SAFETY SCIENCE Monitor

Issue 2 2013 ISSN 1443-8844 VOL 17

Article 2

PROACTIVE INDICATORS TO CONTROL RISKS IN OPERATIONS OF OIL AND GAS FIELDS

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ABSTRACT

Due to increased need for oil and gas, new and more demanding oil fields must be explored in sensitive and challenging areas. Exploration of expert knowledge and new technology must be employed in these challenging situations. This collaboration and use of new technology introduces new ways of operating oil and gas fields. These new practices are often called “field of the future” or “integrated operations” (IO). These new practices are being implemented on the Norwegian continental shelf, leading to increased hydrocarbon recovery and changes in operations and maintenance. These practices may impact health, safety and environment (HSE), but should not increase the risks of major accidents or influence HSE in a negative manner.

In this paper we are suggesting a set of proactive indicators to ensure that risks are controlled when IO is implemented and operated. A proactive indicator is used as a measure of risk, to be controlled in risk management. The indicators have been developed based on analysis of accidents, exploration of theory, interviews and discussions in collaboration with the oil and gas industry.

Our suggested approach is to develop and explore indicators in close collaboration between key stakeholders to increase understanding and control of the relevant risks. Resilience and successful recoveries are not sufficiently explored in the accident reports that has been reviewed, thus accident investigations should include reflections on reasons of successful recoveries and why the incident or accident did not have worse consequences.

The three most important causal factors of incidents seem to be poor design and poor validation of equipment, poor risk analysis of critical operations and deviations from established procedures. A causal factor important in remote operations is miscommunication between actors during critical operations. Several proactive indicators are suggested, among them the level of exploration of safety cases during design and risk perception among stakeholders involved in operations. Important indicators in remote operations are suggested to be the assessment of shared communication and shared risk perceptions when critical tasks are distributed.

To validate the indicators, we are correlating the indicators with actual HSE levels. In addition the indicators should be correlated to indirect measures such as safety culture and risk perceptions where appropriate.

1. INTRODUCTION

This paper consists of five main sections:

- This first section is an introduction to oil and gas production and the need for proactive indicators
- The second section gives a description of our approach, the research design with relevant theory, how empirical results have been gathered and how we have identified indicators based on discussions of causal chains.

- The third section describes the results from interviews and survey of accident reports, and describes the main causal factors and suggests proactive indicators.
- The fourth section gives a discussion of the results and answers the research questions. In addition we have compared the indicators with HSE levels at installations using IO in their operation.
- The fifth section summarizes the conclusion and suggests future work.

The use and consumption of oil, gas and petrochemicals has been increasing in the last decades, and the demand in the future is supposed to increase, as described by EIA (2010). Existing fields are being depleted due to the demand, and several strategies to improve oil and gas production are explored by the industry, such as extracting more oil and gas from existing fields, or exploring more complex and challenging fields as described in Holditch (2008). Examples of complex and challenging fields are fields under deep water, deep wells, fields having high pressure and/or high temperature, fields with difficult conditions in the well or fields in vulnerable areas such as in the arctic. To extract more oil from existing fields or produce oil from challenging fields there is a need to explore new technology, improve knowledge and explore knowledge through collaboration between different centres of expertise. Thus complexity in technology and organisation is increasing in oil production.

The exploration of knowledge through information and communication technology, ICT, has been seen as one enabler to extract more oil or improve production. In the Norwegian oil and gas industry, this area of focus has been called integrated operations (IO). IO has been described in a white paper, Stortingsmelding 38 (2004), as ”*use of information and communication technology to change work processes, to improve decisions, to enable remote operations of equipment and processes and to move functions and people onshore.*” Information and communication technology are integrated with the process control systems used in production, and the systems are distributed between onshore and offshore. Exploration and deployment of new technologies such as IO are also prioritized in the future as described in OED (2010). The main motivations for these new practices are increased income from the fields, operational cost reduction and increased safety. The benefits of IO in the period from 2005 to 2015, on the Norwegian Continental Shelf, has been estimated to be in the order of 52 000 Mill USD, by the industry association OLF (2005). However, the benefits of IO are difficult to quantify but the exploration of technology is expected to increase oil recovery significantly, as discussed in OED (2010).

Safety is defined as: *“freedom from unacceptable risks”*, from ISO (1999). Risk has been defined as *“Combination of the probability of occurrences of harm and the severity of that harm”*, from ISO (1999).

The operating organization is changing; IO enables better utilization of expertise independent of geographical location, leading to functions and staff being moved onshore and subsequent increased interaction with experts placed onshore. Tasks in operations and maintenance have been outsourced to vendors outside the company and this trend is likely to increase. A virtual organization (VO) are thus established, i.e. “*a temporary or permanent coalition of geographically dispersed individuals, groups or organizational units that pool resources, capabilities and information to achieve common objectives”*, from (Grabowski 1998). In figure-1 we have illustrated the new organizational network in IO as defined by the oil and gas industry association (OLF), see OLF (2004), by showing some of the key actors, such as control rooms offshore, onshore operation centres and external experts in a remote collaboration room. These key actors are collaborating to plan and perform necessary operations.

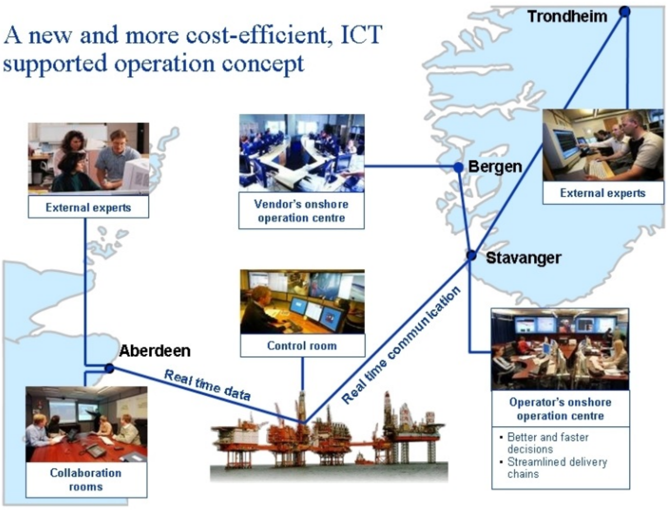

Figure-1: Key actors involved in IO, from OLF (2004).

The implementation of IO is done both by remote support and remote operations. During remote support, offshore is supported by onshore via systems such as video-conferencing. The support from onshore has been focused on production optimization to increase yield from the fields; increased focus on planning; focus on improved maintenance and planning and support of critical operations. Remote operations are actual operations performed remotely from nearby platforms or from onshore installations. There may be a need for remote operations when expert must be involved, when handling special equipment, sharing high workload, handling unwanted incidents, handling equipment when there is no manning or perform special operation during emergencies such as when there is bad weather or other issues. Remote support or remote operations performed internally, by vendors or by external experts are increasing and may be explored to avoid delays, reduce offshore travels or to avoid risks. The level of actual remote operations is minor at present. However, fields with lower production and lower profitability are increasing - due to tail end production. In these marginal fields, remote operations may be used to decrease costs and increase safety. This may lead to increased remote operations of manned platforms during night-time or during normal operations. Health, safety and environment (HSE) must be sustained or improved when remote support or remote operation is implemented. A key issue is to identify risks and uncertainties prior to serious incidents. There is a need for a constant sense of uneasiness, looking ahead to what may happen of unwanted incidents, unwanted combinations of incidents and events or normal variability outside the expected planning envelope, such as described by Weick and Sutcliffe (2001).

Major accidents may happen when oil and gas exploration are done during demanding conditions pushing the boundaries of acceptable performance, as described by Rasmussen (1997), as an example by having to explore fields at great depths or at high pressure, The consequences of an accident could be catastrophic, as seen by the Deepwater Horizon accident, described in NC (2010), with 11 deaths and with an oil-spill of 5 million barrels (800 Million litres) of oil in sensitive areas during 89 days. The causes of the Deepwater Horizon are an area of exploration and discussion, but in NC (2010) the causes are described as systemic. The description of the accidents describes a complex setting with several organisational, technical and human factors issues as causes. The concept of the cause of an event (i.e. an accident) is complex, and may be subject to subjectivity and oversimplification. In the following we have used a definition of the cause of an event from Leveson (1995), p43, “a cause of an event is composed of a set of conditions, each of which is necessary and which together are sufficient for the event to occur.” To prevent future accidents, accident analysis must be carried out on multiple hierarchical levels, in Lewycky (1987) there is suggested an organization of causality in three levels, as described below. This description has been extended to incorporate recovery or avoidance of accidents:

- Level 1: The chain of events - the mechanism of the accident (or the mechanism of recovery or avoidance of accidents).
- Level 2: The conditions or lack of conditions that allowed the events at the first level to occur (this could be barriers).
- Level 3: The constraints or lack of constraints that allowed the conditions at the second level to cause the events at the first level – such as technical conditions, social dynamics, human actions, management systems, organizational culture or governmental or socioeconomic policies and conditions. This could be defined as root causes.

Unwanted incidents may be avoided by learning from accidents from the process industry, such as the Esso gas plant explosion at Longford in 1998, see Dawson (1999), or the BP America Refinery Explosion at Texas City in 2005, see Baker et al (2007). The examples are relevant in our context since the examples are from the oil and gas industry, involving suppliers and collaboration in a network. Relevant issues from Esso, see Dawson (1999), are related to missing risk analysis and risk identification (such as Hazard and Operability Analysis - HAZOP) and missing collaboration between organizational levels: *“The failure to conduct the HAZOP study …. and the reduction of supervision at Longford, including the transfers of engineers to Melbourne … may have been a contributing factor to the explosion..”* from Dawson (1999).

A relevant result from BP in Baker et al (2007), are: *“BP should develop, implement, maintain, and periodically update an integrated set of leading and lagging performance indicators for more effectively monitoring the process safety performance of the U.S. refineries”.*

The above recommendations are related to risk analysis, risk identification and situational awareness, risk monitoring trough indicators, risk communication and collaboration in a distributed organization. We have focused on these issues in the next section. However, one important bias related to the interpretation of the accidents at Esso and BP has been the accident models used in the analysis. The accident analysis are influenced by the perspectives that are chosen, as described by Lundberg (2009), i.e. “What-You-Look-For-Is-What-You-Find”, and to avoid bias it is important to explore different perspectives. In addition the causal analyses are constructed and may be subject to bias. We have in this paper focused both on complex linear models and complex non-linear systems, where safety could be an emergent property. In such a complex setting with a great degree of variability of human performance and major consequences of an incident, the ability to be resilient is important. Resilience is defined in Hollnagel (2006) as – "*the ability of a system or an organization to react to and recover from disturbances at an early stage, with minimal effect on the dynamic stability*." We are focusing on risk identification at an early stage - trying to identify indicators to react to disturbances prior to an incident and become resilient – such indicators are called proactive indicators in this paper.

To reduce the probability of release of unwanted energy, e.g. from ignition of gas or oil, we are using the concept of barriers, since barriers inhibit release or spread of energy. We are using the barrier definition from ISO 17776 (2000), where barrier is defined as a: "*measure which reduces the probability of realizing a hazards potential for harm and reducing its consequence. Barriers may be physical or non physical (procedures, inspection, training or drill)*". The energy and barrier perspective from Haddon (1980) is important, together with the "Swiss Cheese" model from Reason (1997). The "Swiss cheese model" is trying to illustrate that major accidents are usually not caused by a single isolated failure but are caused by several defensive barriers that are not intact, causing penetration. The "Swiss cheese model" is a good mental model, where the defences (barriers) can aid us to identify possible proactive indicators. To identify an indicator we have to identify the major risks related to energy release in IO, then based on these risks we have to identify proactive barriers, and subsequent indicators to reduce the probability of energy release.

