RISK MANAGEMENT IN THE OIL AND GAS INDUSTRY

INTEGRATION OF HUMAN, ORGANISATIONAL AND TECHNICAL FACTORS

by

JON ESPEN SKOGDALEN

Thesis submitted in fulfilment of
the requirements for the degree of
Philosophiae Doctor
(PhD)

Faculty of Science and Technology
Department of Industrial Economics, Risk Management and Planning
University of Stavanger
Norway
2011

University of Stavanger
N-4036 Stavanger
Norway

www.uis.no

ISBN: 978-82-7644-469-8
ISSN: 1890-1387

PhD thesis no. 142

Picture 1. Fire boat response crews battle the blazing remnants of the Deepwater Horizon April 21, 2010. Source: US Coastguard. Reproduced with permission.

PREFACE

The Macondo blowout on April 20th, 2010 raised serious concerns about the safety level in the oil and gas industry. The rig was considered to be a safe and efficient drilling vessel. The very same day as BP officials visited the rig to praise seven years without personnel injuries, gas exploded up the wellbore onto the deck of the rig and caught fire. Eleven workers were killed in the explosions (DHJIT, 2010). The blowout caused oil to gush out of the damaged well for two months, resulting in the worst environmental disaster in US history, impacting local economies, sensitive coastlines and wildlife throughout the Gulf region (USDI, 2010).

According to the National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling (hereafter, the Commission), a result of the Macondo blowout is a dramatic reassessment of the risks associated with offshore drilling. Before April 20th, many believed that drilling in deep waters might be safer than in shallow waters. Since deepwater rigs worked farther off the coast, it would take longer for spilt oil to reach shore, giving more time for intervention to protect the coast. Moreover, the companies working in the deeper waters were seen as the “big guys” who utilized more advanced technologies than the smaller firms working near the coast, which presumably made them more adept at handling challenging conditions (Commission, 2010a). The Commission concluded (Graham et al., 2011):

- The explosive loss of the Macondo well could have been prevented,
- The immediate causes of the Macondo well blowout can be traced to a series of identifiable mistakes made by BP, Halliburton and Transocean that reveal such systematic failures in risk management that they place in doubt the safety culture of the entire industry,
- Just as the Commission learned from the experiences of other nations in developing our recommendations, the lessons learned from the Deepwater Horizon disaster are not confined US own government and industry, but relevant to rest of the world.

This thesis was written in the period 2008–2011. The period started with the financial crisis that was triggered by a liquidity shortfall in the United States banking system. Until the weekend of 12–14 September 2008, the belief that Lehman Brothers would be the subject of bankruptcy was beyond comprehension. Lehman Brothers was one of the largest investment banks in the world. It reported consolidated assets of over $600 billion and liabilities of almost that amount (Taylor, 2009). The financial crisis resulted in the collapse of several large financial institutions, the bailout of banks by national governments and downturns in stock markets around the world. It is considered by many economists to be the worst financial crisis since the Great Depression of the 1930s (Pendery, 2009).

In 2010, the Deepwater Horizon accident caused oil to gush out of the damaged well. President Obama described the accident as the worst environmental disaster in US history. In 2011, the Great East Japan Earthquake occurred. The earthquake triggered destructive tsunami waves that travelled for kilometres onshore. In addition to the loss of life and destruction of infrastructure, the tsunami caused nuclear accidents. Ironically, the Commission pointed to the nuclear industry when it came to learning about improving safety (Graham et al., 2011).

Hope is not a suitable risk management strategy!

From a risk analysis perspective, it is clear that *hope* is not a suitable risk management strategy for major hazards. Unfortunately however, it seems as though it is a common strategy. Accident investigations have shown that signs about the crisis were available for a long time in advance.

The crises mentioned are linked. The downturns in the stock markets added pressure to reduce costs. Several of the decisions related to the Deepwater Horizon accident were related to reducing costs. The diminished faith in atomic energy will add pressure to increase oil production, meaning more offshore drilling and production in extremely hostile environments.

The Macondo blowout influences this thesis in multiple ways related to scope, data, research approach and results. According to the Commission, a result of the Macondo blowout is the need for a dramatic reassessment of the risks associated with offshore drilling (Graham et al., 2011). A basic question is then: "*What is risk?*" Unfortunately, there is confusion concerning the concept of risk. This confusion also influences how risk is analysed and managed. There is a need for uniting forces across scientific disciplines for further improvements within the field of risk management. This includes willingness to accept other views and the movement of system boundaries. The readers of this thesis should have in mind the wish for a broad and multidisciplinary approach.

ACKNOWLEDGMENTS

This thesis is submitted in fulfilment of the requirements for the degree of Philosophiae Doctor (PhD) at the University of Stavanger (UiS), Faculty of Science and Technology, Norway. The courses have been lectured at the University of Stavanger, Norwegian University of Science and Technology (NTNU) and MINES ParisTech - Centre for Research on Risks and Safety (France). Being a student once more has been excellent, and my gratitude goes to all the lecturers.

I acknowledge the University of Stavanger, Fulbright and the Research Council of Norway for their financial support that has given me the chance to gain a deeper understanding of my field of speciality. The financial support gave me also the opportunity to have a research stay at the University of California (UC) Berkeley. I express my deep gratitude to Professor Robert G. Bea. His combination of massive experience and go-ahead spirit can move mountains!

Professor Bea invited me to become a member of the Deepwater Horizon Study Group (DHSG) at the Center for Catastrophic Risk Management (CCRM) UC Berkeley. It has been a privilege and a pleasure to work in a group of international experts. We have had many hours on the phone and have exchanged a large number of emails (715 to be precise), but several of us have never met face-to-face. I hope we will do! Special thanks to Professor Paul R. Schulman (Government Department, Mills College, Oakland), Emery Roe (CCRM) and Anthony Hare (CCRM) for their support and valuable discussions.

The work carried out by the DHSG has been followed by the media and industry. I would like to thank the journalists Leiv Gunnar Lie (UiS) Ole Helgesen (Teknisk Ukeblad) and Maren Næss Olsen (DN) for thorough articles, discussions and media guidance. I would also like to thank Per Dybvik (Statoil), Eivind Høieggen (ENI), Gisle Stjern (Statoil), Malene Sandøy (CopNo), Finn-Roger Hoff (Statoil), Rune Alterås (Norwegian Oil Industry Association) and Ranveig K. Tinmannsvik (SINTEF) for the interest they have shown in our work.

