination of technical and human factors has not yet been reported. Human factors have therefore been integrated with existing technical concepts in the present methodology.

Our tool has the capability to point out the most probable causes behind failures by relating incident observations to failures. The tool has proven its capability of pointing out the most probable technical and human related causes behind accidents in the petroleum sector. The present version points out the underlying causes, a future version is planned to also offer a suggestion of remedial countermeasures.

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1. Introduction

Human errors are practically always involved in accidents. Continuous efforts to reduce human errors have placed increased emphasis on training, motivation, hardware design, and management systems. This has contributed to improved safety performance in the industry, clearly demonstrated through statistical studies, for example the one from the Swedish Rescue and Service Agency (SRS, 2010), as shown in Fig. 1.

The number of fatalities is, however, not an indicator of technical failures. In spite of improved safety awareness and improved technology, the increased challenging environment accompanied by increased technically challenging wells has not lead to an accordingly decrease of non-productive time (NPT) during oil-well drilling. NPT exhibits a much lower declining trend than number of fatalities. In exploration and development drilling, 5–15% of the drilling time is spent on unproductive downtime caused by operational failures that involve human errors, such as stuck pipe, mud losses, and well control incidents (Halliburton Solving Challenge, 2012).

To counteract the problem of too high NPT the industry is spending much effort in understanding, modeling and counteracting technical failures (Dean, 2012; Uniport et al., 2012). Similarly, from an organizational point of view, also huge efforts are being undertaken to improve the NPT, e.g. Thomassen and Sørum (2002) and Bunn et al. (2010). In addition to internal and external accident investigations, modeling work is continuously improving.

Previously, accident analyses revealed factors that were related to the operator performing the task. Today however, the focus has shifted to organizational factors, such as management and safety culture, which form many of the conditions that the operators work under, like training, staffing and high work pressure.

Disasters are rarely caused by only one factor. Reason (1990) suggested that there is an analogy between latent errors in complex technical systems and latent pathogens within the human body (pathogens lead to deceases). The pathogen theory has led to a search for pre-disease or pre-accident indicators, assuming they are remediable. The safety culture of an organization includes

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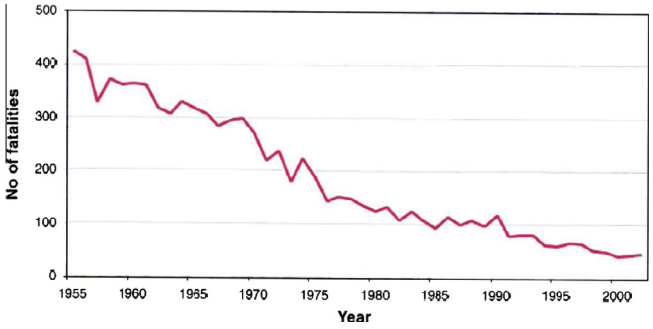

Fig. 1. Workplace fatalities in Sweden during the last 50 years (SRS, 2010).

all issues involving human and technical safety aspects. Several companies, e.g. Tripod (Sharp et al., 2004) and The Energy Institute (EI, 2010) have suggested factors or indicators related to organizational safety. These approaches were adopted in the research presented in the present paper.

Human reliability analysis (HRA) methods are used to quantify the likelihood of human errors in major accidents. The authors of these methods also claim that the methods could be used for retrospective analysis of accidents. However, a problem by using these methods in such a way is that they only include factors that are close to the performing operators and that they do not include factors on the organizational level such as management and organizational safety culture factors.

The overall evaluation capabilities will be improved by combining all contributing factors involved in accidents, as illustrated in Fig. 2. Our approach is based on knowledge modeling principles applied in the CREEK tool (Aamodt, 2004). The original tool was developed in the 1990s (Aamodt (1994) for the purpose of decision support by reasoning from past experiences, referred to as case-based reasoning (CBR). Technical failures and their causes have already been modeled (Skalle et al., 2013). CREEK has also been the basis for a commercial system for prediction in the oil well domain, developed and successfully tested by Verdande Technology, a spin-off company from our university (Gundersen et al., 2012). Now the time has come to integrate human errors with technical errors.

The main contributions of this paper are:

- A new knowledge model related to human error.
- An extension of CREEK's built-in ontology to encompass both technical and human errors integrated in a complete organizational model.

Our approach will enable prediction of failures before they occur, and if they occur, enable solving them more efficiently by revealing the root causes behind the failures.

We claim that the usefulness of the expanded and upgraded method will be enhanced compared to state-of-the-art of accident investigations.

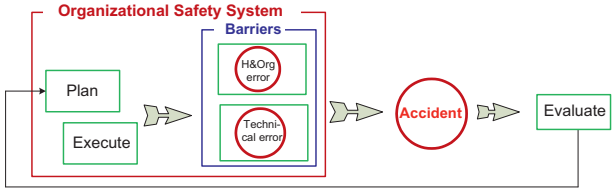

Fig. 2. Three contributing factors involved in an accident: Human & Organizational (H & Org) Error, Technical Error and the resulting Organization Safety Level. Rectangles represent activities, circles represent occurrences.

2. Extended method applied to enhanced investigation of accidents

2.1. Knowledge engineering

The model of drilling-related knowledge developed as part of this research is based on the adaptation of established methods and best practice for knowledge model development – also referred to as knowledge engineering. The term "knowledge" – as used in this paper – refers to all types of explicitly represented structures on the basis of which a system is able to perform reasoning. A sound principle in knowledge engineering is that the resulting model should be described at a conceptual level, independent of computer implementation issues such as programming languages and computer size.

Established results from the knowledge acquisition and modeling community have produced several methodologies and techniques for describing knowledge at the conceptual, implementation-independent level. Influential earlier examples are the Components of Expertise framework (Steels, 1990), and the CommonKADS methodology (Breuker and Van de Velde, 1994). Based on these and other influential knowledge modeling methods, a set of libraries of generic knowledge models have been developed. To enable the reuse of such models, the call for common generic models – more frequently referred to as 'ontologies' – has led to the development of such generic knowledge models within different application areas. Correspondingly, the term 'ontology engineering' is now often used instead of 'knowledge modeling'. Examples from the area of Human Factors are Germanakos et al. (2008) and Philippart and Karwowski (2011). A large ontology that has become an international standard is the ISO 15926 oil&gas ontology (Fiatech, 2011). This ontology has been an inspiration for our ontology, although the cover and the complexity of the ISO 15926 has lead us to develop our own.

Most approaches to knowledge engineering share a common feature: they view knowledge modeling from what is called a "knowledge-level" perspective.Some knowledge levels are applied as distinct levels of description of computer systems, defined to be positioned above the level of data structures and programming languages. The latter is referred to as the "symbol level". A system is described at the knowledge level as an agent with its own goals and with knowledge of how to achieve its goals. The assumption is that an agent always will use its knowledge in a way that ensures the achievement of its goals - provided the agent has the knowledge needed.