Our definition of indicator is a direct or indirect measure such as: "*a number (or ratio) derived from a series of observed facts; can reveal relative changes as a function of time*" from WordNet (2009). BP is using the term leading/lagging indicator. The definition of leading vs. a lagging indicator is difficult. If an indicator is used as a measure of the quality of a barrier, the definition may be imprecise. A barrier could be used both to reduce the probability of an incident (leading) and to reduce the consequences of an incident (lagging). In Hopkins (2007) it is pointed out that a clear definition of a leading indicator is difficult, it is suggested to choose safety indicators to measure the effectiveness of the controls upon which the risk control system relies. In this article we are not necessarily focusing on barriers but trying to avoid accidents by early warnings. A definition of a proactive indicator could be "*indicate the performance of the key work processes, culture and behaviour, or the working of protective barriers between hazards and harms, that are believed to control unwanted outcomes*." from Dyreborg (2009). We would like to use a proactive indicator as a measure of a risk-influencing factor related to processes, culture and behaviour, believed to influence or control unwanted outcomes. In table 1, we have tried to structure the mechanisms in an incident from a working process, releasing a threat that can release a hazard becoming an unwanted event (accident) leading to consequences. The indicators of interest have been indicators of conditions or constraint prior to an unwanted incident as listed in table-1. The conditions to be explored to identify indicators are closeness to performance boundaries during a working process, as described by Rasmussen (1997) and indicators of prevention or indicators of state of preventive barriers. Indicators of constraints have been related to technical conditions, management systems, organizational culture or policies.

Table 1: Indicators of performance that are believed to control unwanted outcomes

Mechanisms	**Working process with threats.**	**Prevention, preventive barriers, halting threats.**	**Unwanted event, release of hazard, Accident.**	**Recovery, containment barriers.**	**Consequences, harm.**
Indicators related to	**Working processes**	**Prevention, preventive barriers**	**Unwanted events**	**Recovery, containment barriers**	**Consequences.**
Conditions	*Indicator of closeness to performance boundaries.*	*Indicators of prevention; Indicators of state of preventive barriers.*	*Indicator of unwanted events.*	*Indicator of state of containment barriers-*	*Indicators of harm; consequences.*
Constraints	*Indicators of technical conditions, management systems, organizational culture, policies.*				

The context of our use of proactive indicators is Integrated Operations and we want to control and avoid consequences such as major accidents or health, safety or environmental (HSE) incidents. Indicators can impact behaviour, attitude or structure in order to impact constraints such as process factors (attitudes and beliefs or social norms, such as safety culture) and risk factors (behaviour and physical and organizational environment) as described in Lund (2004), ref figure 4. We added the proposed impact of indicators in the figure, to indicate the effect of the indicator as a mechanism to modify attitudes, behaviour or structure. Based on Lund (2004), it seems that structural modifications impacts safety and that various preventive measures are used in combination are probably more effective.

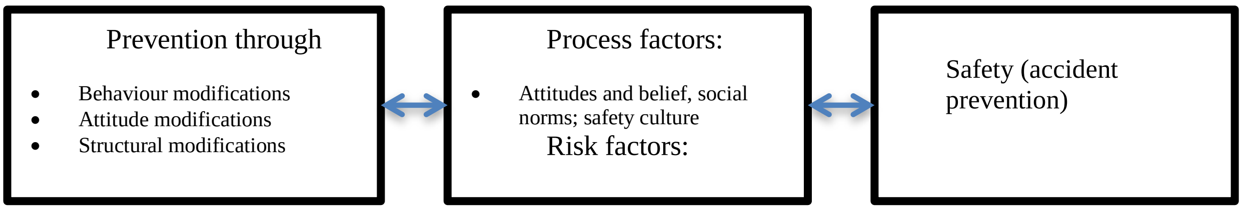

Figure-4: Safety (accident prevention) through working with organization, physical environment and human factors

The effect of structural modifications must be based on a sound understanding of the process to be improved, i.e. based on a theoretical understanding of processes and accidents. The interplay between organizations, technology and human factors has been key issues in our context, focusing on understanding and learning. Thus our perspective has been to improve the safety of the organization based on reflection and double-loop organizational learning as described by Argyris and Schon (1978). We have explored risk factors through discussing our theoretical understanding of key working processes, trying to establish a causal understanding or model of relationships between structure and behaviour impacting impactin safety through accident prevention. The survey of indicators and suggested actions as defined by the National Academy of Engineering, NAE (2004), has been explored in our work.

We want to improve support for exploration of indicators and improved risk communication when IO is implemented. A way to do this is to enhance understanding of potential hazards and to try to motivate actions by the workforce and management, as described by Rowan (1991). This is two important goal of risk communication; however Rowan suggests three important barriers to understanding: *Lack of familiarity, lack of a mental model and existence of misconceptions.* Bier (2001) has suggested the following three barriers that can reduce motivating for action: *Lack of trust, lack of participation in process, lack of power to implement and follow up on suggestion.*

We have tried to establish familiarity and mental models based on the cultural rationality from Plough and Krimsky, see Drottz-Sjöberg, B. -M. (2003). We have tried to "appeal to folk wisdom" by gathering stories about unwanted incidents related to IO in order to create common mental models. Salas (2004) are linking team collaboration to performance. Elements of mental models are explored such as mutual awareness, preplanning and improved training. Better mutual awareness allows the team members to coordinate more efficiently. If an operation is preplanned, it allows team members to communicate more efficiently, leading to better team performance. Teams with members that understand the task after training tend to be high-performing teams. Teams with members who understand the task from multiple perspectives, i.e. of roles other than their own, tend to be high-performing teams. Knowing where expertise is located in the team has a positive and significant effect on team effectiveness and efficiency. To work with misconceptions, we have focused on an open reporting culture with open discussions of unwanted incidents and focus on participatory processes. Relevant incidents and models can be explored to create common understanding.

To build trust, commitment and to avoid misconceptions we are suggesting exploring the ladder of participation, and involving the workforce in partnership and consultation through delegated power related to safety critical areas. In Mumford (1984) a ladder of worker participation is described from the lower level of non-participation trough therapy, informing, consultation, placation, partnership, delegated power to worker control. Mumford mentioned that a group, which has been involved in participative design, is generally enthusiastic about it. To motivate the workforce to suggest and use the specific indicators we based our communication on familiar terms used in the interviews to describe indicators. As suggested by Thompson (2000) we listened to the participants to explore their point of views. Trust is difficult in a major change process such as in IO when functions are moved from offshore location to onshore location. As suggested by Hance (1988) we are trying to share information and involve the stakeholders in the process to developing solutions and actions related to the identified risks. In addition we are focusing on an open reporting culture to foster continuous learning from incidents and accidents. The workshop that prioritized indicators was an open meeting where the participants could suggest indicators. The final result was based on the votes from all the participants themselves. Trust can also be built based on the result of the indicators improving HSE. We are suggesting that trust could improve if this goal is reached or if it is observed that the organization are committed and tries to reach these goals. If it is documented that the identified indicators used in IO increases resilience, oil recovery and safety – this could build trust.

We have discussed challenges of IO with actors in the oil and gas industry; see Johnsen et al (2008a). In addition to complexity and uncertainty, two key issues have been: "*missing situational awareness between the key actors*" leading to misunderstandings and possible accidents and "*increased complexity and tighter coupling between process and ICT systems*" leading to unanticipated problems, stops or deviations in process control systems and actual production.

Based on the preceding discussion, we have defined the following four research questions:

- RQ1: What are the main causal factors leading to major accidents in the oil and gas industry – with focus on Integrated Operations?
- RQ2: What are possible proactive indicators to avoid or mitigate major accidents in the oil and gas industry – with focus on Integrated Operations?
- RQ3: Is missing situational awareness between key actors, a significant causal factor of major accidents in IO?
- RQ4: Is increased complexity and couplings between process and ICT systems a significant causal factor of major accidents in IO?

2. APPROACH – MATERIALS AND METHODS

In this section we describe our approach. First we describe the research design. Then we describe theory off accidents, how we gather empirical results, and how we identify proactive indicators based on a suggested causal chain. Finally we discuss reliability and validity of our approach.

Our focus is remote operations in IO. We have based our work on a qualitative approach, and are not based on a quantitative risk analysis. The research design has consisted of the following five steps, illustrated in figure-2:

1. Explore and describe the relevant theory as a framework and perspective on discussion of indicators.
2. Gather empirical results by exploring major accidents, and by exploring HSE issues in workshops with the industry.
3. Explore (causal) chain or systemic relationships to understand how accident could happen and identify root causes or relevant resilient properties that could be used to avoid accidents. This has been done through open collaborative workshops, exploring unwanted incidents.
4. Identify proactive indicators influencing safety, based on our understanding of causal chains and based on interviews, workshops and accident analysis.
5. Discuss validity and reliability of indicators. Based on the exploration of the indicators, we could improve our understanding of underlying theory and (causal) chain or systemic relationships.

This approach can be seen as a learning approach, improving the safety of the organization based on reflection and the deeper double-loop organizational learning as described by Argyris and Schon (1978). Double-loop organizational learning, indicates that you detect and correct risks by re-examine the fundamental underlying values and issues related to organization, technology and human factors; thus the organizations capacity for effective coordinated action does increase as mentioned by Kim (2004). The research design may be seen as double-loop safety learning to increase understanding of causal relationship and the effect of indicators on the safety level. This safety loop is illustrated in figure-2.

Initially we must define the scope and context of the processes; in this case remote operation of oil and gas fields. A framework or understanding of the critical process must be established denoted by "1) theory" in the figure. This understanding can be based on several theoretical perspectives. As an example, if we are trying to predict the weather, our understanding could be based on theory from thermodynamics and a set of partial differential equations describing how the weather develops. In such a perspective we could use low air pressure as an indicator of rain. In general the process we are considering can be modelled based on different perspectives. If we are looking at accidents, then one perspective of accidents could be a sequential accident model, the "Swiss cheese model", described by Reason (1997).

The next step is to gather "2) empirical results" going through accident report or descriptions of successful recoveries.

Observation of processes or accidents may give us insight into the causal chain, described as "3) causal chain" and relationships leading to an accident. Observation of successful recoveries may also give us insight into the causal relationships on how to avoid or reduce the probability of accidents.

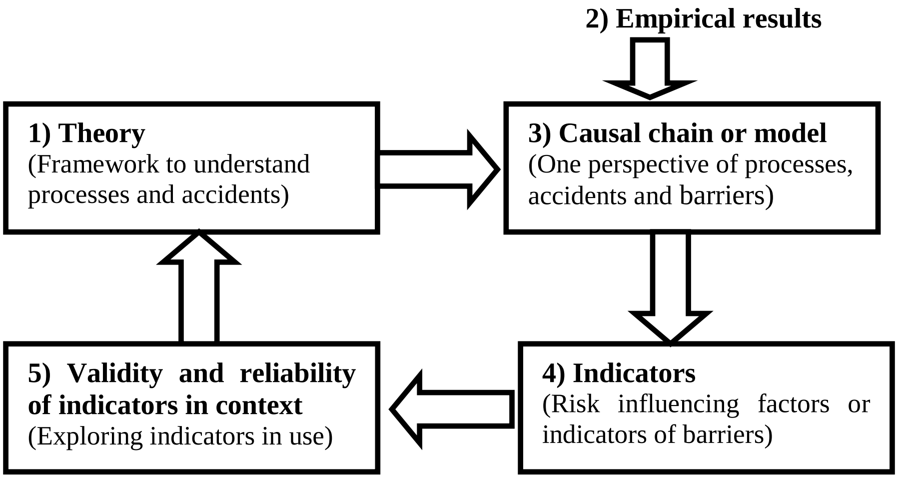

Figure-2: Double-loop safety learning to increase exploration of indicators

Based on the causal chain, we are suggesting risk influencing factors or "4) indicators" to be used to reduce the risks of the processes we are investigating. Data from these indicators should be gathered, structured and stored in order to improve analyses of the indicators, as suggested in NAE (2004).