I would like to thank the administrative staff both at UiS and at Fulbright. Their support has made the administrative process as easy as possible. Special thanks to the administrative coordinator of the research training secretariat at the Faculty of Science and Technology, Elisabeth S Fiskå and Head of International Office at UiS Bjarte Hoem for their great help and support.

I would like to thank Professor Trond Pettersen (UC Berkeley), my colleagues at the UiS, “The Norwegian House, UC Berkeley” and Safetec for a great working environment. Special thanks to Professor Terje Aven at UiS for valuable discussions and contributions to the field of risk management. I wish also to thank my co-supervisor Per M. Schiefloe at NTNU and all my co-authors. A special thanks to junior researcher Jahon Khorsandi (UC Berkeley) for proofreading, discussions and support.

I express my sincere gratitude to my adviser and friend Professor Jan Erik Vinnem. His huge amount of knowledge, positive attitude, engagement in public safety and excellent mentoring make him a true scientist and the best supervisor I could have wished for. He has offered excellent guidance, meaning that every time I have headed off the road he has forced me back on track. His quick responses, usually within minutes on emails and a few hours on paper reviews, have given me the chance to decide the road speed myself. It has been a pleasure and honour to have him as my mentor and adviser!

Thanks to my friends and family for support, especially my parents for their continued support in all my choices.

Finally, I thank my wife Ingrid and our two beautiful kids Jonas and Ina for their great support and love, and for putting everything into perspective.

Jon Espen Skogdalen

Fossegrenda, 30th of October 2011

SUMMARY

The overall objective of this thesis is to provide knowledge and tools for the major hazard risk assessment for offshore installations (and onshore plants) based on an improved understanding of the influence of organisational, human and technical (OMT) factors. This extensive objective was further described by the following sub-goals:

1. Identify and describe human and organisational barriers in risk analysis,
2. Provide knowledge regarding human, organisational and technical factors that influence safety barriers,
3. Define indicators that are suitable for the measurement of barrier performance,
4. Develop models for barrier performance reflecting human, organisational and technical factors

These four sub-goals formed the basis for the more specific objectives in the articles. The Deepwater Horizon accident and Macondo blowout were important inputs for several of the articles. One important acknowledgement is that risk management of major hazards differs from managing occupational safety. Another is that managing risks in the oil and gas (O&G) industry demands a high level due to the potential severe consequences.

Quantitative risk analyses/assessments (QRAs) are used for risk control in the O&G industry. An important part of the QRA process is to identify and describe barriers in risk analysis. A study of offshore QRAs (Skogdalen and Vinnem, 2011b) showed that there were large differences between the analyses regarding incorporation of human and organisational factors (HOFs). The study divided the QRAs into a four-level classification system. Level 1 QRAs did not describe or comment on HOFs at all. By contrast, relevant research projects were conducted to fulfil the requirements of level 3 analyses. At this level, there was a systematic collection of data related to HOFs. The methods for analyzing the data were systematic and documented, and the QRAs were adjusted according to the status of the HOFs.

A second study of QRAs (Skogdalen and Vinnem, 2011a) revealed that the analyses largely only calculated the frequency of blowouts based on the number of drilling operations. The QRAs did not include HOFs related to drilling hazards. As seen in the Macondo blowout, most of the findings were related to HOFs such as work practice, competence, communication, procedures and management. Drilling is an iterative process where changes are made constantly. These changes add, remove or change human, organisational and technical risk influencing factors (RIFs) in order to mitigate hazards and control risks. QRAs have traditionally been focused on technical systems and capabilities. Much less attention has been given to HOFs. Revealing and understanding HOFs are of great importance for ensuring the intended safety barriers when conducting drilling operations.

When a major hazard occurs on an installation, evacuation, escape and rescue (EER) operations play a vital role in safeguarding the lives of personnel. In a study

(Skogdalen et al., 2011a), EER operations were divided into three categories depending on the hazard, time pressure and RIFs. The study contributes to an improved understanding of safety barriers during EER operations.

Surveys are often used to measure the opinions about how organisational, human and technical factors influence safety barriers. A study (Skogdalen and Tveiten, 2011) showed that the perception and comprehension of safety differed significantly on Norwegian offshore installations between offshore installation managers (OIMs) and the rest of the organisation. The basis for the analysis was a safety climate survey completed by offshore petroleum employees on the Norwegian Continental Shelf. The OIMs had the most positive perception of the following factors: safety prioritisation, safety management and involvement, safety versus production, individual motivation and system comprehension. The different safety perception and comprehension may be influenced by group identity, different knowledge and control and issues of power and conflict. The phenomenon of different safety perception and comprehension between these groups is important to bear in mind when planning surveys as well as planning and implementing risk treatment measures.

An important question with respect to the Macondo blowout is whether the accident is a symptom of systemic safety problems in the deepwater drilling industry. An answer to such a question is hard to obtain unless the risk level in the O&G industry is monitored and evaluated over time. The number of kicks is an important indicator of the whole drilling industry, because it is an incident with the potential to cause a blowout. Currently, the development and monitoring of safety indicators in the O&G industry seems to be limited to a short list of “accepted” indicators, but there is a need for more extensive monitoring and understanding of correlation between indicators. Based on the experience of the Macondo blowout, possible indicators for drilling can be related to the subject areas: schedule and cost, well planning, operational aspects, well incidents, operators’ well responses and the status of safety critical equipment. These indicators can be important inputs for QRAs as well as providing knowledge regarding how organisational, human and technical factors influence safety barriers (Skogdalen et al., 2011b).

Accident investigation is the collection and examination of facts related to a specific incident. QRA is the systematic use of the available information to identify hazards and probabilities, and to predict the possible consequences to individuals or populations, property or the environment. Traditionally, QRA and accident investigation have been used separately; however, both methods describe hazards in a systematic way. The research related to including HOFs in QRA brings accident investigation and QRA closer together (Skogdalen and Vinnem, 2011). Over one hundred precursor incidents with the potential to cause major accidents in the North Sea O&G industry, are recorded every year. It is possible to combine accident investigation and QRA to develop new or improved models. This by using the available information from a precursor incident as input into the QRA methodology to identify hazards, probabilities, safety barriers and possible consequences (Skogdalen and Vinnem, 2011).