The useful thing about the knowledge level is that it enables a system (existing or anticipated) to be described in terms of what it does and why it does it completely independent of implementation constraints. The number of knowledge modeling tools that have been developed based on the distinction between the knowledge level and the symbol level have 'operationalized' the knowledge level theory by providing the necessary structures and modeling procedures to enable the development of conceptual knowledge models of real-world systems. Most of these tools share the view that knowledge, in its most general form can be subdivided into three main categories – or viewed from three perspectives: Task knowledge, Method knowledge, and Domain knowledge.

Task knowledge describes what to do, usually in task-subtask hierarchy. Tasks are tightly connected to goals and sometimes used interchangeably. A task is defined by the goals that a system tries to achieve. Method knowledge describes how to do it, i.e. a method is a means to accomplish a task (e.g. to solve a problem). Domain knowledge is the knowledge a method needs about the world to accomplish its tasks. Examples are facts, heuristics, causal relation-

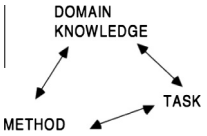

Fig. 3. Knowledge perspectives.

ships, multi-relational models, and – of course – specific cases. For a complete model all three perspectives need to be addressed, and the outcome of one is fed into another, typically in a iterative fashion (see Fig. 3). Our ontology also incorporates this three-perspective view. The focus in this paper, however, is on the Domain Knowledge part of the total model.

On top of this ontology a reasoning system has been built, which enables us to combine reasoning from general domain knowledge with reasoning from situation-specific cases. While we in earlier work have shown how to utilize specific cases supported by general domain knowledge, in a process called knowledge-intensive case-based reasoning (ki-CBR) (Aamodt, 2004; Skalle and Aamodt, 2004), the work reported here focuses on the model-based reasoning part. Our model is based on an extended general domain model in which a new sub-model of human factors has been incorporated.

Our model of general domain knowledge consists of concepts and relations structured in a hierarchical ontology model. Concepts are inter-related through multiple relation types. The model can be viewed as a three-level model, as illustrated in Fig. 4: A top-level sub-model of generic concepts, such as Physical Object, Mental Object, State and Process, a medium-level sub-model of domain-specific concepts, such as Skilled-based Error, Inattention, Organizational Culture, Formation Error, Wellbore Error and Swelling Clay, and a bottom-level sub-model that contains specific facts and situation-specific cases. A combined top-down and bottom-up modeling approach has been taken, by partly developing the model from textbook and in-house expertise knowledge while studying several existing ontologies, and partly by utilizing the specific knowledge obtained from situation-specific accidents to refine existing and accommodate new knowledge.

At the symbol-level the model is represented as a semantic network, in which all concepts are interrelated within one single network. A syntactical regime of the ontology is that the first letter in each word in a concept is written with capital letter, e.g. Swelling Clay, while relations between concepts are written solely with small letters, e.g. has subclass.

In our ontology, as in most ontologies, the top-level concept Thing stands for anything in the world worth naming or characterizing. Everything we want to talk about is a subclass or instance of Thing. Thing has three subclasses; Entity (an actual thing in the real world), Descriptive Thing (a descriptions or representation of an Entity) and Relation (a bi-directional relation between concepts). Examples of some subclasses are found in Table 1.

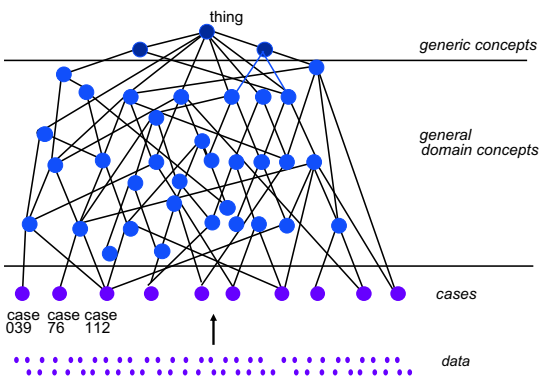

Fig. 4. Top level of the general knowledge model (ontology) on a structural form (only subclass relationships are presented) together with specific knowledge from cases (Aamodt, 1994).

2.2. Technical error and failures in the drilling process

The drilling process enters into an error state before a failure occurs. Note that we have selected to classify technical errors in accordance with location of occurrence as shown in Fig. 5, i.e., either in the formation, the wellbore or in the equipment. This simple-to-accept manner makes errors easy to classify. An error occurs when a parameter, a process or an object exhibit a deviatoric performance. The deviation may rectify itself or it may be persistant, so that it leads to a failure in the long run.

By means of the knowledge model it is possible to model rather complex mathematical relationships. The knowledge model is not depending on recorded parameters, it is sufficient to understand the physics involved and model it as relationships between concepts.

Failures in the drilling process are classified and presented in Fig. 6. Failures are grouped in accordance with where they take place. Failures are the end state and the focus of accident investigations. The end state is a result of both technical and human errors.

2.3. Human error

The scientific subject referred to as human error is a sub topic of Human Factor. Human error is classified in accordance with the work of Rasmussen (1983) and Reason (1990) and with those who later trimmed and extended their work, e.g. Arnstein (1977) and Atkinson (1998). Our model represents a simplified behavioral classification model. Fig. 7 shows the upper levels of the human error hierarchy.

Human errors can in general be of the type Active Error, typically associated with performance of front line operators during execution of a plan. The other type, Latent Error, is more underlying errors done by for example designers or managers that might contribute to active errors. Latent errors are often less apparent than the active errors and they are in time and space more separated from an accident than the active errors. Latent errors are often more hidden and difficult to find than active errors.

Human behavior is subdivided into three levels of performance (Reason, 1990), leading to three corresponding error types:

1. Skill Based Performance (Skill-B.P.): Related to automatized behaviors that occur without cognitive monitoring. This type of performance may lead to errors of type Slip and Lapse
2. Rule Based Performance (Rule-B.P.): Related to misclassification of the situation. May lead to Mistake
3. Knowledge Based Performance (Knowl-B.P.): Related to application of stored knowledge for analytical processing. May lead to Mistake

Skill-B.P. is automatic processing, characterized by regularities of the past being reapplied whenever called upon. Familiar information and hands-on experience are processed rapidly. During smooth, familiar, automated and non-problematic activities, most human activities proceed roughly according to plan.

Rule-B.P. represent an intended action (but the intended plan is wrong), and is, together with Knowl-B.P., the most risky performance of the three since people are not easily persuaded from exe-

Table 1
Examples of General Domain Concepts and their definitions.