"5) Validity and reliability" of the indicators must be assessed. This assessment may improve our theoretical understanding of underlying relationships and causes, enabling us to refine the model or causal chain.

2.1 Theoretical perspectives of accidents and accident causality

The industrial processes of integrated operations in the oil and gas industry, has been described in the preceding section. Key issues of our exploration have been related to collaboration and coordination between onshore and offshore installations. Due to the low probability and serious consequences of a disaster in the oil and gas industry we would like to explore resilience engineering as a perspective in order to avoid or reduce the consequences of incidents. By analysing both accidents and successful recoveries (i.e. almost accidents) we are suggesting to learn from both past accidents and successes in order to avoid accidents and build resilience in the future as illustrated in figure-3. Based on exploration of theory of successful recoveries from resilience engineering and high reliability theory, we have tried to identify causal factors based on past successful recoveries, as suggested in quadrant (1). In addition we are trying to identify indicators and causal factors to strengthen safety through resilience, in (2). We have explored past accidents, and tried to identify causal factors based on accident reports, ref quadrant (3). To avoid future accidents, risk models may be explored to identify indicators of risks (4).

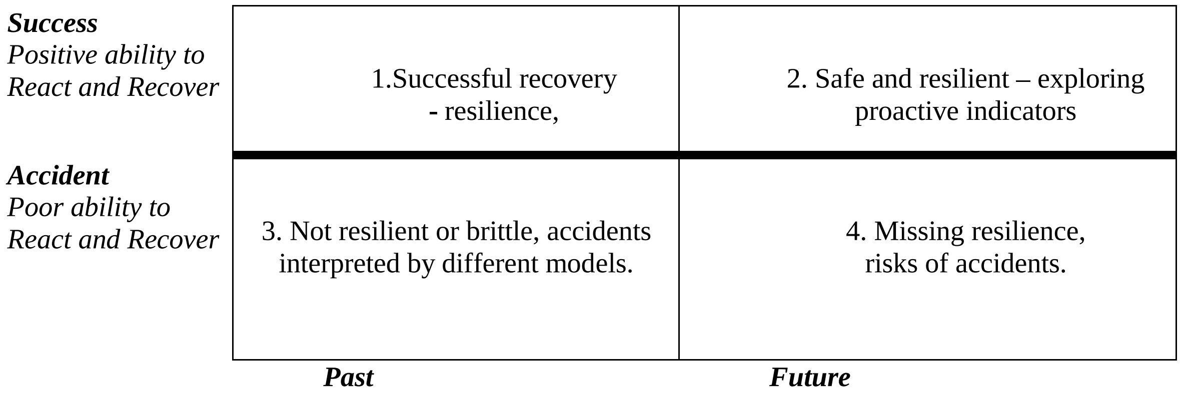

Figure-3: Exploring both accidents and successes to identify proactive indicators

This approach is suggesting exploring both a retrospective approach as used in accident investigation and a predictive approach as used in risk assessment. This is also explored in Øien et al. (2011). We are thus suggesting combining the retrospective approach, to explore learning from both successes and accidents in addition to performing a predictive assessment to explore a risk model in addition to build on resilience. Thus in order to achieve accident prevention, we must try to understand both accidents and successful recoveries. Thus we have tried to identify constraints or the root causes from accident reports in order to get a better understanding of causal relationships. The accident models used are mainly three kinds of models, such as mentioned in Hollnagel (2006):

- Sequential models, assuming simple linear dependences in accidents, explaining accidents as malfunctions or failures, using models such as fault trees.
- Epidemiological models, assuming more complex linear dependencies in accidents, explaining accidents as unsafe acts in combination with weak defences; using barrier models, accidents are caused by missing barriers or holes in barriers. Examples are the "Swiss cheese model" from Reason (1997).
- Systemic models, assuming non-linear dependencies, explaining accidents as a result of complexity and tight couplings or performance variability. Examples of a systemic model based on complexity and tight couplings are mentioned in Perrow (1984) "Normal Accidents".

The models of accidents and successes must be related to our theoretical understanding of key safety critical processes. Thus, during our survey we have explored theory related to root causes. We have performed a literature survey using the suggested factors as keywords to identify relevant publications to mitigate the root cause. As an example - what causes accidents due to "poor design" leading to human errors? Focusing on the design process we have explored the "chain" of activities and principles used in design – an instance of this chain could be the ISO 11064 (2000) standard- suggesting how design of a control centre could be done based on human factors. We have thus tried to identify publications discussing safety related to human factors in design. Based on the identified publications and references, we have tried to identify proactive indicators helping to avoid unwanted incidents or accidents. This is explored further when we are documenting the results in section 3.

2.2 Empirical results based on interviews and accident reports

Interviews and workshops have been performed with two operating companies. Interviews, discussion of questionnaires have been performed with around 10 people at each operator. Due to political issues and uncertainty of the concept of IO, it has been difficult to distribute a survey to a large set of informants. The results in this paper are thus qualitative, not quantitative. The interview questions were based on the e-Operations checklist from CRIOP, see Johnsen et al. (2008). This checklist has been developed in collaboration with the oil and gas industry. Key issues discussed during the interviews have been goals and background for IO implementation, presumed risks related to IO, discussions of unwanted scenarios and unwanted incidents, discussion of barriers, and suggestions of indicators related to safety and resilience of IO. When unwanted incidents were discussed, we tried to identify relevant barriers to avoid the incident or reduce the consequences of the incidents. The suggested barriers could be technical or physical barriers (such as firewalls, safety valves); organizational barriers (procedures, approval of work) or human barriers (experience, knowledge). The approach in the interviews was to discuss barriers and resilient properties. To ensure open discussion between the workforce and the management, we established a workshop with participation from the management and the workforce (with both offshore and onshore experience) in order to understand, explore and prioritize the suggested indicators. Each participant had three votes and the indicators being assessed as most important were prioritized. A list of the indicators was distributed in advance, and the workshop was structured in three main sessions:

- Presentation and clarification of suggested indicators
- Discussion of contents of indicators to ensure common perception
- Prioritization of indicators based on individual voting from each participant

In addition, we have been given access to 26 accident reports, issued between 2002 and 2006. Of these serious accidents, the Petroleum Safety Authority (PSA) investigated 15 accidents. The investigation reports are mainly based on a sequential, complex accident model taking into accord issues from human factors, technology and organization. Root causes and description of the causal chain has been suggested in the reports. The approach followed when analysing the reports has been to summarize the main findings (i.e. the causal chains) and summarize common root causes.

2.3 Identification of proactive indicators based on causal chain

The method to identify proactive indicators has been partly based on risk perceptions from interviews and group discussions (i.e. expert judgments from the participants) in addition to exploration of accident reports and survey of literature related to proactive indicators. We have used HSE (2006) as a guideline to develop performance indicators. In HSE (2006) indicators are used to survey the state of barriers in an epidemiological model. The indicators are used to provide assurance that major hazard risks are under control. If a barrier is used to reduce the probability of an incident, the state of the barrier can be used as a proactive indicator. The taxonomy suggested by HSE (2006) and Dyrenborg (2009) as described in table-1 is explored in this paper. Key issues have been:

- *Consider main challenges, what might go wrong and where.* The guideline points to identifying incident scenarios and the immediate causes of these hazard scenarios. This is listed as "3) causal chain" in figure 2.
- *Identify the barrier or risk control systems in place to prevent a major accident.* A (barrier or) risk control systems is as the name notices a system to prevent or mitigate the consequences of a risk scenario. This is explored in "4) Indicators" in figure 2.
- *Identify the critical elements of each barrier or risk control system and set proactive indicators.* The critical elements of each barrier or risk control system are those actions or processes, which must function correctly to control the risks. This is explored in "4) Indicators" and "5) Validity and reliability" in figure 2.

We have tried to propose indicators based on past exploration of successes (quadrant 1, in figure 3) and past exploration of accidents (quadrant 3, in figure 3). Systemic models have been used. In a systemic model, the malfunctions may be reduced by factors such as less tight couplings, less complexity or other issues from High Reliability Organizations (HRO), ref Roberts (1989).

Based on empirical investigation; the following list of constraints or conditions has been made based on the described properties of HRO organizations, ref Roberts (1989) and LaPorte (1991). This list has been combined with resilient properties described by Woods (2008) and Jackson (2008). We have combined the issues to be able to explore both HRO and resilience when discussing the quality of indicators. Each point is starting with poor ability to react and recover, followed by positive ability. These elements are placed under the two categories in figure-3: 3) not resilient or brittle" or "1) successful recovery". The following issues has been explored and discussed during the interviews and workshops and has been used as a starting point related to discussion of root causes and identification of relevant proactive indicators, in order to explore both successful recoveries and accidents.

Not resilient or brittle causal factors	**Successful recovery based on high reliability organisations (HRO) or resilience**
1. Poor collaboration in distributed operations:	In HRO there is strong focus on shared beliefs and values. A resilient property in distributed organizations is suggested to be the ability and process of inter-element collaboration to support problem solving, thus sharing and creating shared beliefs and values. This can also be called common mental models across the distributed operations.
2. Missing risk assessment - complacency	In HRO there is strong public attention and the organization is always alert. A resilient property could be the ability to detect drift to boundaries or danger zone by identifying situations that can lead to deterioration. Some examples of situations are change of leadership, increased scope of work, severe weather impacting working conditions or incidents disturbing equilibrium.
3. Brittle organization, unable to handle deviations	In HRO there are flexible organizations and relatively abundant resources in critical areas. A resilient property could be the possibility of adjustments or reorganization related to deviations or workload. In addition buffering capacity – capacity to absorb disruptions or having sufficient margins. Capacity could be implemented by functional redundancy (i.e. having multiple ways to perform functions) or physical redundancy. In addition there should be capacity or margins to handle the worst-case scenario and the most likely scenario.
4. Conflicting goals	In HRO there is strong safety commitment from top management, and a resilient property is suggested to be top/down resolution of goal conflicts related to safety both at the blunt end in planning, but also at the sharp end during operations.
5. Poor learning from existing pathogens or failures	In HRO there is focus on maximizing proactive learning. A resilient property at the sharp end could be the ability to focus on bottom/up adaptations (workarounds) from local praxis influencing policies. The "blunt end" approach should be focus on the deeper double-loop organizational learning and organizational reflections on pathogens and failures.

6.	Poor communication	In HRO there is a focus on good communication among many individuals. A resilient property could be the ability to identify relevant signals, indicating a change of mood or climate such as stalls in progress, sarcasm, slippage of schedule, personnel don't return calls or emails or fatigue is high and there is an increase in complaints.
7.	Complexity and unanticipated consequences	In HRO there is extensive system insight, and ability to handle unanticipated consequences. A resilient property could be the ability to improvise, having multiple ways of performing functions to achieve stated goals.
8.	Tight couplings and unanticipated consequences	In HRO there is a goal of no errors and alertness. A resilient property could be the ability to detect drift to boundaries or danger zone

The listed issues have been used as guidewords when discussing mechanisms leading to harm, and when trying to identify indicators related to possible conditions or constraints.

2.4 Discussion of validity, reliability and effect of indicators.

Reliability is defined as the consistency of the measurement, or the degree to which an instrument measures the same way each time it is used under the same condition with the same subjects.

Validity is defined as the strength of our conclusions, inferences or propositions. More formally, Cook and Campbell (1979) define validity as the "*best available approximation to the truth or falsity of a given inference, proposition or conclusion*."

The indicators must be both reliable and valid to ensure that they are consistent and conclusive. Based on exploration and use of the indicators, we could improve our understanding of underlying theory and (causal) chain or systemic relationships. If the indicators are not conclusive and valid, they must be rejected and our understandings of causal chains are not correct. Ideally, to assess the validity and reliability of a proactive indicator we must assess the correlation between the suggested indicator and the HSE level at several installations – as described by actual incidents and accidents. In addition the correlation between the indicator and a broad HSE survey should be performed at several installations. The validity and reliability of the use of the indicator should also be assessed, i.e. if the indicator is explored in HSE management – is safety improved as indicated by the HSE level? A set of installations using the proactive indicator should be selected and the HSE level should be evaluated vs. a set of comparable installations not using the indicators.

