Monitoring major accident risk in offshore oil and gas activities by leading indicators

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Abstract: In recent years, there has been a growing awareness that major accident risks should be monitored using risk indicators. We distinguish between leading and lagging indicators. The reason is that major accidents are rare events and the underlying causes are often fragmented and difficult to measure. However, it is a demanding task to develop appropriate leading indicators, because accident theories are disputed both in research literature and by practitioners. This paper presents the results from a study of a major oil and gas company's risk management processes and its use of indicators related to offshore installations. The work is based on analyses of accident reports, a literature review and interviews with offshore installation managers and platform integrity personnel.

We revealed major differences in attitudes among significant decision makers in relation to the use of risk indicators, spanning from skepticism and no use to in depth registration and analysis. However, all the offshore installation managers addressed the importance of a holistic view on risk and safety. Based on our findings we have developed an indicator set consisting of 16 leading indicators, covering technical, operational and organizational factors influencing major accident risk on offshore installations.

Keywords: Leading indicators, major accident risk, RIF, indicator criteria

1. INTRODUCTION

Major accidents in the oil and gas industry are greatly feared. Events such as the capsizing of Alexander Kielland (1980), the Piper Alpha explosion (1988) and the Norne helicopter accident (1997) are close to the minds of people working in the industry on the Norwegian continental shelf. These kind of accidents are very rare and are often perceived to occur as a completely surprise (today the concept of black swans is often discussed). However, are these events unpredictable? Accident investigations often reveal that there have been misjudgments in the organization, implying that early warnings, cues and signs of something serious and critical for the safety margins have been neglected. These issues have been noticed for a long time [1], addressing need for systemic and holistic approaches to monitor and reflect upon the performance of the high risk systems run by the organizations. Quantitative Risk Analyses (QRAs) have been carried out, identifying and implementing barriers in accordance with High Reliability Organization theory [2-4]. A further development has been to identify risk indicators in order to monitor barriers' performances and thus the total risk level at the various facilities, see e.g. [5-8]. The research on risk indicators and provisions of promising sets of indicator systems has been substantial, based on its normative ideological sense of governance.

Traditionally, the oil and gas industry has focused on so-called *lagging indicators* for monitoring major accident risk. These indicators are reactive as they measure "after the fact"-information, such as number of reported accidents/incidents last month. Examples of such indicators are Total Recordable Incident Frequency (TRIF) and Lost – Time Incident Frequency (LTIF). For a long time it was assumed that such indicators could reflect an installation's major accident risk [9]. This is in line with Heinrich accident triangle (iceberg theory) introduced in 1931, where the main principle was to focus on reducing the minor injuries and incidents [10]. This theory has been rejected by many researchers, who conclude; *relying on personal injury statistics will not reduce the major accident risk* [11-14].

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Several major accidents have further validated this conclusion, for example the BP Texas City refinery disaster in 2005, the Longford refinery accident in 1998 and the Deepwater Horizon blow out in 2010. The organizations all had excellent safety records with regard to personnel injuries and lost–time incidents before the accidents [9, 15-17]. Thorsen [18] analyzed accident statistics from some of the world's largest oil and gas companies over the years 2008-2011. The aim was to find out if the companies with the lowest TRIF–values also had the lowest FAR–values. No correlation was found. The lagging indicators such as TRIF and LTIF do not predict major accident risk.

Major accidents are rare events and the underlying causes are often fragmented and difficult to measure. Thus there is a need to observe features that might be related to the "production" of major accidents. However, it is a demanding task to develop appropriate leading indicators, because accident theories (explanations and causal relations) are disputed both in the research literature and by practitioners. Furthermore, risk conceptualizations and risk modelling are also highly disputed [19-22], which adds another challenge into the understanding of the risk picture. Risk management based upon sets of leading risk indicators might provide valuable information about changes in risk levels and aid the process of implementing effective risk reducing measures. The major issue of the study presented in this article is: *Which leading indicators have a potential to predict major accident risk in the operational phase of offshore oil and gas installations?*

Potential to predict major accident risk is an important, though difficult concept that must be taken into consideration. It is evident that there is a need to look for indicators that can provide a valid picture of major accident risks at offshore oil and gas installations. We emphasize that our foundational issue upon risk is purely epistemic and we claim that risk has no ontology [23]. Thus, potential to predict influences the involved and responsible parties' uncertainties regarding major accidents. We restrict major accident events to events due to hydrocarbon leakages in the operational phase of an offshore installation.