Concept	Definition
Entity	
Process material	Material generated or produced during the drilling process
Facility	All or any portion of a physical construction, including buildings, structures, equipment, roads, and so on
Descriptive Thing	
Synonym	A descriptor with the role of connecting a term used to refer to a phenomenon, with the phenomenon concept itself
Geological description	Description of faults, geological periods, geological processes, reservoirs, etc.
Relation	
Causes always	Strength: 1.0
Causes (typically)	Strength: 0.9
Leads to	Strength: 0.8
Implies	Strength: 0.7
Causes sometimes	Strength: 0.6
Enables	Strength: 0.5
Involves	Strength: 0.5
Indicates	Strength: 0.4
Causes occasionally	Strength: 0.3
Reduces effect of	Strength: 0.5

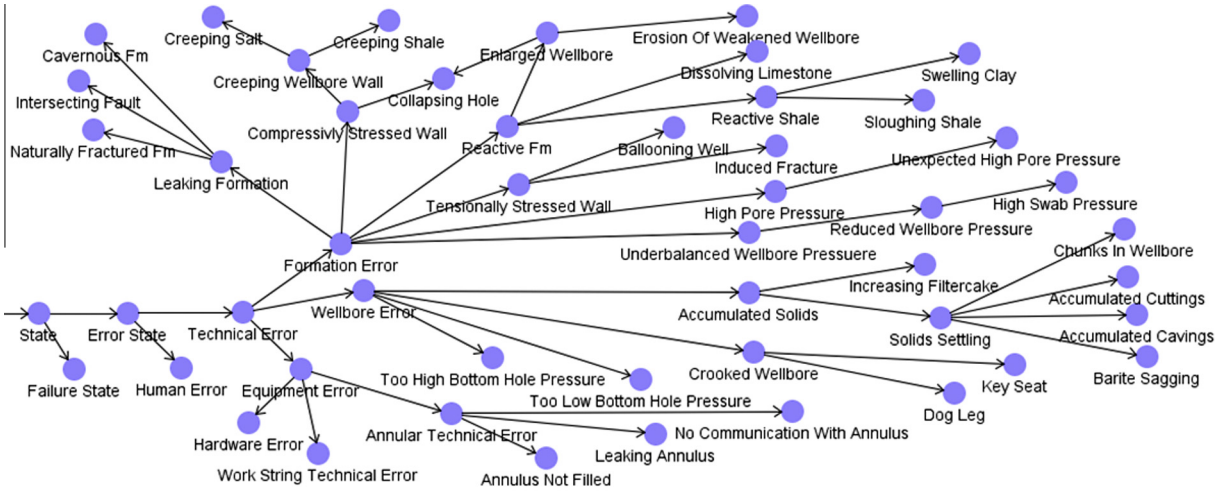

Fig. 5. Subclassification of technical errors in the drilling process.

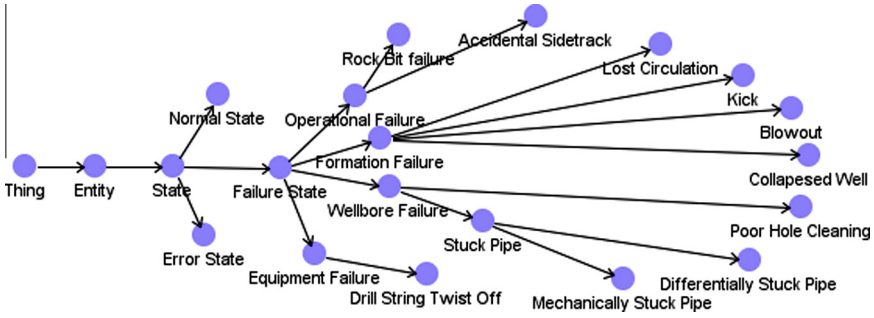

Fig. 6. Subclassification of failures in the drilling process.

cuting an alternative plan (alternative to the wrong one). The Rule-B.P. mode is working by taking information from previous, successful experience, just like the functionality of cases in CBR. Rule breaking, is seen as a contributing factor in almost all serious incidents. One thing is clear: People usually break rules for very good reasons and they do not intend to create a disaster. Rule Based Mistake (RBM) are caused by failure to apply the correct rule or, expressed in another way, applying an inappropriate rule, caused by misclassification of the problem. Rule Based Mistake is less frequent than skill based slips/laps, but more dangerous and more difficult to detect.

Knowl-B.P. comes into play when the Rule-B.P. repertoire is exhausted, triggered by changes in the routines, i.e. during well planning and during handling of critical situations. In this situation, work must be done "on-line", using conscious processing with feedback. Discrete information processing elements are; retrieve; transform; extend; and recombine. Humans sometimes do slips and lapses. The operators' tasks are both rule based and knowledge

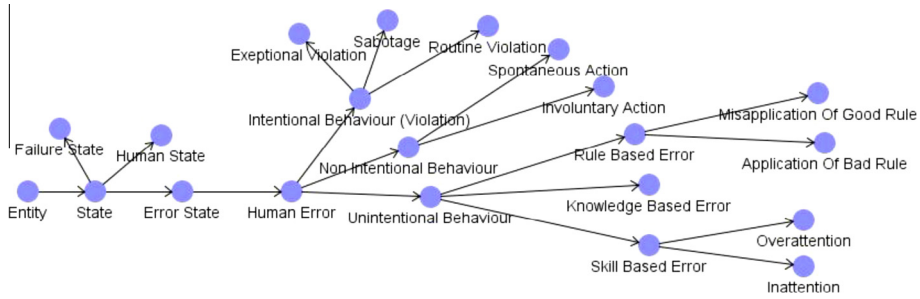

Fig. 7. Human errors are classified as either active (Intentional and non-intentional Behavior) or latent (Unintentional Behavior). Each arrow represents the relation 'has subclass'.

based. To follow a procedure might be both rule based and knowledge based. Procedures do not always specify the work itself and that following procedures need a lot of judgment to adjust the procedure to specific situations with regards to for example timing of subtask, relevance, importance and prioritization. To follow procedures might be both Rule-B.P. and Knowledge-B.P.

Knowl-B.P. resembles the ki-CBR process. Both processes need cases, experience and intelligent processing.

2.4. Organizational safety error

Latent errors are associated with the safety level of the organization and are often committed by its designers, its high level decision makers and by its managers. These errors are the greatest threat to safety of complex systems. The active errors are indirectly inherited from latent errors in the organization. Spotting latent errors is the way to find the root causes of failures. In the latent error view (pathogen metaphor) presented by Reason (1990), the organization and its systems, rather than individuals, are assessed, leading to a search for indicators of organizational reliability.