We have identified a set of indicators based on triangulation, i.e. different approaches to ensure improved reliability and validity. We have explored expert judgments (data gathered by interviews); we have used a survey of accident reports and based our indicators on exploration of theory in order to get a valid and reliable indicator.

We have also explored a report from StatoilHydro by Næsje (2009). We have used the report to explore if there is consistency between our suggested indicators and the HSE level in the company. The report uses incident data from StatoilHydro in 2007 and 2008, looking at TRIF (total recordable incident frequency) and SIF (serious incident frequency). They have also compared incident frequency with survey data from Risk level in the Norwegian Petroleum industry, to identify HSE-related factors perceived by the employees.

3. RESULTS

In this section we have documented the results from the interviews, the review of accident reports and discussion of causal factors and description of a set of suggested indicators. In addition, we have documented a HSE survey of IO installations and offshore installations, used to reflect on reliability and validity of indicators. We have identified causal factors based on interviews or review of accidents. The causal factors have been explored based on discussions from theory, and we have suggested indicators based on suggested relationships or causal chains.

3.1 Results from interviews

Interviews and workshops have been performed with two operators. Interviews, discussion of questionnaires have been performed with around 10 people at each operator. The people interviewed had long and different types of experience with oil and gas operations. Participants were central control room (CCR) operators in offshore operations, operators and participants in onshore operations, and managers. The key six issues or presumed causal factors that were mentioned in the interviews related to IO have been:

I. Missing collaboration between workforce and management; II. Missing risk assessment; III. Deviations from established procedures when work is performed; IV. Conflicting goals between productivity and safety – ability to manage margins; V. Missing offshore experience and missing risk awareness; VI. Unclear organizational responsibility and failures in communication.

These issues are explored in the following, in order to identify suggested indicators:

I. **Missing collaboration between workforce and management.** Understanding and collaboration related to the implementation of IO has been missing in some instances. Guiding documents and operational strategies of remote operations and responsibilities has been missing. However, this may create bottom-up processes and solutions, if that is supported. There has been much focus on technology and little focus on organizational and human issues. There has not been a common understanding of goals and results to be achieved by IO. The implementation process has not always involved the relevant stakeholders. Acceptance of realistic operational goals, understanding, commitment, human factors based design and necessary safety could have been impacted. The quality of the implementation process may be poor. A poor implementation of IO may be an important risk-influencing factor. Missing collaboration between workforce and management during large-scale changes, as implementing IO, could lead to safety issues. Westrum (2003) describes a process rooting out underlying problems in organizations and avoiding erosion of organisational defences. It is suggested that organizations creating alignment, awareness and empowerment among the workforce is better at removing underlying problems and thus has better organisational defences and safety. Assessment of participation and collaboration could be a useful indicator of this, such as IN1: *a subjective assessment of the IO implementation process related to participation and involvement across the organisation*. (This is a constraint related to organizational culture or management systems.) A relevant indicator could also be the number of workshops between management and workers related to implementation of IO, based on collaboration and participation between the workforce and management.

II. **Missing risk assessment – not sufficient crew in control rooms, unacceptable stress.** There is a focus on cost reductions and increased production when IO is implemented. Increased focus on production and production optimization may lead to more stress. It is a focus on increased support from onshore, and a need for stability in communication. There may be differences in perceptions of safety and risks between onshore and offshore, and these differences may impact risk awareness and collaboration. Increased demand and increased stress level may be an important risk-influencing factor. There was a fear of miscommunication and misunderstandings during critical operations. Operators must explore and practice situations of lost communication. Scenarios could be used to explore unwanted incidents across organizational boundaries. Emergency procedures must be established in case of lost communication. These unwanted situations are called Defined Hazard and Accidents or DFU (In Norwegian "Definerte fare – og ulykkeshendelser"), and relevant scenarios should be established and documented related to lost communication or other communication problems. Missing risk assessment could be important. Frola (1984) suggest a relationship between safety in operations and prior risk assessment as a part of a system safety approach. In addition it is important to measure the risk perception of the workforce. The risk perception among workforce in the oil and gas industry has been correlated to the actual risk levels, ref Fleming (1998). An important indicator could thus be the risk perceptions of the workforce over time and related to the onshore and offshore perspective. Differences in risk perceptions should be explored, especially related to shared tasks. Indicators could be: IN2.1: *Measure of the subjective assessment of safety and risk by workforce involved in operations, and a measure of well-being and stress levels*. (An indicator related to closeness to performance boundaries, and working conditions. A broader based indicator related to organizational safety culture could document existing constraints.) An indicator related to working conditions: IN2.2: *Percentage of work conducted based on a work permit with risk assessment* since work should be performed safer and better due to improved planning. (An indicator related to closeness to performance boundaries). IO involves collaboration between more actors and an important issue was fear of miscommunication and misunderstandings. Clarity in responsibility and routines must be established. Scenarios could be explored in a workshop or trough simulator training. Procedures with tight coupling could lead to errors or unwanted incidents. An indicator could be: IN2.3: *Number of scenarios exploring unwanted incidents (fears) in the network or exploring critical differences in situational awareness between the key actors that could impact safety.* (An indicator of prevention and working conditions). One additional indicator may be the percentage of procedures with tight coupling, which are reviewed and trained within the designated period.

III. Deviations from established procedures when work is performed. Some times the procedures had to be changed due to changing working conditions or differences in conditions in the reservoirs. There were several deviations from working procedures and missing support from the procedures. An important factor was necessary time set aside to improve or update the procedures and routines. Procedures are established to ensure safe work practices. Deviations from procedures must be identified – both to identify level of adherence to safe working practices but also to identify if there is a need to allow deviations due to reason such as bad procedures or need for improvisations. An indicator could be the percentage of deviations from established procedures. IN3: *Assessment of deviation from established procedures – percentage of work done as deviations from established procedures* or a subjective assessment of the level of deviations. (An indicator related to closeness to performance boundaries, and working conditions.)

IV. **Conflicting goals between productivity and safety – ability to manage margins.** There is a focus on higher productivity and better yield from the fields when IO is implemented. Managing margins and balancing goals between production and safety should be an important issue. A factor showing that sufficient time is allocated to operations could be the level of optimal production reached in addition to improved HSE levels and the reduction of risk level of major accidents, due to increased attention. The use of IO should aid the offshore installations to increase safety, resilience and production. Implementation of IO may reduce the HSE level if resilience is not achieved. Increased demand on personnel reduced manning and increased stress level may be an important risk-influencing factor. The ability to identify safety margins and manage safety margins during stress or increased pressures is discussed by Rasmussen (1997). An indicator to document less pressure or increased time used on safety work should be important. A relevant indicator is: IN4.1: *An indicator showing % of optimum production reached,* to measure if IO goals are reached. (An indicator related to closeness to performance boundaries, and working conditions.) Such an indicator could also indicate the level of resilience during operations, since resilience should improve continuity. IN4.2: *An indicator related to increased time to do prioritized operational work (safety work or optimize production) related to critical processes*. (An indicator related to closeness to performance boundaries, and working conditions.) A goal of IO has been to reduce unnecessary work especially offshore, and to distribute tasks to the right actor in the network such as onshore. This indicator could be a subjective measurement (qualitative) or based on time reporting (quantitative).

V. **Missing offshore experience and missing risk awareness:** If remote operations are implemented, the operators and collaboration environment onshore must have a good knowledge of the installation they are managing and the relevant risks. Missing offshore experience and missing risk awareness may be an important risk-influencing factor. More involvement from onshore organizations should improve collaboration between onshore and offshore. A focus on increased planning between onshore and offshore could impact safety, since improved planning could lead to more use of work permits with risk assessment. Relevant training and experience building related to collaboration between onshore and offshore could impact safety. Experience is an important factor to understand risks and work safe. Salas (2004) mentions that teams who understand the task from the perspective of roles from other key actors tend to be high-performing teams. There have been examples of incidents due to poor understanding of the whole process in the oil and gas industry. A qualitative indicator could be established to measure this. IN5: *% of workforce trained and having experience related to the whole process between onshore and offshore.* (An indicator related to prevention, and working conditions.) This indicator should be related to team collaboration between onshore and offshore and it could document the level of offshore experience and understanding among actors in the network, established by job rotation and understanding of the whole task to be done.

VI. **Unclear organizational responsibility and failures in communication.** When responsibilities are distributed in a network, it is important to have a clear understanding of responsibilities and how command/responsibilities are placed in a stressful situation. Missing responsibilities or unclear responsibilities may be an important risk-influencing factor related to handling of unwanted incidents. When using resources onshore, it is important that communication is error free/problem free (understood) and that communication infrastructure is available at all times. When there is a need for close collaboration in the distributed organization, routines and technology must support collaboration and help to avoid errors. Availability of communication infrastructure, network/ video/ telephony, may be an important risk-influencing factor in addition to an assessment of clarity in communication. Clarity in task responsibility and clarity in communication is important when tasks are delegated and performed in a team setting. An indicator should measure miscommunication, lack of communication or lost communication. Proactive learning, as mentioned in Salas (2004), seems to improve performance and allows team members to communicate more efficiently, leading to better team performance. Teams that understand the task after training tend to be high-performing teams. It is important to explore unwanted incidents and build knowledge about the incident and root causes such as missing task responsibility, quality of communication or other causes. Suggested indicators are: IN6.1 *Technical stability or availability of communication infrastructure and a subjective assessment of availability of communication infrastructure.* (An indicator related to closeness to performance boundaries.) Technical stability of infrastructure such as telephony, video and networks was deemed important when remote support and remote operations are implemented. The availability of backup solutions of communication infrastructure or alternate ways of communication is important to improve resilience. A relevant indicator could be IN6.2: *A subjective assessment of how fast staff and contractors take the correct action in the event of an emergency related to communication*. (An indicator related to closeness to performance boundaries.) As mentioned in Salas (2004), knowing where expertise is located has a positive effect on team effectiveness and efficiency. In addition it could improve HSE when problems are resolved with high quality, an indicator is: IN6.3: *The number of times there is collaboration with expert centres.* (An indicator related to constraints of management systems.) IO is involving a network of actors, giving a possibility to share knowledge and improve awareness. In Salas (2004), it is mentioned that better mutual awareness allows the team members to coordinate more efficient. IN6.4: *Team mutual awareness could be a qualitative measurement, to be used when it is necessary as example when there is tight coupling or during risky operations.*

In the following we have listed the prioritized indicators after the workshops. We performed a workshop with participation from management and workforce (with both offshore and onshore experience) in order to understand, explore and prioritize the suggested indicators. In the following we have documented the key issues in the discussion. Based on the discussion, the following indicators were selected. The relations to the causal factors are numbered in parenthesis, i.e. (II) is missing risk assessment – sufficient crew in control rooms, acceptable stress.

The *safety commitment* from the top management was demonstrated by the general involvement from management and by arranging the workshop, but this commitment should be measured in relation to the general HSE level.