Our study object was a major worldwide offshore operator company in the oil & gas industry that operates up- and downstream facilities. To monitor and trend the company's risk level, an installation specific indicator set have had our primary focus. It is assumed that the indicators are reviewed by the offshore installation managers (OIMs) on a regular basis. The purpose of the indicators is to restrict attention to the areas that are considered especially important to ensure safe operations, including major accident risk. Examples of existing indicators are: Serious Incident Frequency (SIF); Total Recordable Incident Frequency (TRIF); Number of hydrocarbon leaks (> 0,1 kg/s); Falling Object Frequency (FOF); and Number of hours backlog in maintenance on safety critical equipment (both preventive and corrective maintenance). In addition to the indicator sets, the Company has implemented verification activities, covering both technical and operational barriers, and a technical barrier panel for continuous monitoring and follow-up of the technical integrity. In this study, only the latter is covered, as the platform integrity personnel (PIPs) are responsible for the monitoring tool and they perform evaluations of the technical integrity based on information from several indicators. Our development of leading indicators is to be seen as a supplement to major lagging indicators and verification activities that an offshore oil and gas company needs in its safety management system.

2. THE RECOMMENDED SET OF LEADING INDICATORS

Below we present our recommended indicator set, which covers technical, operational and organizational risk influencing factors that are assumed to influence major accident risks. Monitoring major accident risk requires indicators directed at underlying causes and latent conditions, in order for decision-makers to act upon early warnings before a major accident occurs. The indicator set is presented in table 1.

The indicator set is based on information from interviews, analyses of accident reports and a study of the research literature. None of the identified indicators fully satisfy the criteria that an indicator should meet to fulfill the intention to provide information to predict major accident risk. This implies that they are to be assessed holistically, i.e. as part of the key personnel's (such as OIM and PIP) continued risk image assessment. It has also been a premise for the development of indicators to meet a criterion of being specific to the facility considered. In this concrete case the lagging indicators: Number of hydrocarbon leaks (> 0,1 kg/s); Serious Incident Frequency (SIF), are by the OIMs considered important for major accident risk and should be seen in close relation to the recommended set in table 1.

Table 1: Recommended indicator set

Risk influencing factor (RIF)	Leading indicators	Measurement frequency	Indicator type (org, op, tech)
Monitoring technical barriers	Number of hours backlog in maintenance on safety critical equipment (both PM and CM)	Monthly	Tech/op/org
	Number of failures on safety critical equipment during testing	Monthly	Tech/op
	Status/condition of technical barriers (Number of red traffic lights in the system for barrier control)	Quarterly	Tech
Planning of activities	Number of plans sent onshore for reassessment and improvement.	Quarterly	Org
	Total number of work permits in one specific area (process area)	Monthly	Op
	Total number of work permits for hot work class A and B	Monthly	Op
	Maximum number of simultaneous activities last month	Monthly	Op
Dispensations (DISP)	Number of dispensations on HC – systems	Monthly	Org
Follow-up of and closing of actions and findings	Number of open findings from barrier verifications	Quarterly	Org/tech
	Number of overdue actions in Synergi with respect to HC-leaks	Monthly	Org
Competence and training (offshore and onshore)	Average number of years of experience with the specific systems for personnel	Quarterly	Org
	Average number of years of experience on the specific installation for personnel	Quarterly	Org
	Fraction of operating personnel that have received system training last 3 months	Quarterly	Org
	Number of workers in each personnel category whose training/courses are overdue	Monthly	Org
	Turnover of personnel during last 6 months	6 monthly	Org
Information about risk	Number of SJA operating personnel have attended during last 3 months	Quarterly	Org

The recommended indicator set is developed for use at the offshore installation by management both in offshore and onshore organizations. We claim that the indicator set of 16 individual indicators represents a manageable task to enable daily reflections upon major accident risk. It was deemed important to select indicators that the users could consider relevant, important and meaningful. Having indicators with face-validity [24] is a prerequisite for continuous reflection and learning.

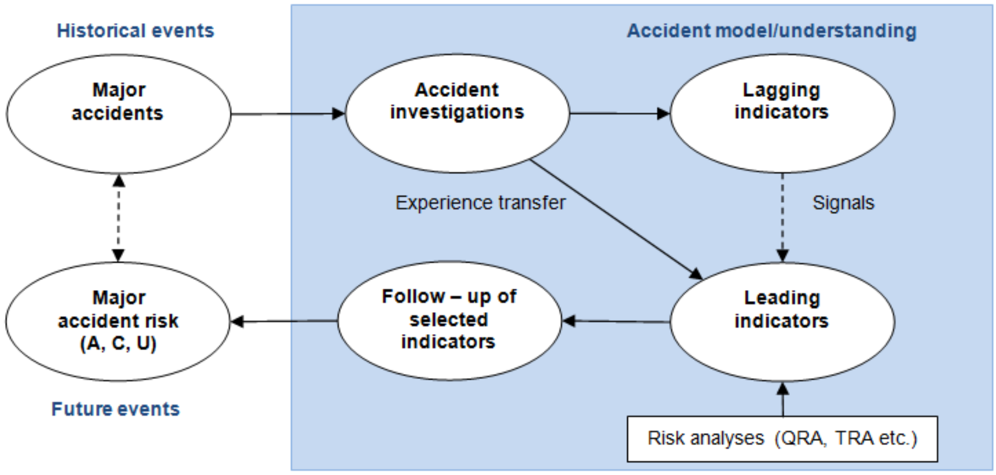
During the time of study we obtained an understanding of plausible measurement frequencies of the indicators, but this recommendation is to be understood as a preliminary guideline. Practical adaptations are necessary. However, since the majority of indicators are organizational it is a demanding task for responsible key personnel to assess, understand, recognize and react within the organization. Below we discuss the rationale for choosing these indicators and the relationships between the indicators and major accident risks.