Accidents will only occur when a sufficient number of barriers fail (Craddock, 2004). The condensate explosion on the North Sea oil platform Piper Alpha has often been used to illustrate this. When problems were encountered with the main condensate pumps, the operator switched to the back-up pumps where a relief valve was missing and there was no protection against condensate ignition, which again was a result of three factors; inadequate work permit, knowledge gaps of the procedure and communication breakdown of equipment status between shifts. This case illustrates how a combination of factors, including hardware and human errors, can combine to allow a serious incident to occur. Our tool is being based on such type of relationships and thus possesses the ability of revealing the combined row of events.

In Fig. 8 we have modeled factors in groups which are in common use today (EI, 2010). In addition we have suggested logical subclasses of the main factors. The factors will function as failure tokens or organizational safety indicators.

To make the intention behind each concept clear and thus avoid confusion, conceptual classification is implicitly included in CREEK through concept definitions. In case of disputes, the concept can be adjusted or extended. As example of a concept definition we pick out, from level two in the model, the concept of Safety Critical Communication (EI, 2010):

> "Reliable and accurate two-way communication (spoken and written) of safety–critical or safety-related information have many routes, for example between control room and field operators, between operators within a shift and at shift hand-over, and not the least from the management to all employees. The feedback loops, including indicators and other relevant info constitute the Safety Info System (SIS)".

There are many factors that contribute to human errors. Some of the factors are representing the front-end operator through factors like Fatigue, Boredom, Inattention and Stress. Other factors might be task-specific such as Complexity, Training, Procedures and Human Machine Interaction, while other factors are more at the organizational levels such as Staffing, Management and Safety Culture. All these factors are included in the model, and most of them are present in Fig. 8.

Human and organizational errors are closely coupled. In Fig. 2 and in the remaining of the paper they are referred to as Human & Organizational (H & Org) errors.

3. Implementing the methodology

Based on the theoretical description in Chapter 2 the methodology will be implemented in seven separate steps:

Step 1: Develop the Creek platform.
Step 2: Expand the ontology into the new knowledge domain of Human Factor.
Step 3: Retrieve relevant findings appearing before and up to the time of the accident.
Step 4: Translate findings into acceptable symbolic concepts.
Step 5: Enter the concepts at their logical location in the knowledge model.
Step 6: Relate concepts through cause-effect relationships.
Step 7: Test the improved method with data from field cases.

Step 1 has been presented previously by Aamodt (1994, 2004). This step also includes the technical part of the ontology (Skalle and Aamodt, 2004). Step 2 is presented in Chapter 2. At the onset of developing a new knowledge domain, the ontology is built on the basis of formal knowledge settled in renowned literature, and is referred to as top-down modeling.

The remaining four steps involve the insertion of new findings (observations and relevant facts) from major accidents; bottoms-up modeling. In these four steps we have exemplified the method by referring to a real case to make the method easier to follow.

Fig. 9 represents the process of developing these four steps of the method, which are presented next:

Step 3: Retrieve findings. To exploit the accident in Well P-01A (the well-name is made anonymous) all relevant pre-accident observations were collected. Observations made during and after the time of occurrence cannot be applied for prediction of the accident.

Well P-01A was a challenging well characterized by narrow mud margins. The selected incident was initiated by a kick (an in-

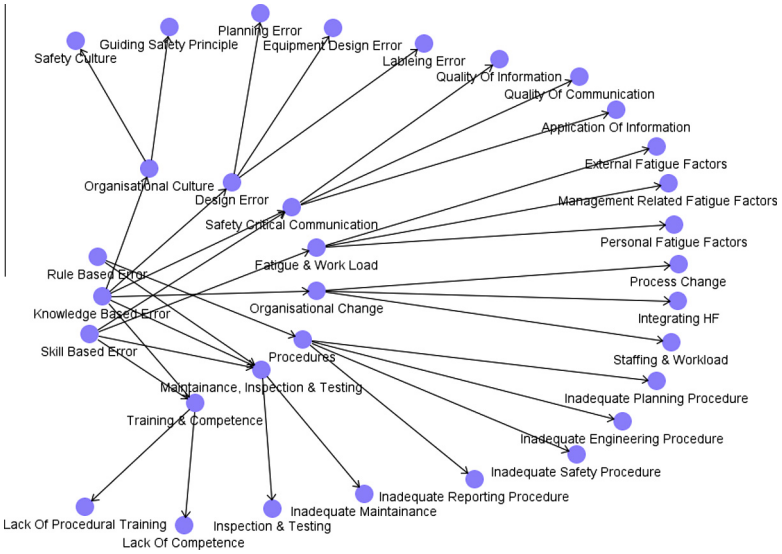

Fig. 8. Latent errors are contributors of organizational safety indicators. The 8 error types and 22 subclasses are related to unintentional behavior. Each arrow represents the relation 'has subclass'.

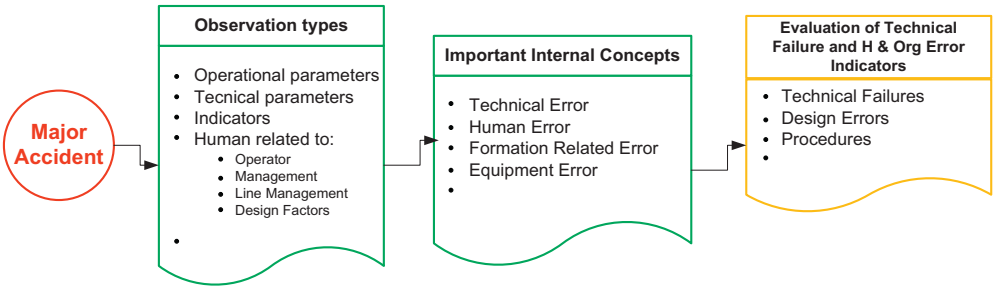

Fig. 9. The process of how to determine failures and the organizational challenges after a major accident is also an indication of how the method must be modeled.

flux from the geological formation) during drilling. A kick in itself is normally routinely handled and classified as an ordinary failure, not a major one. However, the later killing operation was complex and time consuming. Since handling of the kick involved serious operational deviations, requiring five days of repair actions and ending with plugging and abandoning the well, the case was viewed as a major accident.

Originally P-01 was drilled in 1991 and set on production the same year. During oil production the pressure gradually rose to 140 bars in the 13 3/8″ and 9 5/8″ annulus. The Cement Bond Log that was run after cementing the 9 5/8″ casing in 1991 indicated very poor bonding and even partly free 9 5/8″ casing (not completely cemented). The annulus was later squeeze cemented. Planning of a sidetrack (P-01A) began in 2008. The mother well, P-01, was plugged back in November 2009, and the sidetrack was initiated the same year, milled out through the 13 3/8″ casing at 1791 mMD (measured depth). The upper part of the new well, the 12 ½ * 13 ½″ section, was drilled in overbalance of the pore pressure in the sedimentary formation.