This thesis argues for extended and multidisciplinary investigations of precursor incidents. Risk is managed at all levels of an organisation and in a socio-technical system. Communication between the stakeholders is essential, and unfortunately it often fails. More extensive analyses of precursor incidents can be the basis for improving the communication, management of change and understanding of potential accidents. There seems to be agreement among the stakeholders involved in the O&G industry that safety culture, operational aspects, technical conditions and the number of precursor incidents are influencing each other, but there is a lack of understanding on how and why. This understanding can be achieved by combining and improving existing methods within the framework and process of risk management. Examples of existing methods are: QRA, safety monitoring through the use of indicators, the investigation of precursor incidents and accident investigations. Integration of human, organisational and technical factors in risk assessments is a challenge that adds complexity to the existing models, but also can reduce the uncertainty. The more extensive use of indicators can support the monitoring and review process. This is important to ensure that a greater diversity of risk analysis tools actually support the improved management of risk.

There is a need for extensive gathering of data across the O&G industry worldwide. Examples of data are unwanted events, precursor incidents, operational aspects and the technical conditions of safety critical equipment. Knowledge about the factors that influence risk as well as their interaction and status, is essential for managing risk and needs to be supported by data.

The suggestions made in this thesis are only small steps in the process, and further research is necessary to:

- Improve methods for precursor incident reporting,
- Improve methods for precursor investigation,
- Extend the collection of safety indicators,
- Analyse the correlation among safety indicators,
- Improve the understanding of the correlation and possible use of safety indicators,
- Improve the data sets used in QRAs, and
- Establish an industry standard for how HOFs should be incorporated into QRAs.

PART I

PART II – ARTICLES

1. Skogdalen, J.E., Vinnem, J.E., (2011). *Quantitative risk analysis offshore--Human and organizational factors*. Reliability Engineering & System Safety, 96: 468–479.
2. Skogdalen J.E., Vinnem J.E., (2011). *Quantitative Risk Analysis of drilling, using Deepwater Horizon as case*. Submitted for Reliability Engineering & System Safety. 10 May 2011.
3. Skogdalen J.E, Khorsandi J., Vinnem JE., (2011). *Evacuation, escape and rescue experiences from offshore accidents including the Deepwater Horizon*. Journal of Loss Prevention in the Process Industries, Accepted manuscript. DOI: 10.1016/j.jlp.2011.08.005
4. Skogdalen J.E. and Tveiten C. (2011). *Safety perceptions and comprehensions among offshore installation managers on the Norwegian Continental Shelf*. Invited to publication in special issue based on paper delivered to The 5th International Conference Workingonsafety.net. Røros, Norway 2010. Submitted for Safety Science, 12 November 2010. Accepted with revisions 24 May 2011. Resubmitted 09 August 2011.
5. Skogdalen, J.E., Utne, I.B., Vinnem, J.E., (2011). *Developing safety indicators for preventing offshore oil and gas deepwater drilling blowouts*. Safety Science, 49: 1187–1199.
6. Skogdalen JE., (2010) *Safety engineering and different approaches*. Safety Science Monitor, 14.
7. Skogdalen J.E., Vinnem J.E., (2011). *Combining precursor incidents investigations and QRA in oil and gas industry*. Submitted for Reliability Engineering & System Safety, Accepted with revisions 06 September 2011.

Articles, papers, chronicles and working papers not included in this thesis

8. Vinnem J.E., Hestad J.A., Kvaløy J.T., Skogdalen J.E., (2010) *Analysis of root causes of major hazard precursors (hydrocarbon leaks) in the Norwegian offshore petroleum industry*. Reliability Engineering & System Safety. 95:1142–53.
9. Smogeli Ø., Skogdalen J.E., *Third party HIL testing of safety critical control system software on ships and rigs*. Offshore Technology Conference. 2011, Houston, USA.
10. Skogdalen J.E., Tveiten C., *Safety perception and comprehension among offshore installation managers on Norwegian offshore petroleum production installations*. The 5th International Conference Workingonsafety.net. 2010. Røros, Norway.

11. Skogdalen J.E., Vinnem J.E., *Risk influence factors related to helicopter operations in the North Sea*. PSAM10, 2010, Seattle, USA.
12. Skogdalen JE, Vinnem JE., (2010) *Risk influence factors related to evacuation from offshore installations*. Reliability, Risk, and Safety, CRC Press, 2239-47.
13. Okstad E.H., Sørli F., Wagnild B.R., Skogdalen J.E., Haugen S., Seljelid J., et al. *Human and organizational factors effect on safety barriers in well operations*. IADC Drilling HSE Europe Conference & Exhibition 09. 2009,Amsterdam, The Netherlands.
14. Skogdalen J.E., Haugen, S., Heldal F., Holo B., Okstad E., Sunniva A.S., Vinnem J.E., *Analysis of barriers in marine operations on offshore oil installations*. Proceedings of the ASME 28th International Conference on Ocean, Offshore and Arctic Engineering. 2009, Hawaii, USA.

Chronicles [In Norwegian]:

15. Skogdalen JE. *Best in the class, but…*...... Teknisk Ukeblad. 24 February 2011.
16. Skogdalen JE. *Systemic failure caused the BP-catastrophe*. Teknisk Ukeblad. Norway. 16 December 2010.
17. Skogdalen JE. *Great damage, limited learning*. Dagens Næringsliv. 07 May 2010.
18. Skogdalen JE. *High speed train and risk*. Adresseavisen. 02 June 2009.

Working papers (research papers submitted as member of Deepwater Horizon Study Group (DHSG)):

19. Skogdalen JE and Smogeli Ø. *Looking Forward - Reliability Of Safety Critical Control Systems On Offshore Drilling Vessels.* Working Paper. Deepwater Horizon Study Group. January 2011.
20. Skogdalen JE, Khorsandi J and Vinnem JE. *Evacuation, Escape And Rescue (EER) From The Deepwater Horizon Rig*. Working Paper. Deepwater Horizon Study Group. January 2011.
21. Skogalen JE, Utne IB and Vinnem JE. *Developing safety indicators for preventing offshore oil and gas deepwater drilling blowouts*. Deepwater Horizon Study Group. January 2011.

Working papers can be downloaded from:
http://ccrm.berkeley.edu/deepwaterhorizonstudygroup/dhsg_resources.shtml

Updated, rewritten and extended versions of the working papers were the basis for two of the journal articles and one of the conference papers.

PART I

1 INTRODUCTION

1.1 Background

Safety can be defined as those activities that seek either to minimise or to eliminate hazardous conditions that can cause bodily injury. Safety was not considered to be a matter of public concern in ancient times, when accidents were regarded as inevitable or as the will of the gods. Modern notions of safety developed only in the 19th century as an outgrowth of the Industrial Revolution, when a terrible toll of factory accidents aroused humanitarian concern for their prevention. Today, the concern for safety is worldwide and is the province of numerous governmental and private agencies at local, national and international levels (EBO, 2008). The concept of risk and how to analyze and mange risk, are essential parts of safety engineering.