3. THEORETICAL AND EMPIRICAL PREMISES

3.1 Relations between major accidents, risk influencing factors, indicators and risk – a model

Figure 1 illustrates the relations between major accidents, leading and lagging indicators and risk in a risk management perspective. Major accident risk is seen as a combination of events (A), the consequences (C) of these events, and the associated uncertainties (U) [25]. In line with this risk perspective, we define a risk indicator as "*a measurable quantity which may provide information about risk factors influencing major accident risk on an offshore installation*". Risk influencing factors are all conditions that either solely or in combination are assumed to influence the potential of a major accident occurrence. Often it is considered meaningful to categorize such conditions into technological, operational or organizational factors. Indicators are then the tools provided to operationalize the RIFs into a system for managing safety. They are observable. The status or condition of a RIF may be measured by the use of one or more indicators, depending on the complexity and nature of the factor [26]. Through the use of risk indicators, managers and decision-makers may increase their knowledge of important RIFs and hence reduce their uncertainty regarding future potential of major accidents. According to Hale [27], risk indicators have three main purposes: they monitor the level of safety in a system, provide the necessary information for decision-makers of where and how to act, and motivate action.

Figure 1: Relations between major accidents, RIF, indicators and risk



Investigations of historical accidents and precursors provide casual models of how accidents occur, which may provide valuable information of contributing and underlying causes, i.e. broken or defective barriers or RIFs. The knowledge of the casual chains, either derived from accident investigations or modeling of risk factors, may be used to establish indicators for the identified critical barriers, as seen in e.g. [5-7]. However, our understanding of accidents will affect what we look for in accident investigations and risk analysis, and thus what indicators we select for monitoring major accident risk. In addition, the quality of the risk analysis (completeness, level of detail, the goodness of models etc.) might restrict which RIFs to be identified. If the purpose of indicators is to increase our knowledge of major accident RIFs, lagging indicators might be important for prevention of new accidents by giving signals of where to place focus and guide the implementation of risk reducing measures. Hence, lagging indicators is a source of information for establishment and follow-up of leading indicators.

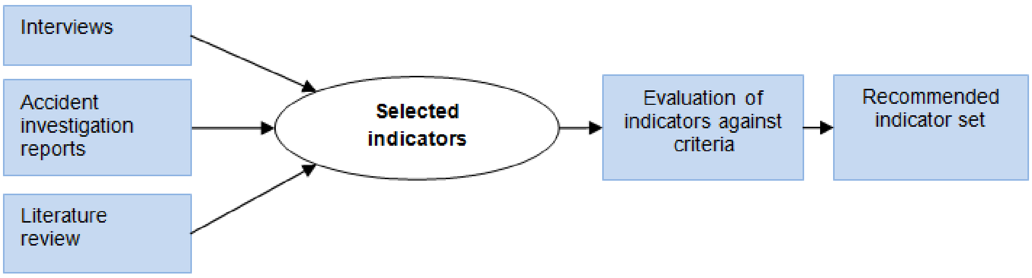
The process is to be seen as a learning process, based on the personnel's ability to assess the context, content of the system and organizational activities which they are committed to. Learning is understood as the personnel and organizations ability to change the systems, their ability to confirm and comprehend practices and activities at the offshore installations considered [28].

According to Kjellen [29] a leading indicator is "*an indicator that changes before the actual risk level has changed*". This implies that leading indicators may provide valuable information of changes in risk levels before the occurrence of a major accident. Thus, leading indicators are preferred over lagging, due to their proactive value. Focusing on leading indicators support a proactive approach to risk management, as the focus is placed on reporting performance of preventive measures, compared to performance in the sense of occurrence of incidents and near-misses [30]. Risk management based on indicators may be problematic in the sense that there might be too much focus and effort on improving the indicator value and too little attention on whether the measure actually contributes to reducing the risk in a sustainable way [31]. Indicators are inputs to the risk management and decision-making processes; they bring attention to specific risk factors and shadow others. The ultimate goal is to provide an efficient set of safety considerations that enable key safety personnel (or all involved) to critically reflect upon their risk images [32] at the installation and support dialectical debates of safety[33].