Three gas tops came with the returning mud from 2469 to 2524 mMD during drilling. While drilling into the formation called Lista, from 2640 mMD, the returning mud's gas concentration was 8%. Fig. 10 presents the wellbore at this stage of the operation. After a flow check at 2665 mMD, 700 l flowed freely from the sediments over a period of 15 min. The well was closed and killed by means of the Driller's killing method, but technical problems continued for several days.

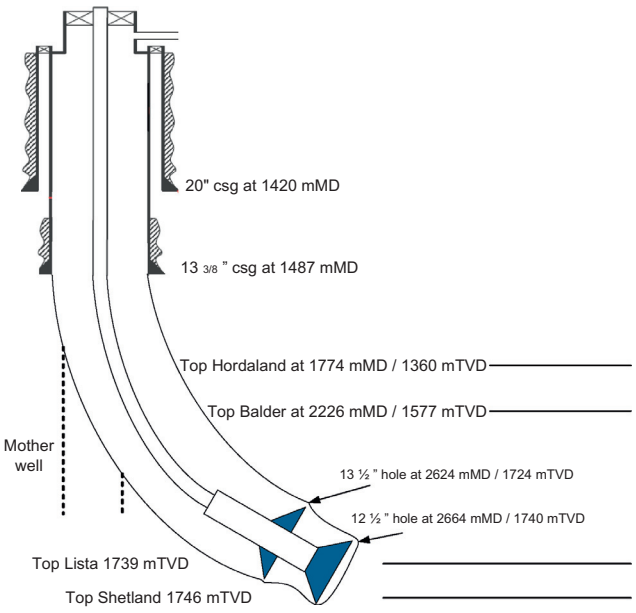

Fig. 10. Wellbore geometry of P-01A at the time of the accident (Utvik, 2010).

The case is defined through deviatory performance (compared to a normal process progress) both during the planning and the execution phase. The Norwegian Petroleum Inspection Agency (PeTil) kept a tight focus on deviations brought about by the operating

organization and its safety culture (Solheim et al., 2010; Etterlid and Gundersen, 2010). One of PeTil's general goals of supervising is to make sure that the parties involved in the petroleum industry keep a high HSE performance level. PeTil has specifically been focusing on drilling in depleted reservoirs due to many incidents in such challenging areas. Incident investigation performed by the operating company focused more on technical factors (Utvik, 2010; Førsund et al., 2010). During the investigation of the accident PeTil reported on transparent conditions and good communication with the operating company.

Step 4: Case observations on symbolic form. The technical, human and organizational (H & Org) related observations have been structured to fit the grammar of the knowledge model and made into applicable symbolic concepts, characterized by being short and unambiguous expressions, applicable and reusable for any accident. The complete case, from its beginning in 1991 to date of the blowout, is presented in the Appendix. Some of the observations made during the critical period, just before the kick, are presented in Fig. 11.

Step 5: Enter concepts into the knowledge model. The next step was to place new concepts in the knowledge model. Most of the technical concepts were already inherent in our model, while H & Org related concepts were not. Fig. 6 above and Table 2 demonstrate the results of this step.

Step 6: New relationships developed from new case observations. In this step the new case observations were related in meaningful and logical relationships to any relevant concept in the existing knowledge model. New concepts make our knowledge model grow. Some of the observations were already inherent in the model, entered during previous failure cases. In Table 3 a selected number of concepts demonstrate normal and bi-directional relationships.

Deviations from normal behavior before and during the accident will be related, either directly or through longer paths, to the failure. Some relationships, shown in Table 3, exemplify how model works.

The examples in Table 3 demonstrate that not much can be done about slips, lapses and inattention, performed by the front-line operators, besides offering good training and practicing good safety culture.

4. Field test (Step 7)

The flow of information during the testing of the model is indicated in Fig. 9. An accident induces observations which point at irregular system states, thereafter to errors, and finally to the failures and to the weak spots in the organization expressed through Organizational Error Indicators.

4.1. Identifying causal paths

In order not to make the presentation too large and complicated we present technical and human related observations separately. The H & Org Error Indicators that were activated during the test are presented in Fig. 12.

In Fig. 13 a detail is shown. The observations which activated the H & Org Error Indicator called Fatigue & Work Load are presented, including the relation names. Such details enable us to estimate the relation strength between observations and indicators (see next chapter).

Now to the other observation-type, the technical one. In Fig. 14 a similar view as for the H & Org errors above is presented; which of the technical error/failure were activated by technical observations. Not surprisingly the observations pointed mainly at the failure Kick (which occasionally causes a Blowout).

4.2. Strengths of causal paths

After the introductory presentation of the two observation types, the main objective of the study remains;

1. Is it, on the basis of human and organizational related observations, possible to point out weaknesses in the organization? 28 observations are H & Org related and are pointing at critical H & Org Error Indicators.
2. Is it, on the basis of all observations, both H & Org and technical related, possible to point out the most probable failure type which is about to occur? 22 of the H & Org related observations are pointing at the correct Failure called Kick, via Technical Error, and thereby strengthening the technical related observations.

In general, the strength of each single path is the product of the strength of all n relations leading from the observation to the target indicator or target failure:

$$\text{Path strength} = \Pi_{i=1->n}\ (\text{relation strength}_i) \tag{1}$$

When there are several explanatory paths pointing to the same indicator/failure, their total explanation strength is determined by adding path strengths:

$$\text{Explanation strength} = \sum_{j=1->m} (\text{path strength}_j) \tag{2}$$

Here m is the number of paths. Calculated explanation strengths will be a good measure of indentifying the most probable indicator.

To exemplify the two equations we apply the details already presented in Fig. 13. Here it is shown that 6 observations are pointing to the Management Related Fatigue Factor. The obtained

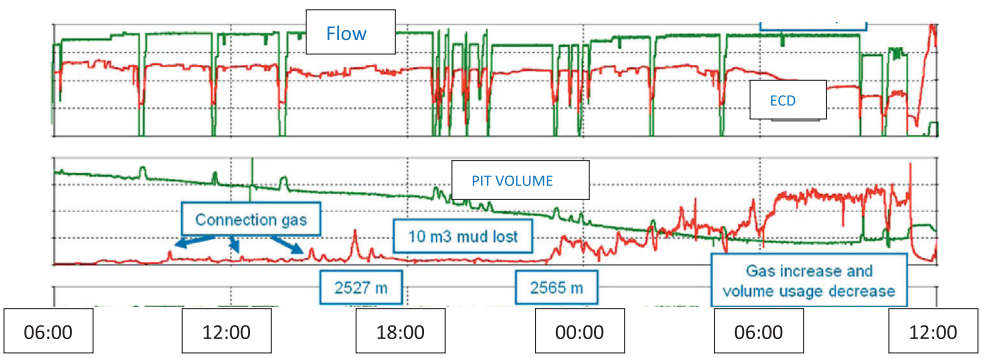

Fig. 11. Some of the observations are found in the real-time drilling data. Corresponding observations are also shown on symbolic form in Appendix 1 under the heading: Technical observations immediately before the accident). The kick occurred at 11:00.