The concept of risk is dealt with in several scientific disciplines, including natural sciences, medical, statistical, legal safety engineering, economics, sociology and psychology. Each discipline tends to focus on different aspects of risk, and traditionally some of the different disciplines' perspectives have been viewed as representing completely different frameworks. None of these disciplines can grasp the entire substance of this issue alone. Only if they combine forces can one expect an adequate approach to understanding and managing risks (Aven and Kristensen, 2005; Aven and Renn, 2010). The concept of risk, and how to analyse risk, has proven to be a difficult one to define (Flage, 2010), as recollected by Kaplan (1997); "*The words of risk analysis have been, and continue to be a problem. Many of you here remember that when our Society for Risk Analysis was brand new, one of the first things it did was to establish a committee to define the word 'risk.' This committee labored for 4 years and then gave up, saying in its final report, that maybe it's better not to define risk. Let each author define it in his own way, only please each should explain clearly what way that is*."

The oil and gas (O&G) industry is often viewed as a leading industry within the field of safety engineering. Even so, on April 20th 2010 the industry experienced one of the largest offshore oil spills ever, resulting in the worst environmental disaster in United States (US) history. The Macondo blowout occurred after a dramatic, three-decade long reconfiguration of how the US and several other nations drill for oil. Technology, law and geology made it possible for oil exploration to move farther from shores, as land-based exploration became less fruitful, and the global demand for energy ramped up (Commission, 2010a).

Oil production off coasts began well over a century ago, but the move into deepwater (>300 m) and ultra-deepwater (>1500 m) is a relatively recent phenomenon (Commission, 2010a). According to the National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling (hereafter, the Commission) the Macondo-blowout requires a dramatic reassessment of the risks associated with offshore drilling. Before April 20th, many believed that drilling in deep waters might be safer than in shallow waters. Since deepwater rigs worked farther off the coast, it would take longer for spilt oil to reach shore, giving more time for intervention to protect the coast. Moreover, the companies working in the deeper waters were seen as the “big guys” who utilised more advanced technologies than the smaller firms working near the coast, which presumably made them more adept at handling challenging conditions (Commission, 2010a).

Drilling in deepwater launched new hazards and potential consequences. The drilling rigs themselves bristle with potentially dangerous machinery. The deepwater environment is cold, dark, distant and under high pressures, and the O&G reservoirs exist at even higher pressures, compounding the risks if a well gets out of control. The Macondo well vividly illustrated all of those hazards. When a failure happens at such depths, regaining control is a formidable engineering challenge and the costs of failure can according to the Commission, be catastrophically high (Graham et al., 2011).

The Macondo blowout was a sequence of events with high complexity, large uncertainty and severe consequences. Complexity refers to the difficulty identifying and quantifying causal links between a multitude of potential causal agents and specific effects. These complexities make sophisticated scientific investigations necessary since the dose–effect relationship is neither obvious nor directly observable. Uncertainty refers to the difficulty of predicting the occurrence of events and/or their consequences based on incomplete or invalid databases, possible changes of the causal chains and their context conditions, extrapolation methods when making inferences from experimental results, modelling inaccuracies or variations in expert judgments (Aven and Renn, 2010).

It was long assumed that the numbers of occupational injuries reflected a facility’s major hazard risk level. Several accidents have shown the failure of such an assumption, for example, the explosion at a Shell Chemical Company plant in Deer Park, Texas in 1997 (EPA/OSHA, 1998) and the BP Texas City refinery disaster in 2005. Relying on injury rates as an indicator of safety level significantly hindered BP’s perception of process risk. As a result, BP’s corporate safety management system for its US refineries did not effectively measure and monitor safety performance. Eventually, an explosion occurred at the refinery, killing 15 workers and injuring more than 170 others (Baker et al., 2007). Since occupational safety is mainly about avoiding slips, trips and falls among employees, it does not represent the management of major hazard risk. Major hazards have the potential to cause major accidents. A major accident in the O&G industry is often understood as an accident out of control with the potential to cause five fatalities or more, caused by the failure of one or more of the system’s safety barriers (HSE, 2010).

Risk management can be defined as the coordinated activities to direct and control an organisation with regard to risk (ISO, 2009a). The main steps in the risk management process are the establishment of the framework, risk assessment and risk treatment. Framework conditions here refer to the internal and external environment of the organisation, the interface of these environments, the purpose of the risk management activity and suitable risk criteria. Risk treatment is the process of modifying risk, which may involve avoiding, modifying, sharing or retaining risk (ISO, 2009a). Two central elements of risk management are to establish an informative risk picture for the various decision alternatives and to use this risk picture in a decision-making context (Aven et al., 2007). Establishing an informative risk picture involves revealing the relevant risk influencing factors (RIFs) that may cause accidents and influence the consequences. A RIF is defined as ‘an aspect (event/condition) of a system or an activity that affects the risk level of this system or activity’ (Øien, 2001b). A given RIF (e.g. an organisational factor) might not be directly measurable. This is denoted as ‘the measuring problem’ within social science research (Hellevik, 1999).

There exist some qualitative knowledge about how human errors may contribute to causing accidents, but there is limited knowledge about how the performance of barriers depending on human and organisational factors (HOFs) quantitatively influences the probability of major accidents and associated risks (Vinnem, 2008a). As seen in the Macondo blowout, most of the findings from the investigations (Bartlit et al., 2011; Graham et al., 2011) were related to HOFs such as work practice, competence, communication, procedures and management. To improve risk management, there is a need for more knowledge related to how human, organisational and technical influence on risk and how this can be analyzed.

1.2 Objectives for the PhD

This thesis has almost the same title as the research project if which it is a part of; Risk Modelling – Integration of Organisational, Human and Technical factors (often referred to as the OMT-project). The main objective of the thesis is:

Provide new knowledge and tools for major hazard risk management for offshore installations (and onshore plants) based on the improved understanding of the influence of organisational, human and technical factors.

The research efforts contribute to bridging the gap between the extensive knowledge about organizational and human factors in general, and the lack of knowledge regarding how to reduce the major hazard risk level due to operational causes.

The following six sub-goals were defined for the OMT-project:

1. Identify and describe organisational and operational barriers for risk control,
2. Provide new knowledge about the effectiveness of organisational, human and technical factors for the performance of operational barriers,
3. Define indicators for these factors that are suitable for the measurement of barrier performance and establish methods on how to measure the status of these factors,
4. Develop new models for barrier performance reflecting organisational and operational management factors,
5. Demonstrate the use of the models through case studies and proposed risk reduction measures and
6. Analyse experience data to identify those risk management regimes that are most effective.