3.2 Criteria for analyzing and developing the set of indicators

A prerequisite for the study of indicators was to use investigations performed and key personnel in the case organization and combine the data gathered with other literature on risk influencing factors (RIF). Based on existing indicator sets, literature review and governing documentation in the organization, we selected a large set of potential indicators. In order to identify useful indicators, we assessed the indicators against five criteria that the indicators should meet in order to fulfill the intention to provide information to predict major accident risk. The study process is illustrated in figure 2.

Figure 2: Process for identification of indicators



A combination of indicators that covers all the criteria was sought in accordance with Herrera [31]. Based on a holistic view on risk indicators we assessed each indicator against the following criteria:

1. It must be possible to *observe* and *measure* the identified RIFs. We must be able to see whether the results represent a deviation from a norm or not [34]. Further, it must be possible to express the status of the indicator in a way that can be recorded and compared with previous and future results.

2. The indicator must be *reliable*. The data which the indicators are based on need to have a high degree of consistency and accuracy [35]. Having reliable data is a prerequisite for meaningful analyses and establishment of risk reducing measures. The indicators also need to give the same measurement/result when used by different people on the same situation [27].

3. *Sensitive to changes*: The indicator must allow for early warnings by identifying changes that have an impact on the major accident risk. Herrera [31] argues that this criterion is especially important as leading indicators should provide a clear indication of changes over a reasonable time.

4. The indicator must be *intuitive* and *meaningful*. The meaning of the indicator must be self-evident and the measurement must be assessed as important for the prevention of major accidents. The indicator must be comprehendible and easy to use in order to be effective.

5. The indicator must be *robust to manipulation.* The indicator must not allow the organization to "look good" by e.g. change the reporting routines, rather than making the necessary changes to reduce the major accident risk[30].

3.3 Interviews with key personnel

We interviewed key personnel (7 OIMs and 5 PIPs) to get insight into the practical use of risk indicators and how indicators fit into the context of managing major accident risks. Focusing on major accident risk in day-to-day operations seems to be challenging. One of the OIMs expressed: *"It's a tendency to focus on minor injuries, which might overshadow what we really are afraid of – the major accidents".* Another remarked: *"Operating personnel have inadequate understandings of major accidents".* The same challenge was also revealed in the interviews with the PIPs. One of them said: "*A major accident have a huge potential, but very low probability which makes it hard to keep focus".* However, several of the respondents claimed that there was much focus on avoiding major accidents in daily operations.

We found large variations between the interviewed OIMs regarding what indicators they perceived as important for monitoring major accident risk. About half of the OIMs highlighted the formally established indicators "SIF" and "number of HC-leaks", as these indicators are meant to measure serious accidents, incidents and near-misses, which was considered to hold major accident potential. Respondents had a clear understanding that these indicators were reactive, but it was stated that these indicators were important for implementing risk reducing measures. They were therefore considered to have a proactive value. On the other hand, some of the OIMs did not find any indicators suitable for monitoring major accident risk. It was stated that the statistical data was too limited for establishing reliable trends and it was deemed challenging to measure the effect of risk reducing measures. This specifically applied to the lagging indicators. However, it was stated that the indicator "Number of hours backlog on maintenance for safety critical equipment" could indicate weaknesses in the quality of technical barriers or a high workload. This could impact major accident risk.

Several of the OIMs pointed out that most of the established indicators were best suited for aggregation to company level, and that they were not applicable for their specific installation. The indicators were also used for benchmarking between installations and companies. This was considered to create a risk of overshadowing the installations specific risk factors. About half of the OIMs expressed that their focus on indicators in day-to-day operations was limited. Some quotes:

"*I feel that it's wrong to spend lots of time on indicators, as these will not make us better. What makes us better is to avoid accidents and this is not reflected in the indicators".*

"I strive to see which indicators that are related to major accident risk. I don't feel that TRIF and SIF are indicators that may provide information about major accident risk".

The PIPs had a different attitude towards the use of risk indicators. They are responsible for evaluation of the installations technical integrity, i.a. by collecting and analyzing information from several indicators. The majority of the PIPs addressed the importance of indicators, as several of the indicators measured important aspects of the safety critical systems and equipment. However, one of the PIPs explained that *"Indicators do not reflect major accident risk. The competence of the people assessing the indicators is much more important".* When evaluating the barrier status, the PIPs claimed that they reviewed a selection of indicators and verified the quality and reliability of the data input. Offshore personnel are responsible for registration of failures of safety critical equipment during testing, which is critical for the quality of the safety information system. Hence, the PIPs' installation specific knowledge and experience plays an important part in understanding the indicator values. In addition, they valued the importance of having a holistic approach, where they assessed the entire indicator set with respect to major accident risk. The PIPs highlighted indicators like "Number of failures on safety critical equipment", "Backlog of maintenance on safety critical equipment" and "Number of open findings from technical barrier verifications" as especially important for managing major accident risk.