Table 2
Two selected (of totally 8) Human & Organizational Error (H & Org) Error Indicators with their 5 (of totally 22) subclasses (hsc = has subclass) are presented here with one more subclass level. The latter level (to the right) is represented by observations.

H & Org Error Indicator	hsc	hsc
Organizational Culture	Safety Culture	∗Ignorance Of culture
		∗Inadequate safety plan
		∗Inadequate audit procedure
		∗Own requirement not complied with
		∗Inadequate peer assist and peer review
		∗Risk workshop not held
		∗Management too little involved during killing
		∗More vacation than normal during Christmas
		∗Sister organization were under-utilized
	Guiding Safety Principle	∗Little gratitude to coworkers
		∗Co-workers view not listened to
		∗Low reward culture for error discovery
		∗Risk form inadequately filled in
		∗Document neither signed nor dated
		∗Conflicting goals/standards
		∗Confusing directions
		∗Unclear what was expected
Design Error	Planning Error	Inadequate planning of challenging wellbore
	Equipment Design Error	∗Inadequate warning systems
		∗Inadequate devices
		∗Inadequate engineering design
	Labeling Error	∗Too many info-systems
		∗Misleading labeling
		∗Poor design of alarm system

Table 3
Selected relationships, new and existing ones, between observation and model-internal concepts.

Inadequate Training	leads to	Lack Of Competence
Lack Of Competence	causes sometimes	Slips and Lapses
Slips and Lapses	causes occasionally	Technical Error
Equipment Failure	is involved by	Inadequate Maintenance
Underbalanced Pressure	is implied by	Increased Mud Gas Level

results after activating the two equations are expressed in Table 4. The explanation strength of these 6 paths are pointing at Management Related Fatigue Factors with a strength of 2.07. The total explanation strength of all the 40 observations were 32.6, thus translating the explanation strength to 2.07/32.6 100 = 6.35% of all human related observations. This number is indicated with a circle in Fig. 15 in the next chapter.

4.3. Resulting causal pattern (set of paths)

The final results are presented in Fig. 15 and in Table 5. Fig. 15 presents the activated H & Org Error Indicators, while Table 5 presents the probable end-state (Failure) of all observations.

Resulting findings from our method do not differ much from the main findings of the other accident-investigations (Førsund, 2010; Solheim et al., 2010). Procedures and Organizational Culture would probably also be the main indicators through competing methods. However, we claim that the results obtained through our methodology enable an improved causal specification, revealed immediately after failures, due to these facts:

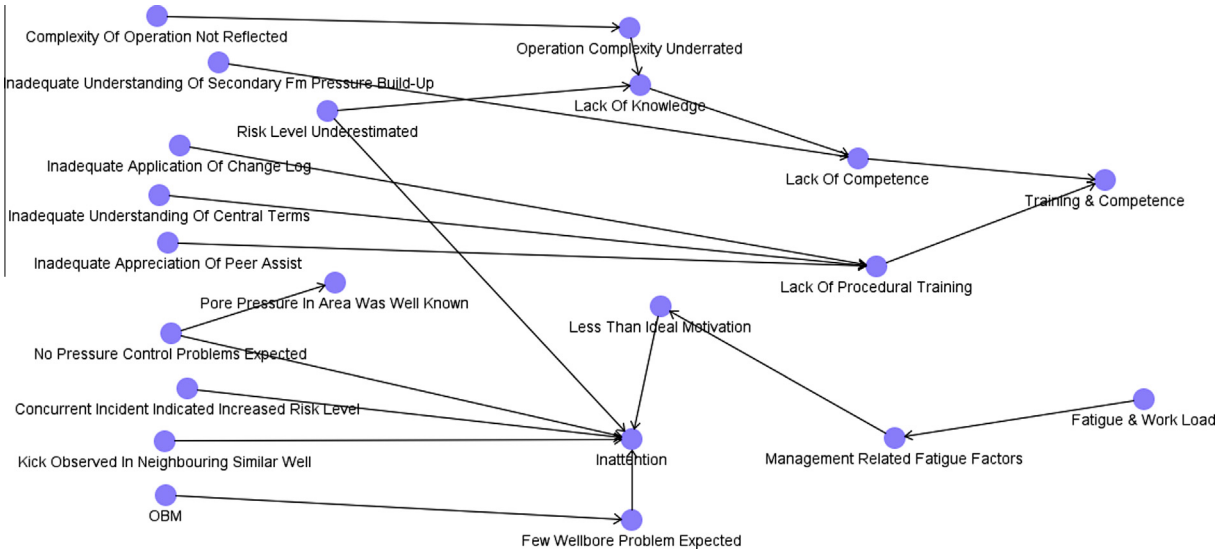

Fig. 12. H & Org Error Indicators: Cause-effect paths leading from observations (far left) to weak points in the organization (right). Of the totally 8 H & Org Error Indicators only two of them are examplified here. Only around 25% of all the 28 observations are therefore presented in this figure. Each arrow represents the relation 'has subclass'.

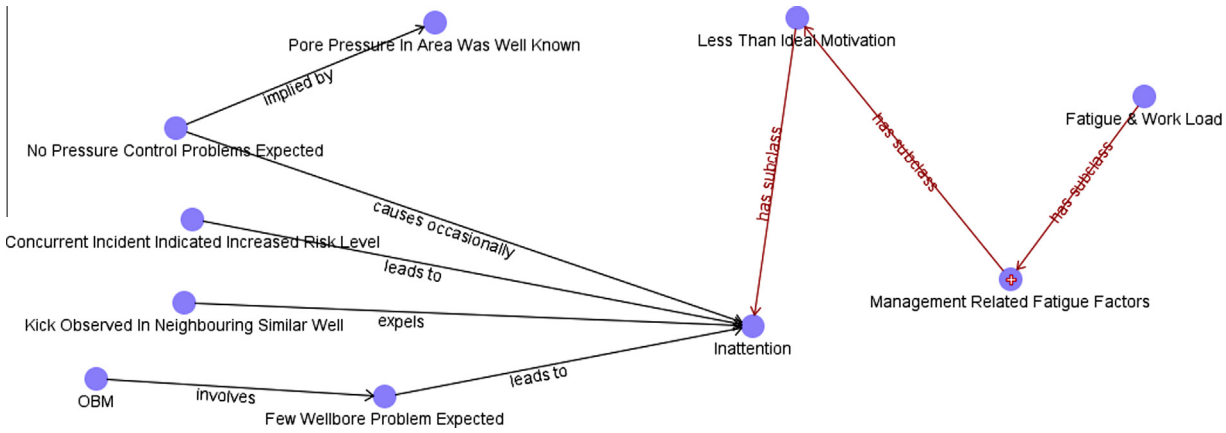

Fig. 13. A segment from the bottom part Fig. 12, is selected and presented here. Relation names are include (hsc in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- The findings are supported by two different types of observations; technical and human/organizational.
- The findings are supported by a sustainable person-independent knowledge model.