The numbering did not indicate the prioritisation of the sub-goals. The objectives for the PhD were related to the sub-goals 1–4 of the OMT project. The sub-goals were further specified during the PhD process:

1. Identify and describe human and organisational barriers in risk analysis,
2. Provide knowledge regarding human, organisational and technical factors that influence safety barriers,
3. Define indicators that are suitable for the measurement of barrier performance,
4. Develop models for barrier performance reflecting human, organisational and technical factors.

Figure 1 summarises the PhD’s objective, sub-goals and articles.

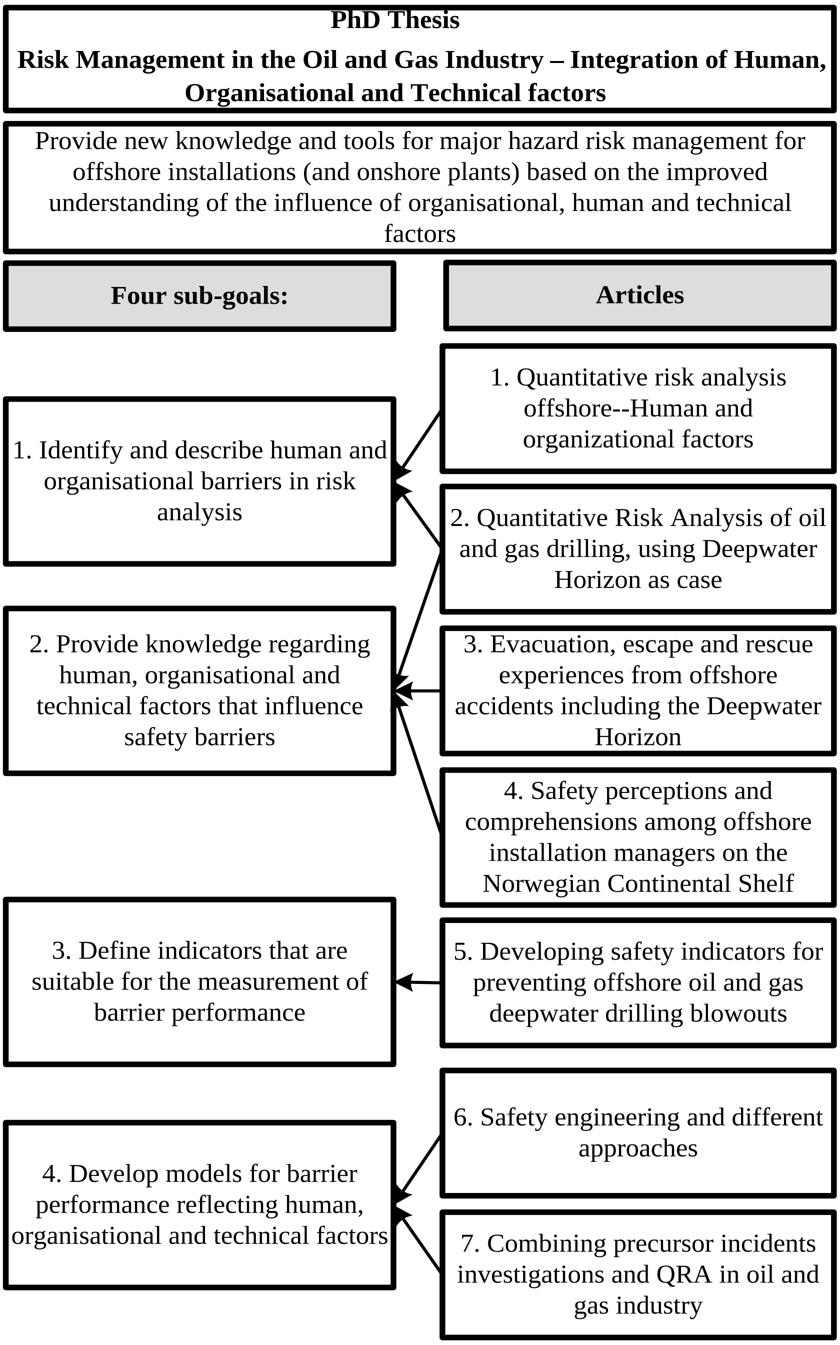


Figure 1 PhD Structure

The research is summarised in the following table describing the objectives and/or main result in each of the articles. Each article had separate objectives and sub-goals.

Table 1 Articles and objectives and/or main results

	Article	**Objectives and/or main result**
1.	Quantitative risk analysis offshore - human and organizational factors	The article had three objectives. The first objective was to study how the legislation on offshore activities on the Norwegian shelf have influenced the development of QRAs. Secondly, a set of QRAs was investigated to see in what way the legislation was reflected, and if and how HOFs were included. Thirdly, the different levels of the integration of HOFs in QRAs were classified.
2.	Quantitative Risk Analysis of drilling, using Deepwater Horizon as case	The article had the following objectives: 1. To describe the modelling of the blowout using QRAs, 2. To describe RIFs for deepwater drilling, and 3. To discuss the QRA's ability to reflect individual facilities, operations and environments. A set of 15 QRAs was reviewed to describe how blowout modelling was carried out by the operators in Norway. A literature review and the results from the investigations of the Deepwater Horizon accident were the basis for describing the RIFs for deepwater drilling.
3.	Evacuation, escape and rescue experiences from offshore accidents including the Deepwater Horizon	The objectives were to: 1. Categorise offshore accidents according to the RIFs during evacuation, escape and rescue (EER) operations, 2. Review EER operations from Deepwater Horizon, 3. Suggest possible improvements based on the findings. The EER operations from the Deepwater Horizon were reviewed based on testimonies provided by the crewmembers during the Joint Investigation by the United States Coast Guard and the Bureau of Ocean Energy Management, Regulation and Enforcement.