The respondents were divided with respect to management of major accidents through the use of risk indicators. Most of the OIMs perceived indicators as being lagging or reactive, only measuring previous incidents and accidents. In the daily risk management the OIMs emphasized being proactive, ensuring safe execution of work operations through proper activity planning, both offshore and onshore, field management, and having highly competent and trained personnel. Focus on such factors, was considered to constitute the most vital part of the proactive safety work. However, this was generally not seen in the context of indicators. The indicator term was mainly used in the context of the performance management system, which does not cover the organizational and operational factors which the OIMs deem as important for managing major hazards. The PIPs also recognized the importance of organizational and operational factors, as technical barriers must be maintained and tested in order to function as intended. This requires manual intervention on safety critical systems.

3.4 Accident investigations

Njå [36] problematized the selection of incidents that are investigated. Before anyone is asked to investigate an accident, there must be an event recognized by someone and the event must enforce an action. It is a "blink and wink"-situation, where the blink represents the events occurring in the company. While the blinks continue to occur, the winks are the sudden considerations – "what happened" – and the time is stopped. One initial question is thus: When does a blink become a wink. Which criteria should govern the winks? In the company studied there was a formal system for launching accident investigations which could be assessed as a systematic approach to responding to events. However, there might be biases in the systems, which we did not further assess, but rather selected amongst available investigations in the company's safety information system (Synergi).

We selected 6 random accident investigations in Synergi, within the most serious classification level; incidents with leak rates above 1 kg/s. The purpose was to analyze and assess whether existing indicators in the company could have provided early warnings before the leaks occurred. Two of the accidents were investigated by the Petroleum Safety Authority (PSA). They found that both accidents could have resulted in major accidents under slightly different circumstances. However, the internal investigation reports argued that neither of the accidents was likely to escalate to a major accident due to a low ignition probability. The reason for this claim was that the technical barriers installed to prevent escalation functioned as intended. The indicators "Backlog in maintenance for safety critical equipment" and "Number of failures on safety critical equipment" had positive values; not much backlog in maintenance and few failures of safety critical equipment. This was seen as contributing to preventing leaks form escalating into major accidents

However, all investigations revealed that none of the existing indicators in the company could have captured changes in the risk level with respect to the causes of the accidents. The underlying causes were to a large degree linked to organizational and operational factors, which are not reflected in the company's indicator sets. A short summery of the common root causes are given in the following:

- *Inadequate activity planning* with respect to risk assessments, coordination, and the time set out to perform the work operations, both onshore and offshore. In two investigations, high activity level was seen as a probable contributing cause.
- *Competence and training* was highlighted as contributing causes in all investigations. To have personnel with adequate installation specific competence, combined with experience, both offshore and onshore, was deemed especially important. One investigation stated that the turnover rate had been high, both in the offshore and onshore organization, which might had affected the overall installation specific competence in the organization. Lack of training and non-compliance with internal competence requirements was also noted.
- *Lack of experience transfer* was found to be a contributing cause in several of the investigations. PSA claimed that the Company had not sufficiently ensured that information from previous accidents had been used as learning basis for continuous improvement.

4 THE RATIONALE BEHIND THE SELECTED SET OF INDICATORS

4.1 Evaluation process

Through the interviews we developed insights into decision-makers' understanding of major accident risk. We identified several organizational and operational risk influencing factors, which were not covered by the Company's set of existing indicators. The investigations supported these findings. Through the literature review we identified and analyzed a large number of indicators [5-9, 37-42]. All identified indicators were then evaluated against the criteria described in section 3.2. Few documents/papers discuss the reasoning behind the selection of criteria and we have not seen any papers from the indicator research discussing how the recommended indicators are assessed against any criteria. According to Herrera [31], indicators are often selected because they are simple rather than inherently meaningful. In total we ended up with 31 indicators for further assessment.

The criteria were weighted according to their perceived importance, as shown in table 2, on the basis of the literature review and interviews. The criteria "Sensitive to change" was assigned the highest weight, as it is crucial to have indicators that may provide early warnings about changes in the risk levels [30, 31].