In the technical part Kick was pointed out as the obvious failure. The observations, exemplified in Fig. 14, points to no other failure than kick, besides of Lost Circulation. The analysis is therefore stepping one level back to find all the errors leading up to Kick on basis of all reported observations. This analysis of failures, based on 100% of the observations, is summarized in Table 5.

Stepping one level back in our knowledge model enables us to present the causes in a deeper causal view:

- Narrow Pressure Window has the highest explanation strength of all errors and is caused by charging formation through leaking annulus combined by lowered fracture pressure.
- Too Low Mud Weight is the triggering and the formal cause of the kick (leading to influx), and is mainly caused by Narrow Pressure Window and Technical Error.
- Technical Error is a general internal concept mainly pointed at by Human and Organizational Error Indicators. One important concept group which triggers Technical Error is the "Underestimation Of Risk Level". The low explanation strength of Technical Error is derived from long and thus weak explanation paths. An observation of this type, Pore Pressure In Area Was Well Known, is included in Table 4, where it obtains a path strength of only 0.05 due to its long path.

One important point with respect to technical failures is that all technical observations are available before the accident occurs. Thus failures have the potential of being revealed before the accident.

5. Discussion

The complete ontology is the catchment area for the observations of a new case; an observation can have a widespread implication. It is therefore two approaches which may improve the assessment of a case; the knowledge model must be improved (through more concepts and more detailed relationships) or a case must contain more observations. Future extensions could also include an advice-giving module for suggestion of remedies.

To be able to thoroughly evaluate the methodology, testing it on real-world operations is called for. As part of continued research we will be working with the company Verdande Technology to identify a suitable test site.

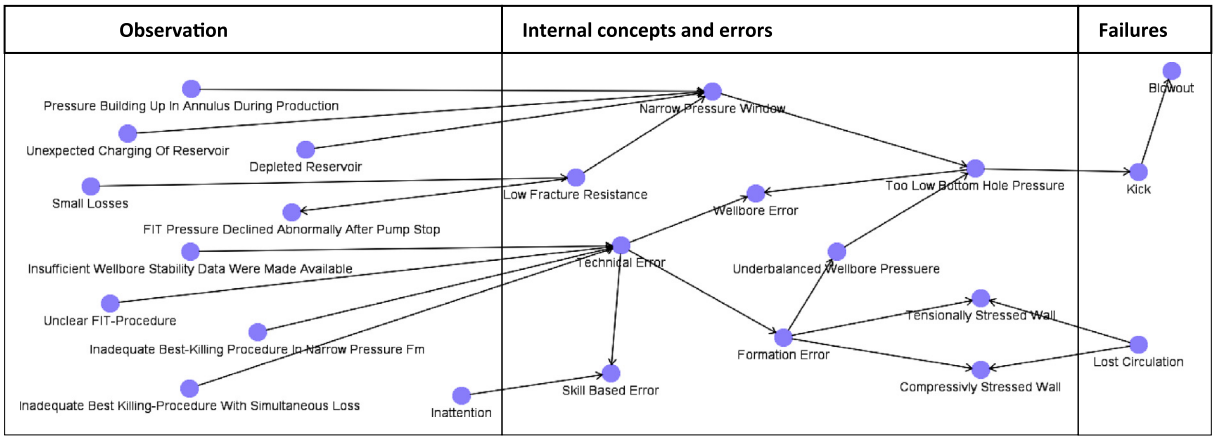

Fig. 14. Technical Errors: Cause-effect paths leading from observations (left) via internal concepts and technical errors (in the middle) to failures (to the far right). Like in Fig. 12, only a small part of the totally 29 technical observations were picked out to exemplify how failures are activated. Each arrow represents the relation 'has subclass'.

Table 4
The path strength from 6 observations in Fig. 13 which are triggering the indicator Management Related Fatigue Factor (is subclass of Fatigue and Work Load).

Observations	Involved relation strengths					Path strength	Triggered indicator
Pore pressure in area was well known	0.7	0.3	0.3	0.9	0.9	**0.05**	Management Related Fatigue F
No pressure control problems expected	0.3	0.9	0.9			**0.24**	Management Related Fatigue F
Concurrent incidents indicated increased risk level	0.8	0.9	0.9			**0.65**	Management Related Fatigue F
Kick observed in neighboring similar well	0.2	0.9	0.9			**0.16**	Management Related Fatigue F
OBM	0.5	0.8	0.9	0.9		**0.32**	Management Related Fatigue F
Few wellbore problems expected	0.8	0.9	0.9			**0.65**	Management Related Fatigue F
Resulting explanation strength						2.07	

Bold numbers represent the product of the involved relation strengths.