	Article	**Objectives, sub-goals and/or main result**
4.	Safety perceptions and comprehensions among offshore installation managers on the Norwegian Continental Shelf	The objective was to reveal if the perception and comprehension of central factors related to safety climate were shared by the offshore installation managers (OIMs) compared with the rest of the organisation. In addition, the safety advisers' comprehensions were analysed because of their role as safety representatives and close cooperation both with the management and the rest of the organisation. The analysis was performed using the questionnaire data (survey) from the "Trends in risk levels on the Norwegian Continental Shelf" (RNNP) project carried out in 2007.
5.	Developing safety indicators for preventing offshore oil and gas deepwater drilling blowouts	The article had two main objectives. The first objective was to assess the safety indicators in the RNNP project and determine their relevance as early warnings for O&G blowouts. The second objective was to discuss possible areas for extensions related to well integrity and thereby how to prevent blowouts.
6.	Safety engineering and different approaches	The objective was to evaluate whether central principles and elements in the generic OMT method were comparable with the main principles of resilience engineering.
7.	Combining precursor incidents investigations and QRA in oil and gas industry	The article suggested combining accident investigation methodology and QRA to investigate precursor incidents. The objectives were to describe how the methods could be combined and to discuss how the results could be used in risk management.

1.3 Limitations

This PhD thesis is written for scientists, safety professionals, managers and others with an interest in safety and risk analysis. Some knowledge about the O&G industry is beneficial, but not essential.

Several attributes may be used to describe risk in the O&G industry depending on the scientific view and how the system boundaries are defined. These attributes and boundaries are described in each of the articles. Several of the topics such as risk, risk analysis, risk management and indicators could separately form the basis for individual PhDs. Some may thus find several topics superficially examined. If so, bear in mind the wide scope and multidisciplinary approach.

The thesis includes terms like human, organisational, operational, factor, element, assessment and analyze. The definitions and distinctions of the terms are not always easily understandable. In the process of wrapping up the thesis, a final literature review was carried out in an effort to come up with consistent definitions. It did not succeed. A multidisciplinary approach introduces cross-disciplinary communication problems that cause difficulties about the concept of risk and its elements. The work to build a common ground for improved cooperation across the different scientific disciplines working with the concept of risk, is therefore important.

Our judgments about risk acceptability are influenced by many factors that often are not included in risk analyses. The perception of risk does not differ between risk knowledge on one side and value judgment regarding its acceptability or tolerability on the other side. It is of importance that research related to risk, such as this thesis, does not withdraw anyone’s right to raise a personal opinion about risk perception. There is no “safe or unsafe”, “right or wrong” or “yes or no” answer when it comes to hazards, especially not related to hazards with low frequency and high impact.

1.4 Structure of the thesis

This thesis comprises two main parts: *Part I - Main report* and *Part II - Articles*. The main report is a synthesis of the research articles and does not include all the results or the detailed discussions of the results, but references are made to the articles. The first chapter of the main report describes the background and objectives of the thesis and limitations for the work. Chapter two describes the research approach. Chapter three describes central elements. The main results are presented in chapter four followed by suggestions for further work. Part II consists of research articles published or submitted for publication in international journals.

1.5 Abbreviations/acronyms

ALARP	as low as reasonably practicable
BOP	blowout preventer
BORA	barrier and operational risk analysis
the Commission	the National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling
EER	evacuation, escape and rescue
HSE	health, safety and environment and Health and Safety Executive [United Kingdom]
HOF	human and organisational factor
HRA	human reliability analysis
O&G	oil and gas
OIM	offshore installation managers
OMT	organisational, human and technical (Used in relation to the "OMT method")
PSA	Petroleum Safety Authority Norway
QRA	quantitative risk analysis/assessments
R&D	research and experimental development
RIF	risk influencing factor
RNNP	trends in risk levels on the Norwegian Continental Shelf

2 RESEARCH APPROACH

2.1 Types of research

Research and experimental development (R&D) comprises creative work undertaken on a systematic basis in order to increase the stock of knowledge, including the knowledge of man, culture and society, and the use of this stock of knowledge to devise new applications. Three types of research can be distinguished based on their intended use (OECD, 2002):

i. Basic research is experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundations of phenomena and observable facts, without any particular application or use in view.
ii. Applied research is original investigation undertaken in order to acquire new knowledge. It is, however, directed primarily towards a specific practical aim or objective.
iii. Experimental development is systematic work, drawing on knowledge gained from research and practical experience that is directed to producing new materials, products and devices; to installing new processes, systems and services; or to improving substantially those already produced or installed.

The article; *Safety perceptions and comprehensions among offshore installation managers on the Norwegian Continental Shelf* , (Skogdalen and Tveiten, 2011) is mostly related to basic research. Basic research analyses properties, structures and relationships with a view to formulating and testing hypotheses, theories or laws. The reference to “no particular application in view” in the definition of basic research is crucial, as the performer may not know about actual applications when doing the research or responding to survey questionnaires (OECD, 2002). The article also includes elements of experimental development. In social sciences, experimental development can be defined as the process of translating knowledge gained through research into operational programmes, including demonstration projects undertaken for testing and evaluation purposes (OECD, 2002).

The rest of the articles are mostly related to applied research. Applied research is undertaken either to determine possible uses for the findings of basic research or to determine new methods or ways of achieving specific and predetermined objectives. It involves considering the available knowledge and its extension in order to solve particular problems. The results of applied research are intended primarily to be valid for a single or limited number of products, operations, methods or systems. Applied research gives operational form to ideas. There are many conceptual and operational problems associated with these categories. They seem to imply a sequence and a separation which rarely exist in reality. Moreover, there may be movement in both directions (OECD, 2002).

2.2 Multidisciplinary approach

Installations in the O&G industry are man-made structures and thereby have the advantage of intentionally controlling the cause and effect relationship when designing and operating the system. This is contrary to naturally developing functions in natural systems. A system and its complexity can also be divided into static or, physical conceptual or dynamic. Physical systems are made up of physical components, whereas conceptual systems are some kind of an organisation of ideas or a set of specifications and plans. In a dynamic system the elements are combined with activity, whereas in static systems they are not (Fet, 1997). Any attempts to analyse the various aspects of risk in the O&G industry should take into consideration the complex system perspective. The scientific basis of risk analysis cannot be judged by reference to criteria from traditional scientific fields such as the natural or social sciences alone. The scientific foundation of this thesis is therefore both that of natural and social sciences.

In social sciences, it is more common to use qualitative methods than it is in natural sciences, which traditionally emphasise objectivity and quantification. Both qualitative and quantitative methods have been used in this PhD project. Examples of data are; surveys, a set of QRAs, testimonies and literature reviews. Almost the entire information gathering was carried out over the Internet, mainly using traditional bibliographic databases such as Google Scholar, Scopus and Compendex. The Internet is a paradigm shift in research, and the change is rapid. From starting the PhD project in 2008 to finishing it in 2011, the amount of literature and data expanded tremendously. The Deepwater Horizon accident introduced the possibility of performing independent research/investigation based on the available data from public sources published on Internet. Government agencies such as *Mineral Management Services/ Bureau of Ocean Energy Management, Regulation and Enforcement* published large amounts of data. Live feeds and videos were broadcast from the testimonies of the survivors.