Table 2: Indicator criteria with assigned weight

Nr.	Indicator criteria	Weight
1	Observable and measurable	1
2	Reliable	2
3	Sensitive to change	3
4	Intuitive and meaningful	2
5	Robust to manipulation	1

All indicators were assigned a grade based on how they were considered to meet the various criteria. A letter grading system from B-F was chosen, with corresponding numerical values (B=3, C=2, D=1, E= -1 and F= -3). Grade B implies that the indicator is judged to satisfy the criteria, while F implies that the indicator is highly incongruent with the criteria. This approach was adapted from various assessment systems within the company in order to reflect their view. However, our concern was a generic approach for assessing the indicators' congruence with the intention of the criteria. Appendix A provides the total score for all identified indicators

4.2 Results

Of the 31 indicators included in the sample, our analysis gave 16 leading indicators covering technical, organizational and operational factors. The selection was based on the total score of each indicator, in addition to a subjective assessment to reduce the size of the indicator set, in order to have a manageable set. Initially, all indicators with a total score less than 10 were excluded. Several of these indicators could have provided information of the organization's ability to manage and understand the risk of major accidents (e.g. nr. 26, 29 and 30 in Appendix A) However, it is challenging to obtain reliable measurements. Some of the indicators had a total score above 10, but were excluded as they were assessed to have limited additional value in relation to the RIFs.

The RIFs that govern the set of indicators all implies that the organization deviates from norms, artifacts, assumptions deemed important. Below we argue for the rationale behind each indicator as a subset of the RIF category.

Monitoring technical barriers. The indicator *"Number of hours backlog in maintenance for safety critical equipment"* was considered to be an important leading indicator by the respondents. The same was found for the indicator "*Number of failures on safety critical equipment during testing*". Poor or inadequate maintenance is often found to be a contributing cause to major accidents [43]. It is important to have a continuous focus on maintenance activities, as backlog in maintenance increases the risk of systems and equipment not functioning as intended. If this indicator shows a negative trend it implies a need to increase the maintenance activity. *"Number of failures on safety critical equipment* *during testing"* also provides early warnings. Further analysis of the indicator and test result are needed in order to identify proper actions. The test results may indicate weaknesses in the maintenance strategy, possible design weaknesses, incorrect use of components or equipment, or a need to adjust the test intervals. The status and condition of the individual barriers provides valuable information addressing need for follow-up actions. In the research literature, a more detailed follow-up of backlog and testing of particular equipment is suggested, e.g. for safety instrumented systems and alarms [39, 40]. This responsibility is assumed to lie within the platform integrity unit as part of the technical barrier panel.

Planning of activities. A high activity level may increase uncertainty with respect to the occurrence of accidents, and especially during simultaneous activities [37]. *Number of work permits* may reflect the activity level on the installation and thereby provide information about the risk level. The OIMs highlighted the Work Permit system (WP) and the interaction with the onshore organization as particularly important for managing major accidents. They were concerned with having control of number of WPs and types of WPs, and ensuring that all activities were based on risk assessments and that they were understood by the operating personnel. A challenge was revealed, regarding the interaction with the onshore organization. The onshore organization is responsible for the operations plan, and shall ensure that all plans are risk assessed and hold high quality before they are sent offshore. Several OIMs claimed that the operations plans often were inadequate, with lack of quality and risk assessments, which they considered to increase the risk of accidents.

Indicators related to activity level are frequently suggested in research literature, e.g. [6, 37, 40, 44]. Amongst our four recommended activity indicators one contain interaction with the onshore organization. If the indicator "*Number of plans sent onshore for reassessment and improvement"* is increasing this might indicate a risk of e.g. critical maintenance activities being postponed. In addition, it can provide insight into the organizations quality assessment and management processes.

Dispensations (DISP). Several OIMs addressed the importance of keeping control of number of dispensations (DISP). We have included the indicator *"Number of dispensations on HC – systems"*, as this may indicate a risk of major accidents due to non-compliance with regulatory requirements with respect to a highly critical system. In addition, all approved DISPs requires implementation of compensating arrangements. Some OIMs highlighted a challenge with maintaining adequate overview of all arrangements, especially with respect to the operational ones. A negative development of this indicator may thus provide early warning and indicate a need for deeper analysis to see how the DISPs and arrangements affect the major accident risk level.

Follow-up of and closing of actions and findings. A high number of overdue actions/risk reducing measures might increase the risk of major accidents and also reduce the performance of consequence reducing barriers [44]. The indicator *"Number of open findings from technical barrier verification"* might indicate weaknesses in the technical barriers, as long as the findings are not closed. The PIPs are responsible for closing findings. Through the interviews the PIPs complained about their ability to close findings due to the sheer volume of these. In one of the investigations it was highlighted that lack of resources within Platform Integrity created a situation where they did not have time to implement measures, in addition to evaluation and follow-up the technical barriers. We have also included the indicator *"Number of overdue actions in Synergi with respect to hydrocarbon leaks*". For this indicator to be useful, the actions effect on the major accident risk must be analyzed and understood. The safety information system must allow for a categorization of severity level for the actions, in order to extract the data.