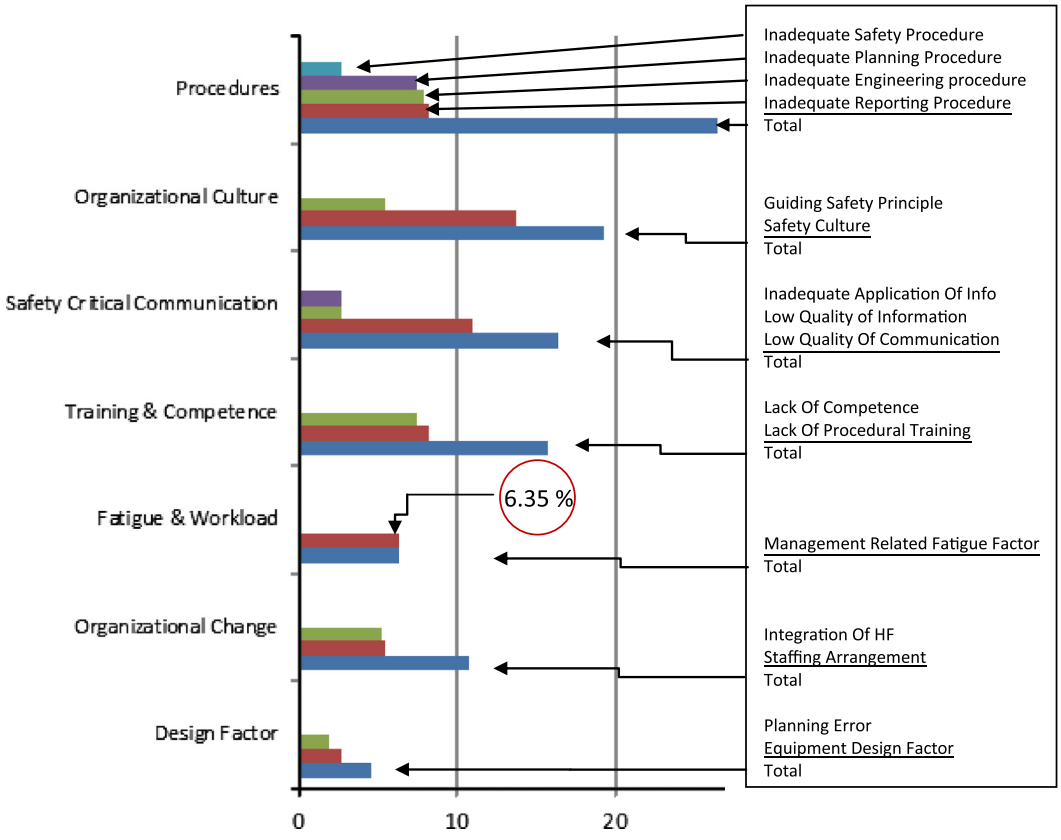

Fig. 15. The resulting explanatory strength of 7 (of totally 8) activated Human & Organizational Error Indicators.

Table 5
The four main errors and their explanation strength. H & Org errors are contributing through Technical Errors by around 12% of the total explanation strength.

Error	Failure	# of Observations	Explanation strength (%)
Narrow pressure window	Kick	12	51.6
Too low mud weight	Kick	38	34.7
Technical error	Kick	22	12.4
Formation error	Lost circulation	9	1.3
Total		57	100.0

The existing ontology enables one interesting extension of the method: The three distinctive human cognitive levels are; the skill, the rule and the knowledge based levels. Knowledge based performance is the highest of the three cognitive levels, while the skill based level represents the lowest level. However, the skill based level represents the fastest reaction pattern, especially when the skill level has reached a high level through proper training. It can be very motivating to distinguish between the three error types or error levels. Training can then be tailor-made for improving employees' performance during complex procedures, generated by new, emerging technology. Which cognitive level is the weakest will be indirectly revealed by applying the present methodology. This potential has not been focused in this paper.

Another potential application of the resulting findings is to improve the next upcoming drilling operation through re-planning. Another potent utilization of this method would be to install it on a continuous basis and continuously update the status of technical errors and H & Org Error Indicators. Thus the observations will be accumulating and thereafter turning the checking routine into a continuous prediction. The most probable latent errors can then be reported in real-time.

One important advantage of the present tool: Whenever a new accident occurs it may result in new concepts, new observations and new relationships. New knowledge is imbedded in the model and thus making it a tool which learns; it becomes upgraded by the most recent knowledge.

6. Conclusion

Technical and Human & Organizational Error have been modeled as an ontological hierarchy. The causes behind a failure were determined by identifying paths of relations from the observations to any potential errors, leading to the failures.

The tool was tested on one major accident during oil-well drilling operations. The test resulted in:

- The weakest Technical and Human & Organizational Indicator were revealed.
- The causes behind the indicators were revealed.
- The tool has the potential of predicting accidents before they occur.
- The tool is learning and upgrading itself while being used.

We need to include more cases and more observations to increase both the accuracy and the trustworthiness of the results. We plan to explore more of the tool's capabilities. Although accuracy is sacrificed for probability in the knowledge model, this could at the same time be the strength of the model: Complex mathematical expression can be expressed through logical, probabilistic relationships.

Acknowledgements

We would like to thank Tor Busch for many suggestions related to organizational behavior. Thanks also to the Petroleum Inspection Agency of Norway (PeTil) for searching up all relevant documents and information in their data bases, and to Verdande Technology for granting permission to use their knowledge editor. NTNU has been the sole funding body of the present research.

Appendix A

All the case observations related to technical information (totally 29 observations and to human & organization related information (totally 28 observations) are expressed on symbolic form, in chronological sequence of occurrence during the complete case (with explanatory case-specific comments).

Time	Case observations
Historical technical information	
1991	Poor bond behind casing (9.265″)
1991	Free path behind casing
2000	Water injection (in Shetland)
2000	Squeeze cementing (9.625″) (2009)
2004	Secondary Fm pressure effects
2005	Unexpected charging of reservoir (Shetland ->Lista, secondary pressurized fm)
2005	Pressure building up in annulus during production
2006	Blending off annular pressure regularly (from 2000 to 2009)
2006	Annular casing pressure leveled off
> Nov. 2009	*H & Org related deviations during planning* Pore pressure in area was well known No pressure control problems expected Conventional drilling method selected (no pressure control problems were expected) Unclear FIT-procedure Insufficient wellbore stability data were made available Inadequate best killing-practice in narrow pressure Fm Inadequate best killing-practice with simultaneous losses Insufficient risk evaluation of leak behind casing Insufficient communication of pressure build-up in Fm (Shetland Gp) Important risk info did not release proper attention Own requirement not complied with Risk coordinator not appointed Insufficient risk analysis Comparative analysis method not performed Complexity of operation not reflected Documents neither signed nor dated Risk form inadequately filled in Risk not formally documented Quality of DBR is person-dependent Specific experiences are spread (a challenge to gather) Experienced personnel not available during planning Risk workshops not held Sister organizations were under-utilized Change of planned drilling method (MPD -> Conv.) not reported Inadequate planning of challenging (narrow pressure window) Wellbore Inadequate compliance with steering documents Inadequate understanding of central terms (like DG and Well Verification Board) Inadequate appreciation of peer assist Inadequate peer assist and peer review Inadequate application of change log Deficient follow-up of planning
Nov. 2009	H & Org related deviations during drilling/accident Insufficient follow-up of low quality cement job More vacation than normal during Christmas Important info not reported Mud loss not reported Adding of light mud not reported (10 m^3) Insufficient understanding of secondary Fm pressure build-up Management too little involved during killing
Nov. 2009	Technical observations before the accident FIT declined abnormally after pump stop Depleted reservoir OBM ECD close to pore pressure Concurrent incidents indicated increased risk level
Dec. 2009	Technical observations immediately before the accident Increased mud gas content (to 18.4%)

(*continued on next page*)

Appendix A (*continued*)

Time	Case observations
	Three Cnx gas tops (reported from the interval 2469–2524 mMD) Gas tops originated from normal pressurized chalk layers Light mud mixed into mud pit (10 m^3) Small mud loss (from 2550 mMD) Mud gas content increased again (to 8%) (from 2563 to 2640 mMD) Decreased ECD(At the same time) Still high mud gas content Kick observed in neighboring similar wells
Dec. 2009	Technical observations during the accident Pumping did not reduce influx rate Well flowing at low rate (influx of 700 l during 15 min) Mud loss during killing Unable to kill well Killmudweight too low (1.68) Had to apply heavy kill pill (only a pill of 2.1 kg/l–12 m^3 could stabilize the well)

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