2.3 Scientific quality

The Deepwater Horizon accident introduced new tools for gathering and communicating information. Blogs, Twitter, Facebook and LinkedIn were all essential in order to gather as close to real-time information as possible. Wikipedia had the most updated status reports on the crisis. There are several aspects related to quality and ethics when using social network tools. One of these is that the information sometimes is only available for a short time, and therefore it is a challenge to ensure solidity. There is also misinformation and hidden agendas.

The Research Council of Norway defines scientific quality by three main criteria (NRC, 2000):

i. Originality; to what extent the research is novel and has innovative use of theory and methods
ii. Solidity; to what extent the statements and conclusions in the research are well supported
iii. Relevance; to what extent the research is linked to professional development or is practical and useful to society

In some cases, these aspects may be contradictory. High solidity owing to thoroughness may restrain creativity, while research of little originality still may be very useful to society. In multidisciplinary research, it is necessary to separately evaluate the synthesis of the research elements in addition to their quality.

An essential part of the quality assurance of the research in this thesis was carried out by using peer reviews through publication in international journals. Stakeholders in the O&G industry were also consulted formally and informally. Seminars and international conferences were attended to present a status of the research, to get feedback from peers and to learn about the latest progress in the field of research.

One of the goals of science is to achieve improved knowledge and thereby control of the natural world. The world is facing existential environmental challenges and threats, such as global warming and nuclear accidents. Such problems include crucial uncertainties, and the quality assurance of scientific research and information provided for decision-making is of high importance. These scientific issues have a global and long-term impact, and quantitative data are often inadequate (Utne, 2007). Science can only to a limited extent provide explanations of natural phenomena and theories based on experiments. Policy-makers want straightforward and certain information as inputs into their decision-making processes. However, issues regarding policy-related research involve a high degree of uncertainty, and often social and ethical aspects as well. Simplicity and precision in predictions are unfeasible in many cases. Uncertainty is found at all levels in scientific research. Measuring uncertainty is in itself not an exact operation, and risk assessments are often based on computer models or expert opinions (Funtowicz and Ravetz, 1990).

Risk and uncertainty is briefly reviewed in chapter 3. The results from a risk analysis should never be the sole basis for decision-making (Apostolakis, 2004). The decision should be risk-informed. The risk analysis summarises the knowledge and lack of knowledge, and thus provides a basis for risk-informed decisions. The work in this PhD provides elements that may support the risk assessment process. The risk assessment can support managerial reviews and judgments, but never replace the risk management process. Doing the opposite is a violation of good ethics.

2.4 Ethics in research

Just as ethics is about a vision of a good life, research ethics is about a vision of good knowledge. The term “research ethics” refers to a diverse set of values, norms and institutional regulations that help constitute and regulate scientific activity. Ethics in research encompasses two normative systems: one to ensure good scientific practice and the other to safeguard individuals and society at large (NENT, 2008).

I have to my best effort conducted my activities as a researcher with integrity and honesty. I hope that in the process of collecting information I have not lost track of any references. If I have, I apologise. Keeping track of information during the writing process was challenging. I have tried and will continue to try to act in accordance with good research ethics. I will not allow considerations based on ideology, religion, ethnicity, prejudices or material advantages to overshadow my ethical responsibility as a researcher.

3 RISK

3.1 The concept of risk

There is no agreed definition of risk. The concept of risk is used as an expected value, as a probability distribution, as uncertainty and as an event (Aven and Renn, 2010). Some common definitions are (Aven and Renn, 2009):

1) Risk equals expected loss (Willis, 2007)
2) Risk equals expected disutility (Campbell, 2005)
3) Risk is the probability of an adverse outcome (Graham and Wiener, 1997)
4) Risk is a measure of the probability and severity of adverse effects (Lowrance, 1976)
5) Risk is the combination of a probability and the extent of its consequences (Ale, 2002)
6) Risk is equal to the triplet (s_i, p_i, c_i), where s_i is the *i*th scenario, p_i is the probability of that scenario and c_i is the consequence of the *i*th scenario, i = 1, 2, . . ., N, (Kaplan, 1991; Kaplan and Garrick, 1981)
7) Risk is equal to the two-dimensional combination of events/consequences and associated uncertainties (will the events occur, what will be the consequences) (Aven, 2007; Aven, 2008, 2009)
8) Risk refers to the uncertainty of outcome, of actions and events (SU, 2002)
9) Risk is a situation or event where something of human value (including humans themselves) is at stake and where the outcome is uncertain (Rosa, 2003; Rosa, 1998)
10) Risk is an uncertain consequence of an event or an activity with respect to something that humans value (IRGC, 2005)

These definitions can be divided into two categories: (1) risk is expressed by means of probabilities and expected values (definitions 1–6) and (2) risk is expressed through events/consequences and uncertainties (definitions 7–10) (Aven and Renn, 2010). Probability is the predominant tool used to measure uncertainties in reliability and risk analyses. Aven (2010) argues that these perspectives and definitions are too narrow. They do not reflect that probabilities are imperfect tools for expressing uncertainties. The assigned probabilities are conditioned on a number of assumptions and suppositions. They depend on the background knowledge of the system in mind. Uncertainties are often hidden in background knowledge, and restricting attention to the assigned probabilities could camouflage factors that could produce surprising outcomes. By jumping directly into probabilities, important uncertainty aspects are easily truncated, meaning that potential surprises could be left unconsidered. However, other representations also exist, including imprecise (interval) probability, fuzzy probability and representations based on the theories of evidence (belief functions) and possibility. Many researchers in the field are strong proponents of these alternative methods, but some are also sceptical (Aven, 2011a; Aven, 2011c).

In 2009, an ISO guide on risk management terminology was issued (ISO, 2009a). The guide provides basic vocabulary for developing a common understanding of risk assessment and risk management concepts and terms among organisations and functions, and across different application areas. Aven (2011b) argues that the guide fails to produce consistent and meaningful definitions of many of the key concepts covered. A main focus is placed on the risk concept, which is defined as the effect of uncertainty on objectives, but many other definitions are also looked into, including probability, vulnerability, hazard, risk identification and risk description. A main problem relates to the definition of risk, which is defined as "*the effect of uncertainty on objectives*". The meaning of this term is not clear and different interpretations are possible.