Competence and training. We selected five indicators covering several aspects of this RIF. In the research literature, indicators related to competence and training is frequently suggested, e.g. [7, 8, 37, 42]. The formal competence of personnel and/or experience from similar operations affects the ability to perform the work operations with high standards and in accordance with procedures and requirements. Competence and experience also plays an important part with respect to identification of potential danger/risk at an offshore installation [45]. All investigations highlighted the importance of having installation specific competence and experience, as knowledge of components, systems, barriers etc. is assumed to be better for personnel with more experience. The indicator *"Number of workers in each personnel category whose training/courses are overdue"* is assumed to reflect how updated the competence is for e.g. operators. However, training/courses needs to be specified with defined deadlines and the quality of the training will be an important aspect. The indicators should also cover the competence onshore, e.g. the competence of PIPs who are responsible for evaluating the status of technical barriers. In addition, the indicators should be divided for the different personnel group, e.g. operators, maintenance crew, inspection crew etc. *Turnover of personnel* was identified in the investigations as an important aspect to control, as high degree of turnover may increase the risk associated with inadequate experience and system specific competence.

Risk perception/Understanding. According to the OIMs, offshore personnel have a diverse understanding of the installation specific risks, especially major accident risk. It is not straight forward to establish indicators measuring this RIF. Risk perception is a diffuse concept and difficult to measure directly. According to Øien et al. [37], understanding of risk may be enhanced through basic knowledge of the risk concept and through specific knowledge of installation specific risks found in e.g. the TRA. They suggest the use of indicators measuring the proportion of personnel taking risk courses, proportion who are informed about risk analyses and attendance at SJA-meetings. However, the quality and content of the training/courses that is offered will also affect how this can contribute to increased risk understanding [46, 47]. We have selected the indicator *"Number of SJA operating personnel have attended during last month"* as increased attendance at SJA meetings is assumed to increase competence among offshore personnel regarding safety critical operations and associated risk factors.

5. DISCUSSION

We fully agree with the OIMs who claimed that their major aim was to obtain a holistic understanding of the safety level at the installation, in which major accident risk was included. However this must be more than gut feelings. We recognize that expert knowledge is characterized by an expert who generally knows what needs to be done based on mature and practiced understanding. An expert's skill has become so much a part of him that he needs to be more aware of it than he/she is of his/her own body. When things are proceeding normally at the installation, experts do not solve problems and do not make decisions, they do what normally works. While most expert performance is ongoing and non-reflective, when time permits and outcomes are crucial, an expert will deliberate before acting [48]. However the complex systems that make up offshore installations require more than individual expertise, and there is a need to specify concerns important for hazards developing into major accidents. Leading indicators is part of the risk image process, and we propose some important features for the set of indicators addressing comprehensiveness, applicability and manageability in the oil and gas industry:

- The indicators must all together be representative for and cover the major risks the oil and gas industry wants to be protected against.
- The indicators must be sufficiently detailed so that the variety and range of concerns are illustrated. It is important that the indicators provide information on how a situation or accident can develop in many directions, and that it is possible for the safety and emergency preparedness system and the personnel to influence on the development.
- The indicators must be realistic. Realistic could refer to logical and reasonable sequences of events that might occur.
- The indicators must be simple and easy to understand. A complicated indicator may lead to unnecessary disputes and may require that much time and many resources must be used to explain and discuss the indicators.
- The indicators should be logically consistent, in a way that it is possible to pinpoint connections between the indicator and characteristics of accident scenarios.

- The indicators must be dynamic and easy to change so that experiences from accidents or from training and exercises can be added and visualized. Such experience transfer is important for the organization in order to learn from own and others experiences.

The concept of leading and lagging indicators is disputed among researchers and practitioners. There are no agreed definitions of what "lead" and what "lag" are, and where along the casual chain one should make a distinction. Hopkins [49, 50] argues that the distinction is not fruitful, while Dyreborg [51] and Hale [27] claim that it has implications for organizational learning and that the distinction is essential when the indicators purpose is to provide information of where and how to act. The evaluation of all identified indicators clearly demonstrates that no single indicator can give adequate information about changes in the risk level with respect to major accidents. Therefore, one needs to look at the total indicator set to determine if changes in a single indicator are critical to the total major accident risk. If the lagging indicators show a negative trend, the leading indicators need to be analyzed and evaluated in order to see if these indicators have captured the changes. Such experience transfer may result in an alteration of the recommended indicator set. In addition, the indicator set might provide information about the quality of the management and organization, through the ability of planning work operations and activities, follow up of competence level and follow-up and closure of actions and finding. Lord Cullen's [52] report on Piper Alpha noted that the system was comprised of degraded systems with numerous indications of major accident risk. Without key personnel's attention, recognition and action prone behavior, major accident risk indicators might be dangerous[53].