(II) **Missing risk assessment -** It was agreed to establish proactive indicators that can be used to measure the safety commitment by performing workplace surveys, measuring subjective assessment of risks in operations in addition to assessment of quantitative HSE indicators. Stress and well-being should be measured. This should be done periodically to identify and follow trends. The differences in HSE perceptions (risk perceptions) between onshore and offshore should be explored. The prioritized indicator was *IN2.1-Subjective assessment of safety and risk, the well being and stress;*

(II) Collaboration between onshore and offshore was agreed as important to explore. Shared situational awareness between onshore and offshore should be an area of training related to critical and coupled tasks. To ensure good communication and shared situational awareness - some practical issues such as different shift schedules between onshore and offshore should be resolved. One example mentioned was onshore changing shifts at 16:00 while offshore were changing at 19:00 – this could mean that hand-over should be performed at 16:00 and 19:00. A suggested indicator was amount of time used to train on critical situations using simulator or scenario training, exploring hazardous operations (DFU) related to tightly coupled systems. In general the level of scenario training, in combination with simulator training, should be increased. The scenarios should involve onshore, offshore and suppliers in order to increase competence on how unwanted incidents should be resolved. The prioritized indicator was: *IN2.3-Training or scenario analysis of hazardous operations (especially tight couplings).*

(IV) **Ability to manage margins -** IO should increase efficiency, and give people offshore more time to work with operations, more time to do the job right and getting more out of the oil field. This can be seen as managing margins or "balancing on the line" focusing on safety while optimizing production. This could lead to less complacency and more alertness. An important indicator is increased time to optimize production, or discuss work with others. It is not well understood at present why the production varies so much from the optimum, but one issue mentioned is to have enough time to focus on operations. One important indicator related to production is % production rate related to optimum production from the field. Deviations in this indicator should be explored in order to identify what is hindering optimum production, and this exploration could increase understanding between onshore and offshore. One such example was given, during the summertime the production is high – and the reason was given as "nobody is disturbing the operators from onshore". The prioritized indicator was: *IN4.1-a % of optimum production reached.*

(V) **Missing experience and missing risk awareness -** The role and importance of the central control room (CCR) operator was seen as changing, becoming more important leading to an increased stress level to the operator. To increase the knowledge and competence of the CCR operator, simulator training exploring DFU's and a certification scheme were suggested. The simulator could be used to test the knowledge and understanding of the CCR operator.

(VI) **Failures in communication -** One of the fears from the workforce were loss of communication between onshore and offshore facilities. Offshore personnel have been critical of moving functions from offshore to onshore. It was compared to flying in passenger jet plane when the pilot is placed on the ground. Since this was seen as a major fear (dread), it was decided to recommend indicators related to the stability of the technical communication and to train (perform scenario training) related to the loss of communication to build experience and knowledge of how such an unwanted incident should be handled. The prioritized indicator was: *IN6.1-Technical stability of communication infrastructure.* Communication was seen as an important task in building understanding and trust between onshore and offshore. The experts onshore should especially be utilized, and one indicator of interest could be the number of times the expert centre was contacted. The prioritized indicator was: *IN6.3-Number of times there is collaboration with expert centre.*

These suggested indicators are used together with the accident reports to propose a first set of indicators. We are trying to use some sort of "triangulation" using interviews, surveys of accidents and exploration of theory in order to get a set of valid and reliable indicators.

3.2 Results from review of accident reports

The main causes found in the accident reports, based on our investigation of the reports were:

I. **Poor design and poor validation and verification of actual use of the equipment** in 14 cases.
II. **Missing risk assessment prior to the accident** in 11 cases and **poor planning of the work** in 8 cases related to safe job analysis i.e. missing risk assessment.
III. **Deviations from established procedures or governing rules** in 9 cases. In addition to poor procedures in 6 cases
IV. **Conflicting goals between production and maintenance backlog –** prioritized maintenance or changes not performed at due date in 8 cases.
V. **Poor learning from incidents and poor systematic evaluation of repeated incidents** in 8 cases. In general poor training in 6 cases.
VI. **Miscommunication between different actors during critical operations** in 7 cases.
VII. **Poor involvement in safety matters from management** in 7 cases.

The accident analysis was influenced by the perspectives in the method, as described by Lundberg (2009), i.e. "What-You-Look-For-Is-What-You-Find", the cause of successful recovery was not sufficently explored, i.e. "why did it not become a worse accident?" Thus resilience, and ability to "bounce back" was not sufficiently analyzed in the accident reports.

It seems that when an accident was happening, it was in a way "waiting to happen" – in that there were several faults, erosion or holes in the barriers, in combination with missing barriers. An identified strength was good emergency readiness related to evacuation from the platform during the incidents documented and described in the accident reports. For each of the suggested root causes we are trying to focus on a model to understand the underlying problem or challenge. Based on our understanding we have proposed a set of possible indicators that may be explored; and we have a short reflection on reliability of the indicator.

The key seven issues from exploration of the accident report are listed in the following:

I. **Poor design and poor validation and verification of actual use of the equipment**. The cause "Poor design or poor validation" could lead to incidents since design influences safety and resilience. Safety and resilience in design may be influenced by many factors. Human Factors is an important perspective, ref ISO 11064 (2000) as an example of the design process. Design is a complex activity involving many stakeholders. The different stakeholders and perspectives and experiences can influence safety as discussed by Turner (1997). Several incidents documented in the accident reports pointed to poor design as a root cause. Poor design may have been uncovered if verification and validation activities are performed with relevant experienced stakeholders. The design should follow a Human Factors based design philosophy as ISO 11064 (2000), to ensure that human factors and human variation is taken into account. Resilience could be built into the system by increased buffering capacity of critical areas, by establishing functional or physical redundancy. Resilience could be assessed by the ability to handle worst-case scenarios and likely scenarios i.e. flexibility at boundary conditions should be assessed. Drift to boundaries or danger zone should be indicated by the design. Indicators to be used could be time or number of scenario analyses performed trying to validate or verify the design. Reliability and validity of such an indicator is difficult to establish and measure – if there is success – no incidents are happening. But if resilience is measured, i.e. the ability to manage margins or have tolerance – some degree of validity could be ensured. The validity of this indicator should be explored further. Suggested indicators: A1.1: *Number of scenario analyses performed trying to validate or verify the design* and A1.2: *Number of successful recoveries* in combination with A1.3 *Subjective assessment of resilience of the design.*

II. **Missing risk assessment prior to the accident**. The cause "Poor identification of risks" may be based on "after the fact bias". In retrospect, after an accident, it is probable that the actual risks had not been assessed properly. However, some of the accidents involved complex processes with high risks, where the risk assessment had not been systematically explored on a broad basis involving relevant stakeholders. In this case, the missing risk analysis is a cause. This is not hindsight; complex processes should be analysed thoroughly and based on an updated risk analysis, involving relevant stakeholders. In Lund (2004) the effects of several preventive measures are highlighted, showing that when they are used in combination, they may influence social norms and cultural factors and subsequently safety. Such a broad based approach to risk identification, risk mitigation and improved safety is also suggested in Alteren (2004), Antonsen (2007) and Richter (2003). Resilience should be a part of the risk assessment and issues such as "buffering capacity"; "flexibility", "tolerance" or the ability to "manage margins" should be incorporated into the risk assessment. Indicators to be used may be the percentage of complex operations where risk analyses are performed or percentage of time used on risk analysis as part of total planning work. Another indicator could be the percentage of work having work permits where risk analysis has been performed; a low number of work activities with work permits including risk analysis may indicate missing planning and missing risk evaluations of work. This should be compared between similar installations. Reliability and validity of the suggested indicators are debatable. A combination of improbable events may be the cause of the accidents, and then it may be hindsight to blame missing risk evaluation. However it seems that a broad based approach to risk analysis and risk management have effect on safety as suggested by Lund (2004). A2: *Number of scenario analysis of complex operations and percentage of complex operations with risk analyses.*

III. **Deviations from established procedures or governing rules**. The cause "Deviations from established work procedures" must be explored. Over time there may be a slow erosion of compliance with work procedures, the employees may perform shortcuts and skip activities and there is usually a slow drift of routines and procedures. This could be due to production pressures or due to increased complacency, ref Rasmussen (1997). This kind of drift and/or production pressure may be difficult to identify when nothing goes wrong. In Itoh (2004) the importance of employee participation related to working procedures and work orders was highlighted related to safety. Our view is that safety is improved by human practice and collaboration, ref Dekker (2006). Safety commitment from the top could balance the production pressure, and could be expressed by resources used to improve working procedures. Work procedures should be designed with resilience in mind, exploring bottom up adaptations, and maximizing proactive learning. Allowing flexible procedures could increase "buffering capacity" and resilience. In this perspective it is very important to be able to "manage margins" in order to understand closeness to performance boundaries, when there is deviance from procedures. Evaluation of percentage of deviations of work orders should be established in order to be able to manage margins. At the same time there should be a periodic assessment of the quality of work orders and procedures by the employees in order to ensure that the procedures are relevant and of necessary quality. Indicators could be percentage of work orders with deviations and a qualitative assessment of quality of work procedures from the workers. Reliability and validity of such an indicator is complex. Deviations from a work order may be a sign of successful improvisation; it may be a sign of large distance between the persons writing a work order and the workers performing the actual work; or it could be an indication that there are too many procedures. A combination of the two suggested indicators should be explored, suggested indicator is: A3: *Percentage of work orders with deviations and a qualitative assessment of quality of work orders - related to deviations from established work orders.*

IV. **Conflicting goals between production and maintenance backlog**. The cause "Prioritized maintenance or changes not performed at due date" should be explored. Preventive maintenance and low maintenance backlog in critical areas seem to correlate with improved safety, but no clear evidence of correlation has been found. Using hindsight you often find a large backlog when there has been a significant incident, such as in the major accidents Bhopal, Piper Alpha and BP Texas City. In Ray (2000) it is suggested that better maintenance is associated with lower injury rate. In IAEA (2001) and Parida (2006) a framework is described, and in Kumar (2000) relevant indicators in oil and gas are discussed. The equipment should be resilient, i.e. the system should have "tolerance" and can degrade gracefully even if corrective or preventive maintenance has not been performed. There is a question of "managing margins" and there is need for an assessment method and an indicator of the criticality of the maintenance. Indicators related to backlog of preventive and corrective maintenance – especially related to safety critical equipment should be established. These indicators should be supported by risk assessment from the local workforce, to get their human assessment of the criticality of maintenance. A systematic and clear relationship between maintenance backlog and safety issues has not been verified, but using hindsight from major accidents it has been shown that maintenance could have been an important barrier. Further explorations and literature survey should be performed to identify correlation between maintenance activities and safety. Suggested indicator are: A4: *Backlog of preventive and corrective maintenance and risk perception among stakeholders involved in operations* – related to prioritized maintenance or changes not performed at due date.

V. Poor learning from incidents and poor systematic evaluation of repeated incidents. The cause "Poor systematic learning from incidents" is complex. Systematic learning in an organization from incidents and accidents are dependent on many factors such as possibility to report and document incidents, openness and the possibility of sharing incidents, ability to have resources and time to learn, ability to change fundamental values in an organization, often called double loop learning – see Argyris (1974). In Reason (1997) this is also called "a learning culture", something that may be difficult to establish. Shell has developed a tool called "Hearts and Minds" trying to document development from a blame culture, through a rule base culture to a learning/proactive culture – see Hudson (2002). It is suggested by Hudson (2002) that the focus on a learning culture has improved safety. In Johnsen (2008b) accidents and incidents are proposed to follow an experience curve, i.e. safety are proportional to accumulated experience, and incident rate are inverse proportional to accumulated experience. These kinds of models can be explored to identify differences in learning. One effect of learning may be an improved ability to manage margins, creating better understanding on how close the organization is to performance boundaries and how the organization can anticipate future trajectory. A general assessment of this could be based on a cultural tool such as "Hearts and Mind". Time and effort must be used to assess prior incidents; an indicator could be number of reviews of prior incidents and reviews of mitigating actions. Secondly – mitigating actions must be executed; an indicator could be the time lag between planned implementation of mitigating actions and actual implementation of the actions. A suggested indicator is time used to review and reflect on prior incidents and time lag between planned actions and actual actions related to prior incidents. Another indicator could be an assessment of safety culture based on "Hearts and mind methodology" to identify the degree of "learning organization". Reliability and validity of the indicators is difficult. Hindsight bias may influence our perceptions of poor learning. In general, a learning organization should have fewer accidents but having more reports and reflections of incidents and errors. The suggested indicators should be explored in collaboration with the industry in order to validate the indicators quantitatively. Suggested indicator are: A5: *Assessment of "safety culture"*, incorporating issues as t*ime used to review and reflect on prior incidents, time lag between planned critical mitigating actions and actual actions* – all this should be explored related to poor systematic learning from incidents.