OIMs claimed that consciousness about major accident risk in the day-to-day operations was challenging. Maintaining motivation and awareness that the indicators predict changes to the risk level is crucial [30]. Most hydrocarbon leaks occurring in offshore environments have been found to have operational and organizational causes [54]. The company's existing indicators were to a large degree lagging and we revealed a gap between the company's established indicator set and the actual causes of the investigated accidents. Further, several of the OIMs expressed a negative attitude towards risk indicators and misconceptions regarding the purpose of indicators. Hale [27] claims that indicators should motivate action. Hence the indicators must communicate this significance to key personnel. Our indicator set has been developed to reflect underlying factors and latent conditions that key personnel found to be important. We observed a general lack of trust amongst the OIMs regarding whether indicators might contribute to increased understanding of major accident risk. There seems to be a lack of understanding of the proactive and predicative value of indicators, especially with respect to measuring organizational and operational risk factors. This aspect of risk indicators needs to be communicated and utilized in the daily risk management process.

6. CONCLUSION

Through our study of major risk indicators we have found a comprehensive research literature that provides numerous suggestions about what indicators to use. The vast amount of normative well intended indicator sets stands in contrast to the practical approaches used by key personnel responsible for safety on the offshore installations.

Our recommended set of leading indicators have been developed on the basis of a literature review, existing systems in an offshore oil and gas operator company, six of its accident investigation reports and interviews with key personnel. Comprehensiveness, applicability and manageability formed basic prerequisites in our work. However, we do not think that there exists a universal set of indicators. We also think that our research needs to be challenged. We conclude that the need for further development and understanding of the use of leading indicators for monitoring the risk level on an offshore installation is important.

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Appendix A: Evaluation of identified indicators

Nr.	Identified indicators	Indicator criteria 1	2	3	4	5	Total score
1[*]	Number of hours backlog in maintenance for safety critical equipment (both PM and CM)	B	B	B	C	B	25
2[*]	Number of failures on safety critical equipment during testing	B	C	B	C	C	22
3	Total number of WPs in a specific area (process area)	B	C	D	C	C	16
4	Total number of WPs for hot work class A and B	B	C	D	C	C	16
5	Total number of WPs on HC-systems	B	C	D	C	C	16
6	Total number of WPs	B	C	D	C	C	16
7	Average number of years of experience with the specific system for personnel	C	D	C	C	D	15
8	Average number of years of experience on the specific installation for personnel	B	C	D	D	B	15
9	Maximum number of simultaneous activities in one specific area	C	C	D	C	C	15
10	Fraction of operating personnel that have received system training last 3 months	C	C	D	C	C	15
11[*]	Status/condition of technical barriers (E.g. Number of red traffic lights in the system for barrier control)	B	D	D	C	D	13
12[*]	Number of open findings from barrier verifications	B	C	D	D	D	13
13	Number of workers in each personnel category whose training/courses are overdue	C	C	D	D	C	13
14	Total number of dispensations on HC-systems	C	D	D	C	C	13
15	Number of plans sent onshore for reassessment and improvement.	C	D	D	C	D	12
16	Number of near-misses with major accident potential	C	D	D	D	D	12
17	Number of WPs approved outside of WP - meetings	C	D	D	C	D	12
18	Number of SJA operating personnel have attended during last 3 months	C	D	D	D	C	11
19	Turnover of personnel last 6 months	B	B	E	D	B	11
20	Number of overdue actions in Synergi with respect to HC-leaks	B	C	E	C	C	10
21	Number of dispensations exceeding design	C	D	D	D	D	10
22	Fraction of relevant personnel with formal training in use of SJA	B	C	E	C	C	10
23	Number of dispensations that are overdue	C	C	E	D	C	8
24[†]	Number of HC-leaks (<0,1kg/s)	B	C	E	D	C	8
25	Number of implemented operational arrangements to maintain approved dispensations.	D	D	E	C	D	5
26	Portion of operating personnel taking risk courses last 12 months	D	D	E	D	C	4
27[†]	Falling Object Frequency (FOF)	B	C	E	E	C	4
28[†]	Serious Incident Frequency (SIF)	B	C	E	E	C	4
29	Portion of operating personnel informed about risk analysis last 3 months	D	D	E	D	D	3
30	Number of reviews of major accidents/near misses on other installations/facilities (experience transfer)	E	E	E	C	D	-1
31	Number of cases of inadequate decision support from onshore last 3 months	E	E	E	E	E	-9

[†] Indicators highlighted by the OIMs and PIPs