VI. Miscommunication between different actors during critical operations. The cause "Miscommunication between actors during critical operations" seems important in Integrated Operations. Risk communication could be a challenge in a stressful situation; misunderstandings and poor communication can lead to serious incidents. Communication is dependent on many different factors such as communication procedures, situational awareness, working procedures; organizational factors and culture among the stakeholders involved in communication– see Henderson (2002). The first step may be to focus on communication in diverse teams; such as explored in CRM (Crew Resource Management) see Baker (2006). If remote operation is an issue, the stability, quality and resilience of the communication infrastructure are becoming more important. To build resilience it may be important to have buffering capacity in critical communication, and indicators documenting loss of communication or miscommunication during critical operations. From the HRO theory there is a focus on shared beliefs and values, ensuring good communication, supporting extensive system insight and having no tolerance of errors in critical communication that should be explored. Technical indicators should be established related to the number of communication breakdowns in critical equipment such as networks, radio, telephony etc. to be able to "manage margins" in a proactive way. In a human factors perspective, the organization and participants should understand these issues trough systematic team training, such as CRM. In addition there must be a qualitative evaluation of team communication, team mutual awareness using periodic questionnaires focusing on how critical communication among relevant actors is performed, evaluating clarity in responsibility, mutual awareness of processes and risk awareness, ref MacMillan (2004). Actual indicators: could be number of breakdowns in critical communication equipment and level of team training focusing on communication – such as Crew Resource Management (CRM). In addition a qualitative indicator based on a periodic assessment of team mutual awareness, quality of communication in critical operations, process awareness and risk awareness. Reliability and validity of these indicators related to safe performance is a theme to be explored further. In Salas (2004) there is shown relationships between team performance, task work knowledge and team situational awareness and in Baker (2006) – team training results in improved communication and safety-related attitudes. The relation to safety should be explored. Relevant indicators are A6.1: *Number of technical breakdowns in communication*, A6.2: *Assessment of quality of critical communication*– related to miscommunication between actors during critical operations, A6.3: *Level of relevant team training (CRM).*

VII. Poor involvement in safety matters from management. The cause "Poor involvement in safety matters from management" gives an important signal to the workforce related to safety. An important indicator could be a qualitative assessment of involvement and interest from management related to safety. A7: *Qualitative assessment of involvement in safety from management* – assessing if management "walk the walk" – "talk the talk".

3.3 Combining results from interviews and accident reports

We have combined the different factors from the interviews and the accident analysis. The indicators and causal factors are similar and can be combined, an additional causal factor – "poor involvement in safety matters from management" identified as a part of review of accidents has been added. The causal factors or root causes has been structured between constraints and conditions since constraints are more fundamental issues related to the "blunt end "of planning. The indicators should help exemplify the causal factors. The constraints related to management systems, organizational culture and policies are suggested to be:

Ia**. Poor design and poor validation and verification and Ib. Poor collaboration between workforce and management**. Suggested indicators are: S1.1: Number of scenario analyses performed trying to validate or verify the design or changes and S1.2: Subjective assessment of involvement and influence of different stakeholders in change processes, during concept design or later. (Influencing HSE in design, governing documents, procedures etc.);

II. **Missing risk assessment and/or poor planning**, suggested indicators are: S2.1: Subjective assessment of risk in operations. I.e. questionnaire to assess if risky operations are carefully planned, governing documents are used, is the work permit system adhered to, workers assessment of risk (onshore vs. offshore), HSE influence, HSE knowledge and relevancy, HSE in operation, assessment of stress and level of collaboration across silos during risk assessment. S2.2: Percentage of work with formal work permits (i.e. with assessment of risk) including work involving remote collaboration or remote operations. S2.3: Number of scenario analysis (or use of simulator) used to train on hazardous operations (DFU) related to tightly coupled systems. (Such as involving third parties or collaboration across several organizational silos.)

V. **Poor learning from incidents or poor training**, and **missing risk awareness**; suggested indicators are: S5.1: Qualitative assessment of ability to learn across teams (in different organizations or silos) and assessment on learning from prior incidents. S5.2: Qualitative assessment of training and experience of key stakeholders involved in IO. (Such as offshore experience when collaborating from onshore.) (The CCR involved in IO should have good training, and there should be a certification scheme of the CCR.)

The above-mentioned issues are a part of the "blunt end" and must be a part of the planning cycle; however this could be an important periodic indicator. The conditions related to closeness to performance boundaries, prevention and state of preventive barriers are suggested to be:

III. **Deviations from established procedures or governing documents**, suggested indicators are: S3.1: Percentage of work orders with deviations and a qualitative assessment of quality of work orders with deviations.

IVa. **Managing margins of production**, and IVb. **Conflicting goals between production and maintenance backlog**, suggested indicators are: S4.1: Production (or production loss) vs. optimum production as a % of optimum production; S4.2: Qualitative and quantitative assessment of maintenance backlog. (Qualitative assessment of risk perception among stakeholders involved in operations related to maintenance. Quantitative assessment of prioritized maintenance or changes not performed at due date.)

VI. **Miscommunication between different actors during critical operations,** suggested indicators are: S6.1: Technical stability (% up time) of communication, video/ telephone/ network; S6.2: Qualitative assessment of communication in teams (local and remote) – related to miscommunication between actors during critical operations, concurrent operations.- Level of alertness related to communication; S6.3: Utilization of outside experts – i.e. % utilization of third party during problem solving; S6.4: Level of relevant team training (such as CRM).

VII. **Poor involvement in safety matters from management,** suggested indicators are S7.1: Subjective assessment of safety involvement from management and support of HSE and actual guidance or involvement.

All these indicators should be validated related to actual operations; this has been explored at one large operator, and is discussed in the next session.

3.4 Exploring results from a survey of the HSE effect of Integrated Operations

We have suggested a set of proactive indicators in the preceding section. The health, safety and environment (HSE) performance of several IO installations in StatoilHydro are explored in a report from Næsje (2009). We have used this documented HSE performance from StatoilHydro to check the validity and reliability of the indicators. The HSE result from StatoilHydro is based on comparison of TRIF (Total Recordable Incident Frequency), SIF (Serious Incident Frequency) and RNNP (Risk Level in the Norwegian Petroleum Industry). We have first correlated issues from installations having a high level of Integrated Operations, and high level of HSE. Then we have correlated issues from installations having a high level of HSE.

High level of HSE in IO installations is correlated to the following indicators through the appropriate issues from the survey:

- "S2.1 Subjective assessment of risk based on that governing documentation is used, and the work permit system is adhered to", since the survey issue "I think it is easy to find what I need in the governing documents (requirements and procedures)" is correlated to high HSE in addition to "the work permit (WP) system is always adhered to".
- "S2.2 Percentage of work with work permits" since the survey found that "the work permit (WP) system is always adhered to" is correlated to high HSE.
- "S6.2 Assessment of communication" since the survey issue "I always know who to report to in the organization" is correlated to high HSE.

In addition, the focus on cooperation between onshore and offshore has been correlated to high HSE; through the survey question "Increased cooperation between the facility and land through IT systems has lead to less safe operations" thus the indicator "S6.2 Assessment of communication" should be explored. In addition the survey question "Communication between me and my colleagues often fail in a way that may lead to dangerous situations" is negatively correlated to high HSE, also supporting the need to explore the indicator "S6.2 Assessment of communication".

High level of HSE in general is correlated to the following indicators through the appropriate issues from the survey:

- "S1.2 assessment of involvement and influence" since the survey issue "My manager appreciates my pointing out matters of importance to HSE" is correlated with high HSE level.
- "S2.1 Subjective assessment of risk" since the survey issues "I am thoroughly familiar with the HSE procedures", "the HSE procedures cover my work tasks" and "I ask my colleagues to stop work which I believe is performed in an unsafe manner" is correlated with high HSE level.
- "S2.2 Percentage of work with formal work permits" since the survey issue "Risk-filled operations are always carefully planned before they are begun" is correlated with high HSE level.
- "S5.1 Assessment of ability to learn" since the survey issue "Information about undesirable incidents is used efficiently to prevent recurrences" is correlated with high HSE level.

- "S6.2 Qualitative assessment of communication" since the survey issue "There are often concurrent work operations, which lead to dangerous situations" is correlated with high HSE level.
- "S7.1 safety involvement from management" since the survey issue "I can influence HSE matters at my workplace", "My supervisor is committed to the HSE work on the facility" and "Does your immediate supervisor helps and supports you in your work, if you need it?" are positive correlated with high HSE.

Thus, based on Næsje (2009) we have seen that some of the indicators are correlated with high level of HSE, such as:

- S1.2 assessment of involvement and influence
- S2.1 subjective assessment of risk (IO seems to give a positive contribution)
- S2.2 percentage of work with work permits (IO seems to give a positive contribution)
- S5.1 assessment of ability to learn
- S6.2 assessment of communication (IO seems to give a positive contribution)
- S7.1 safety involvement from management

4. DISCUSSION

In this section we discuss the results of our work related to the research questions. The research questions we defined were:

- RQ1: What are the main causal factors leading to recent accidents in the oil and gas industry?
- RQ2: What are possible proactive indicators to avoid or mitigate accidents in the oil and gas industry – with focus on Integrated Operations?
- RQ3: Is missing situational awareness between key actors, a significant causal factor of accidents in IO?
- RQ4: Is increased complexity and couplings between process and ICT systems a significant causal factor of accidents in IO?

Our aim is to answer these questions below.

4.1 RQ1- main areas and causal factors of accidents - proposed causal factors in IO.

Based on the interviews and exploration of accident reports we have identified three areas influencing accidents:

Poor planning and missing risk assessment (at the blunt end):	Related to causal factor I: Poor design and verification and validation and poor collaboration between workforce and management and II: Poor planning of critical operations/missing risk analysis and poor use of formal work permits. These causal factors have been contributing factors in 33 cases.
Poor operation in critical areas (at the sharp end):	Related to causal factor III: Deviations, IV: Poor management of margins, VI: Miscommunication and VII: Management attention. These causal factors have been contributing factors in 37 cases.
Poor learning and awareness (at the blunt end):	Related to causal factor V. Poor learning and poor training/awareness. These causal factors have been contributing factors in 14 cases.

These groups indicate that the foundation of safety is being established by planning and risk assessment prior to work being done. In operations key issues seems to be management focus, management of margins (drift to danger or conflicting goals between productivity and safety), communication across teams and the ability to learn from prior incidents. These factors are not independent; poor learning may lead to poor design or poor planning of critical operations. Missing risk assessment and poor planning of work may also be due to poor management of margins since production pressure or other factors may lead to less focus on safety related issues or skipping of necessary activities. However – based on the accident reports and the interviews - the three most important causal factors are found to be poor design, missing risk analysis and poor management of margins. Due to the distributed nature of IO – the most important causal factor in IO seems to be miscommunication in critical situations.

To improve safety we have tried to explore knowledge from accident analysis and accident avoidance, the causalfactors can be structured in the following manner. Poor design and poor collaboration is suggested to be mitigated by improved design, exploring standards such as ISO 11064 (2000) and trying to explore an indicator such as S1.1 and S1.2.

Missing risk assessment is suggested to be mitigated by improved risk assessment including qualitative issues such as S2.1, S2.2 and S2.3.

Deviations from procedures are an area of exploration and learning, mitigating actions must be explored, but the issue can be identified through S3.1.

Management of margins must be expored based on the safety critical processes in operations; we have selected issues based on integrated operations of operational processes and maintenace. In drilling and oil and gas production there are several key safety critical processes that should be explored. One issue is indicators related to gas emissions, a key issue when discussing major accidents. Our focus has been to explore resilience and management of production margins through S4.1 and maintenace through S4.2.

Poor learning and missing risk awareness must be explored based on key processes, based on our focus we have suggested to measure poor learning through qualitative assessment based on indicators such as S5.1 or S5.2.

Miscommunication has been identified to technology and organisational issues and should be mitigated through establishing improved technical communication, improved team training and communication supporting safety and exploration of knowledge from remote experts.

Involvement from management should be explored through indicators such as S7.1, in order to identify mitigating actions.

In the following table-2 we have listed the suggested indicators with references to theory, interviews and review of accident reports.

4.2 RQ2 - proactive indicators to mitigate accidents

The identification of causes, causal chains and establishment of indicators or risk influencing factors are difficult. It seems challenging to establish reliability and validity of the suggested indicators. In the following we have referenced the contributions that may support some of the suggested indicators. We have given references to theory, our interviews and accident analysis and the performed survey.

Relationship between theory and indicators are:

- S1.2 “Involvement of stakeholders” may be supported through a relationship between broad based preventive measures and safety as mentioned in Lund (2004).
- S2.1 “Subjective assessment of risk” may be supported through a relationship between risk perceptions in the work force and actual risk levels as mentioned by Fleming (1998). An indicator documenting the risk perceptions could be explored to assess risk levels in operations where relevant.
- S2.2 “Work permits with risk assessment” may be supported through a relationship between risk assessment and safety, as documented in Frola (1984).

Indicators from interviews and analysis of accident reports are listed in the following. Based on the most important causal factors found as root causes in accidents, we suggest prioritizing indicators related poor design, missing risk analysis, poor management of margins and miscommunication in critical situations. In addition, based on the validation found in Næsje (2009), we suggest prioritizing the following indicators:

- S1.1 Number of scenario analysis to validate or verify design
- S1.2 Assessment of involvement and influence (supported by survey and theory as mentioned prior)
- S2.1 Risk assessment from stakeholders (supported by survey and theory as mentioned prior)
- S2.2 Percentage of work permits with risk assessment (supported by survey and theory as mentioned prior)
- S2.3 Number of scenario analysis of hazardous operations
- S5.1 Assessment of ability to learn (supported by survey)
- S6.2 Assessment of communications in teams (supported by survey)
- S7.1 Safety involvement from management (supported by survey)

In some areas we have not identified an explicit relationship between safety and the indicators. We have not found an explicit relationship between deviations from governing documentation and safety. However the deviations should be assessed and analyzed in order to identify the reason behind deviations and possible consequences. Causes could be poor quality of governing documentation, missing training of operators, need to improvise in order to resolve a crisis or other reasons to be identified. An indicator related to deviations from governing documentation could be used as a signal to explore the reason behind the actual deviations.

We have not found an explicit relationship between maintenance backlog and safety. The missing relationships may be due to poor quality of data – however the maintenance backlog could be used as a risk-influencing factor to be explored in a qualitative survey to assess the state of maintenance. The indicator could be used to focus more on the area.

Some causal factors and indicators are based on research and are reliable and valid in the context of their use. The causal factors are interrelated and several root causes can be suggested. Since the factors are interrelated and not all indicators have been validated, we are suggesting using triangulation as an approach. Our suggestion is to use several of the suggested indicators, deemed to be relevant in the area to be managed, as an indicator of the risk level. Exploration and test of validity and reliability of the indicators could be used to increase our understanding of possible causal chains. The stakeholders should discuss validity and reliability of the indicators in relevant arenas of collaboration to ensure involvement and understanding by the users.

We have thus suggested a set of causal factors, and a set of indicators to be used as proactive indicators related to implementation of IO. The indicators must be validated and assessed related to IO implementation. Based on interviews, exploration of accident reports, exploration of theory and exploration of a survey, we have suggested a set of indicators in table-2:

Table-2: Final suggested indicators

Causal factors	Suggested indicators	Support from accident analysis, theory and survey
I. Poor design and poor validation and verification Poor collaboration between workforce/ management	S1.1: Number of scenario analyses performed trying to validate or verify the design or changes S1.2: Subjective assessment of involvement and influence of different stakeholders in change processes, during concept design or later. (Influencing HSE in design, governing documents, procedures etc.);	Poor design is often found as root cause and supports S1.1 S1.2 is supported by theory – Lund (2004) and correlated to high HSE.
II. Missing risk assessment and/or poor planning	S2.1: Subjective assessment of risk in operations. I.e. questionnaire to assess if risky operations are carefully planned, governing documents are used, is the work permit system adhered to, workers assessment of risk (onshore vs. offshore), HSE influence, HSE knowledge and relevancy, HSE in operation, assessment of stress and level of collaboration across silos during risk assessment. S2.2: Percentage of work with formal work permits (i.e. with assessment of risk) including work involving remote collaboration or remote operations. S2.3: Number of scenario analysis (or use of simulator) used to train on hazardous operations (DFU) related to tightly coupled systems. (Involving third parties, collaboration across organizational silos.)	S 2.1 is supported by theory – Fleming (1998) and correlated to high HSE. Poor risk assessment is often found as root cause and supports S2.1. Interviews prioritized S2.1. S 2.2 is supported by theory – Frola (1984) and correlated to high HSE. Poor risk assessment is often found as root cause and supports S2.2. Poor pre planning and poor anticipation is often found as root cause and supports S2.3. Interviews prioritized S2.3.
III. Deviations from established procedures or governing documents	S3.1: Percentage of work orders with deviations and a qualitative assessment of quality of work orders with deviations.	Deviations from work orders is often found as root cause and supports S3.1

IV. Managing margins Conflicting goals between production and maintenance backlog	S4.1: Production (or production loss) vs. optimum production as a % of optimum production. S4.2: Qualitative and quantitative assessment of maintenance backlog. (Qualitative assessment of risk perception among stakeholders involved in operations related to maintenance. Quantitative assessment of prioritized maintenance or changes not performed at due date.)	Interviews prioritized S4.1 Missing maintenance is often found as root cause and supports S4.2. No support from theory.
V. Poor learning from incidents or poor training. Missing risk awareness.	S5.1: Qualitative assessment of ability to learn across teams (in different organizations or silos) and assessment on learning from prior incidents. S5.2: Qualitative assessment of training and experience of key stakeholders involved in IO. (Such as offshore experience when collaborating from onshore.) (The CCR involved in IO should have good training, and there should be a certification scheme of the CCR.)	S5.1, learning from prior incidents, is correlated to high HSE.
VI. Miscommunication between different actors during critical operations	S6.1: Technical stability (% up time) of communication, video/ telephone/ network. S6.2: Qualitative assessment of communication in teams (local and remote) – related to miscommunication between actors during critical operations, concurrent operations. - Level of alertness related to communication S6.3: Utilization of outside experts – i.e. % utilization of third party during problem solving. S6.4: Level of relevant team training (such as CRM).	Interviews prioritized S6.1. S6.2 is correlated to high HSE and has been prioritized as an important causal factor related to IO. Interviews prioritized S6.3.
VII. Poor involvement in safety matters from management	S7.1: Assessment of safety involvement from management, support of HSE and actual guidance or involvement.	S7.1 is correlated to high HSE.

4.3 RQ3 and RQ4 - missing situational awareness or complexity

We have not found that missing situational awareness or complexity has been a direct or referenced causal factor in accidents, but accidents have often happenden when many concurrent activities have been performed, and when there has been poor planning and missing risk assessment. Complexity is an important challenge in operations. However, we have seen that high level of HSE is correlated to awareness of concurrent work operations that may lead to dangerous situations. This supports the need for situational awareness in dangerous operations. High level of IO is negatively correlated to failed communication that means that the possibility of miscommunication decreases at installation with a high level of IO; however this issue is not correlated with HSE level. This may be changed when critical operations are performed between onshore and offshore and should be assessed by the suggested indicators, situational awareness in dangerous operations.

5. CONCLUSIONS AND FUTURE WORK

We have suggested a set of causal factors and a set of indicators to be used to survey the risk level of integrated operations. We have suggested that the foundation of safety is being established by planning, ensuring safety in design and in the actual risk assessment prior to work being done. Especially during implementation of new technology or new procedures as in IO, it is important to perform planning and assess risks; this could be an important factor to assure safety. Deviation from work orders could also be an important issue in IO, since we are involving stakeholders from different organizations having different risk perceptions and different experience, background and safety culture. Management of margins when there are conflicting goals between production and maintenance could be an important issue due to the focus of increase yield or increased efficiencies when IO are implemented. Miscommunication between different actors during critical operations could be one of the key issues in IO, when involving different organizations in operations. Poor involvement in safety matters from management is a key issue in HSE, but especially important when changes are implemented. Poor learning from incidents or poor training could also be an important issue when implementing IO, since we are implementing new technology, new ways of organizing and performing work.

The cause of successful recovery was not sufficently explored, i.e. “why did it not become a worse accident?” a key bias was“What-You-Look-For-Is-What-You-Find” as described by Lundberg (2009). Thus resilience and the ability to “bounce back” were not sufficiently analyzed in the accident reports and should be included in future accident investigations.

We have developed a set of proactive indicators based on exploration of theory and collaboration with industry. The process developing indicators in collaboration with the industry has been an important activity in it self related to risk communication and creating understanding and support for the selected indicators. In addition it is of great interest to follow up if the indicators in general will improve resilience and improve the HSE level. We are planning to assess the effectiveness of the proactive indicators by three criteria:

- Actual HSE levels - documenting incidents and process upsets
- Risk perception from offshore and onshore workforce
- Assessment of safety culture (a broad based assessment)

We are going to focus on different areas such as maintenance, operations and drilling. Within each area we should analyze the different work processes between onshore and offshore. The criticality and safety aspects of the different work processes should be analyzed.

6. ACKNOWLEDGEMENTS

The Centre for Integrated Operations in the Petroleum Industry at NTNU has supported this work.

7. REFERENCES

Argyris, C., Schön, D.A., (1974). “*Theory in practice: increasing professional effectiveness.”* Jossey-Bass, San Francisco.

Argyris, C. and Schön, D. (1978) “*Organizational Learning A Theory of Action Perspective*” Addison-Wesley.

Alteren B., J.Sveen, G.Guttormsen, B.E.Madsen, R.Klev, O.Helgesen (2004) “*Smarter together in Offshore Drilling – a Successful Action Research Project?*” In C.Spitzer, U.Schmocker, V.Dang “PSAM 2004 – Proceedings of the 7th International Conference on Probabilistic safety assessment and Management” ISBN-185233827X, Page 1302-1308, Springer – London.

Antonsen S., Ramstad L.R, Kongsvik, T. (2007) “*Unlocking the Organization: Action Research as Means of Improving Organizational Safety*” Safety Science Monitor, Issue 1 2007, Article 4, Vol 11.

Baker P.D., Day R., Salas, E., (2006). “*Teamwork as an Essential Component of High-Reliability Organizations*”, Health Serv Research 2006 August; 41(4 Pt 2): 1576–1598.

Baker et al. (2007) “*The BP U.S. Refineries Independent Safety Review Panel*” retrieved from http://www.chemsafety.gov /index.cfm?folder=current_investigations&page=info&INV_ID=52

Bier, V. M. (2001). “*On the state of the art: risk communication to the public*”. Reliability Engineering & System Safety, 71, 139-150.

Cook, T.D. and Campbell, D.T. (1979). “*Quasi-Experimentation: Design and Analysis for Field Settings*”. Rand McNally, Chicago, Illinois.

Dawson, D. & Brooks, B. (1999). “*Report of the Longford Royal Comission: The Esso Longford Gas Plant Accident.”* Melbourne: Government Printer for the Stat of Victoria.

Dekker, S. (2006). “*The Field Guide to Understanding Human Error”*, Ashgate

Drottz-Sjöberg, B.-M. (2003). “*Introduction to risk communication. Current trends in risk communication: theory and practice.”* Oslo: Directorate for Civil Defence and Emergency Planning.

Dyreborg, J. (2009) “*The causal relation between lead and lag indicators*” in Safety Science, Volume 47, Issue 4, April, Pages 474-475

EIA (2010) U.S. Energy Information Administration “International Energy Outlook” July 2010, report DOE/EIA-0484, retrieved from www.eia.gov/oiaf/ieo/index.html at 01.08.2010.

Fleming, M., Flin, R., Mearns, K. and Gordon, R. (1998). “*Offshore workers perceptions of risk: Comparisons with quantitative data.”* Risk Analysis, 18 (1), 103-110.

Frola F.R and Miller C.O.(1984) “*System safety in aircraft acquisition*” Technical report, Logistic Management Institute, Washington D.C.

Grabowski, M., & Roberts, K., (1998) "*Risk Mitigation in Virtual Organisations."* Journal of Computer Mediated Communication, Volume 3, Issue 4, June.

Haddon, W. (1980): “*The Basic Strategies for Reducing Damage from Hazards of All Kinds*.” Hazard prevention, Sept./ Oct. 1980.

Hance BJ, Chess C, Sandman PM. (1988) “*Improving dialogue with communities: a risk communication manual for government.”* Trenton, NJ: New Jersey Department of Environmental Protection, 1988.

Henderson J., Wright K., Brazier A. (2002), *“Human factors aspect of remote operation in process plants*”, Prepared by Human Reliability Associates for the Health and Safety Executive, retrieved at: http://www.hse.gov.uk/research/crr_pdf/2002/crr02432.pdf, at 1/3-2008.

Holditch, S.A., Chianelli R.R (2008) “Factors That Will Influence Oil and Gas Supply and Demand in the 21st Century” MRS bulletin, Volume 33, April 2008 retrieved from www.mrs.org/bulletin at 8/5-2010.

Hollnagel E.,Woods D., and Leveson N., (2006) "*Resilience engineering: concepts and precepts",* ed. Ashgate, Aldershot.

Hopkins A.“*Thinking About Process Safety Indicators*” (2007) - Paper at the Oil and Gas Industry Conference Manchester, November 2007.

HSE (2006) “*Developing process safety indicators*” ISBN 0 7176 6180 6.

Hudson, P. and van der Graaf, G. C. 2002: *“Hearts and Minds: The status after 15 years Research.”* (SPE 73941) International conference on HSE in Oil and Gas Exploration and production. Kuala Lumpur 20-22 March 2002.

IAEA 2001. “*A Framework for the establishment of plant specific operational safety performance indicators*”, (report), International Atomic Energy Agency, Viena, Austria.

Itoh K, Andersen H.B, Seki M. (2004). “*Track maintenance train operators’ attitudes to job, organisation and management, and their correlation with accident/incident rate.”* Journal Cognition, Technology & Work, Springer London, Vol 6, No 2/May, 2004, Pages 63-78.

ISO/IEC Guide 51 (1999) "Safety Aspects – Guidelines for their Inclusion in Standards." ISO.

ISO 11064 (2000) “*Ergonomic design of control centres*” see ISO standards at: http://www.iso.ch/iso.

ISO 17776 (2000) “*Petroleum and natural gas industries -- Offshore production installations -- Guidelines on tools and techniques for hazard identification and risk assessment*” see ISO standards at: http://www.iso.ch/iso.

Jackson, S.,Madni, A. M. 2008 “*A Practical Framework for the Architecting of Resilient Enterprises”* In Hollnagel E, Pieri F., Rigaud E. 2008 “Proceedings of the third Resilience Engineering Symposium” Ecole des mines de Paris.

Johnsen S.O., Bjørkli C., Steiro T., Fartum H., Haukenes H., Ramberg J., Skriver J.. (2008): “*CRIOP – A scenario method for Crisis Intervention and Operability analysis*”. SINTEF (2008) ISBN 9788214042962. See www.criop.sintef.no

Johnsen S., Ask R., Røisli R. (2008a) "*Reducing Risk in Oil and Gas production"* from Goetz E., Shenoi S. "Critical Infrastructure Protection" - Springer : Chapter 7: ISBN 978-0-387-75461-1.

Johnsen, S., Håbrekke, S. (2008b)."*Can organisational learning improve safety and resilience during changes.*" In Safety, Reliability and Risk Analysis: Theory, Methods and Applications. Taylor & Francis ISBN 978-0-415-48513-5. pp 805-815

Kim, D.H. (2004) “The link between individual and organizational learning” in “How organizations learn” Stakey, K., Tempest, S. McKinlay, A. ; Thomson Learning.

Kumar, U. and Ellingsen, H. P. (2000). "*Development and implementation of maintenance performance indicators for the Norwegian oil and gas industry."* Proceedings of the 14th International Maintenance Congress (Euro maintenance 2000), 7-10 March, Gothenburg, Sweden, pp. 221-228.

LaPorte and Consolini (1991) "*Working in Practice But Not in Theory: Theoretical Challenges of High-Reliability organizations*" J Public Adm Res Theory.; 1: 19-48

Leveson, N. (1995). "Safeware – system safety" Addison-Wesley.

Lewycky, P. "Notes toward an understanding of accident causes", Hazard Prevention, pages 6-8, March/April 1987.

Lund, J. Aarø, L.E. (2004) "*Accident prevention. Presentation of a model placing emphasis on human, structural and cultural factors*" Safety Science 42, s271-324

Lundberg, J., Rollenhagen, C. , Hollnagel, E. "What-You-Look-For-Is-What-You-Find – The consequences of underlying accident models in eight accident investigation manuals" Safety Science, Volume 47, Issue 10, December 2009, Pages 1297-1311

MacMillan, J., Paley, M. J., Entin, E. B., & Entin, E. E. (2004). "*Questionnaires for distributed assessment of team mutual awareness*". In E. Salas (Ed.), "Distributed assessment," in The handbook of human factors and ergonomic methods. Taylor and Francis

Mumford, E. (1984) "*Participation – from Aristotle to today*" in Bemelmanns, T.M.A "Beyond productivity:information systems development for organizational effectiveness" North_holland, P.95-104.

NAE (2004), National Academy of Engineering "Accident precursor analysis and management", The National Academies Press, Washington.

NC (2010) National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling, "DEEP WATER - The Gulf Oil Disaster and the Future of Offshore Drilling" retrieved at 16/1-2011from www.oilspillcommission.gov/sites/default/files/documents/DEEPWATER_ReporttothePresident_FINAL.pdf

Næsje, P. (2009) "*Effects of Integrated Operations on Offshore Installations' Health and Safety performance"* – SINTEF A12025, ISBN: 978-82-14-04826-1.

OED 2010 – "Økt utvinning på norsk kontinentalsokkel " retrieved at 20/1-2011 from www.regjeringen.no/upload/OED/pdf%20filer/Oktutvinning.pdf

Oljeindustriens Landsforening (OLF - Norwegian Oil Industry Association) 2004: "*The Future of the Norwegian Oil and Gas Industry*". [retrieved 2007 01.08]; Available from: http://www.olf.no/io/rapporterpresentasjoner/?23939.pdf.

Oljeindustriens Landsforening (OLF - Norwegian Oil Industry Association). 2005. "Integrated Work Processes." retrieved 1/2-2010 www.olf.no/Rapporter/Dokumenter/051101%20Integrerte%20arbeidsprosesser%2C%20rapport.pdf.

Parida A. 2006. "*Development of a Multi-criteria Hierarchical Framework for Maintenance Performance Measurement Concepts, Issues and Challenges*" PhD thesis Luleå TU.

PSA accidents from 2008- reports in Norwegian, retrieved from www.ptil.no at 2/2 - 2009:

1-"Gransking av gassutblåsning på Snorre A, brønn 34/7-P31A 28.11.2004"
2-"Granskingsrapport etter hendelse knyttet til oljeforurensning på Draugenfeltet 19.5.2003"
3-"Gransking av gasslekasje på Valhall PCP 12.1.2004"
4-"Rapport etter dødsulykke på Byford Dolphin 17.04.2002"
5-"Dødsulykke, Nyhamna 28.6.2005"
12-"Gransking av ulykke med personskade på boredekk Statfjord C 25.3.2005"
13-"Brann på Åsgard B 15.10.2005"
14-"Gransking av alvorlig personskade på Oseberg B 26.4.2005"
15-"Utslipp av hydraulikkolje fra transportsystem for utblåsningssikringsventil (BOP gaffel) på Eirik Raude"
16-"Granskingsraport etter hendelse knyttet til gasslekasje fra 6" rørledning fra Jotun A"
17-"Gransking av ankerkjetting utrausing på Ocean Vanguard 14.12.2004 brønn 6406/1-3"
20-"Rapport etter gransking av to helikopterhendelser; feillanding og nesten feillanding på Ringhorne"
21-"Gransking av brønnspark I brønn 2/8-A08B Valhall DP i desember"

22-”Gransking av alvorlig gasslekasje fra trykkavlastning på Visund 19.1.2006”
23-”Gransking av alvorlig personskade på Valhall 2.4.2004”
24-”Gransking av hendelse med personskade på Ekofisk 2/4-X 13.1.2006”
25-”Utslipp av hydraulikk på Eirik Raude 12.4.2005”
26-”Utslipp av baseolje Gullfaks A 28.02.2004”
27-”Gransking etter hendelse knyttet til brønn 2/4 C-16 på Ekofisk”
28-”Gransking av alvorlig personskade på Oseberg B 26.4.2005”

Perrow, C. (1984): “*Normal Accidents.”* New York: Basic Books.

Rasmussen, J. (1997). “*Risk Management in a Dynamic Society*” Safety Science, 27, 183-213.

Ray P.S, et.al - Batson R.G, Weems W.H, Wan Q., Sorock G.S, Matz S. And Cotnam J. (2000). “*Impact Of Maintenance Function On Plant Safety*” American Society Of Safety Engineers, August 2000, Page 45-48,

Reason, J. (1997) “*Managing the Risks of Organizational Accidents.”* Aldershot, UK: Ashgate.

Roberts, K. (1989) “*New challenges in Organizational research: high reliability organizations*”, Organization & Environment, Vol. 3, No. 2, pp 111-125.

Rowan K.E. (1991) “*Goals, obstacles and strategies in risk communication; a problem solving approach to improving communication about risks.*” Journal of applied communication research 1991; 19:300-29

Richter, A. (2003): “*New Ways of managing Prevention: A Cultural and Participative Approach”*. Safety Science Monitor 1: 2003.

Salas E., Fiore S.M. (2004) “*Team Cognition*” Washington.

Stortingsmelding 38, (2004) retrieved at 3/12-2009 from www.regjeringen.no/nb/dep/oed/dok/regpubl/stmeld/20032004/Stmeld-nr-38-2003-2004-.html?id=404848.

Thompson KM, Bloom DL. (2000) “*Communication of risk assessment – information to risk managers*”. Journal of Risk Research 2000, 3:333-52.

Turner, B., Pidgeon N., (1997) “*Man-made disasters*” 2nd ed. Oxford, Heinemann.

Westrum, R. (2003). “*Removing Latent Pathogenes*” from 6th Australian Aviation Psychologists’ Conference, Sydney.

Weick, K.E. and Sutcliffe, K.M. (2001) “Managing the Unexpected: Assuring High Performance in an Age of Complexity” Vol.1. New York: Joh Wiley and sons.

Woods, D.D. and Wreathall J. (2008). *“The stress-Strain Analogy of Organizational Resilience.”* In “Remaining Sensitive to the Possibility of Failure”. E.Hollnagel, C.Nemeth and S.Dekker. Burlington, VT. Ashgate.

WordNet – Retrieved from the lexical database at /wordnet.princeton.edu/ 4/11-2009.

Øien K., Utne, I.B., Herrera, I.A. (2011) “Building Safety indicators: Part 1- Theoretical foundations” Safety Science 49 (2011) 148-161.