Aven and Renn suggest the following definition for risk: "*risk refers to the uncertainty about and severity of the events and consequences (or outcomes) of an activity with respect to something that humans value*" (Aven and Renn, 2009). More formally, according to this perspective risk is seen generally as the two-dimensional combination of (i) the events A and the consequences C of these events, and (ii) the associated uncertainties U (will the events occur and what will be the consequences?) (Aven, 2008; Aven, 2010). The resulting perspective is often referred to as the "ACU perspective".

In engineering risk analysis, a distinction is commonly made between aleatory and epistemic uncertainty (Apostolakis, 1990; Helton and Burmaster, 1996). Aleatory uncertainty refers to variation in populations, and epistemic uncertainty to the lack of knowledge about phenomena. The latter usually translates into uncertainty about the parameters of a model used to describe variation. Whereas epistemic uncertainty can be reduced, aleatory uncertainty cannot, and is therefore sometimes called irreducible uncertainty (Flage, 2010; Helton and Burmaster, 1996).

The author of this thesis agrees with the arguments presented by Aven related to the concept of risk, but in this thesis the definitions in ISO 31000 have mostly been adapted. The thesis has a broad and multidisciplinary approach and the use of an ISO standard is therefore preferable. The author views the arguments by Aven as precisions regarding the concept of risk that do not contradict the ISO definitions.

3.2 Risk management

According to ISO 31000, risk management can be defined as the coordinated activities to direct and control an organisation with regard to risk. As illustrated in Figure 2, the main steps in the risk management process are the establishment of the framework, risk assessment and risk treatment. Framework conditions refer to the internal and external environment of the organisation, the interface of these environments, the purpose of the risk management activity and suitable risk criteria. Risk treatment is the process of modifying risk, which may involve avoiding, modifying, sharing or retaining risk (ISO, 2009b).

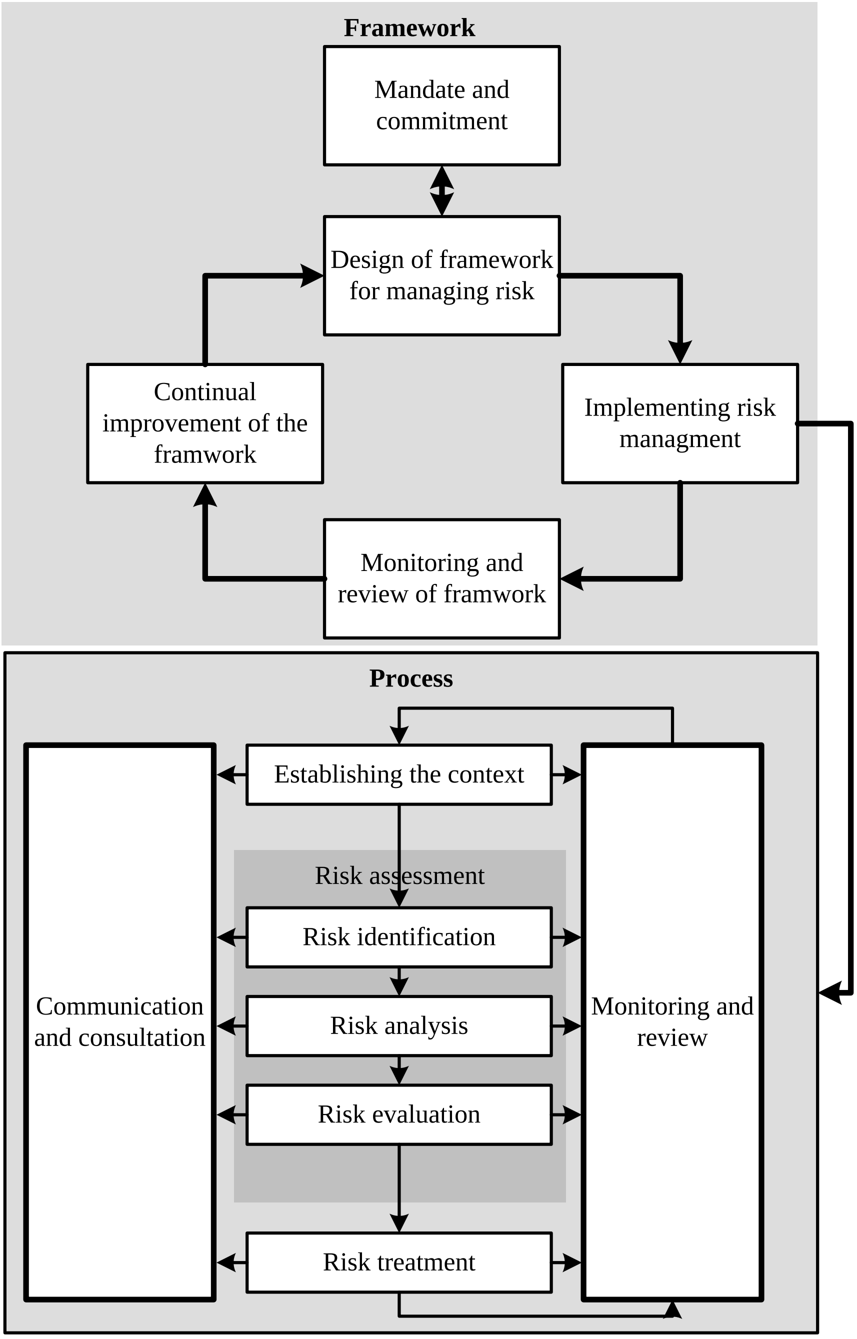


Figure 2 ISO 31000 relationship between the risk management framework and process (ISO, 2009b)

Organisations manage risk by identifying it, analysing it and then evaluating whether it should be modified by risk treatment in order to satisfy their risk criteria (ISO, 2009b).

In a socio-technical system (Rasmussen, 1997) (e.g. an offshore installation), the following levels are all stakeholders in the process of risk management:

1. The work and technological system
2. The staff level
3. The management level
4. The company level
5. The regulators and associations level
6. The government level

In 1997 Rasmussen described this system as being stressed by a fast pace of technological change, by an increasingly aggressive competitive environment and by changing regulatory practices and public pressure (Rasmussen, 1997). These elements were all contributors to the Deepwater Horizon accident.

Risk management contributes to the demonstrable achievement of objectives and improvement of performance in, for example, human health and safety, security, legal and regulatory compliance, public acceptance, environmental protection, product quality, project management, efficiency in operations, governance and reputation (ISO, 2009b). At the outset, risk management is presented with three potential outcomes (Aven and Renn, 2010):

- *Intolerable situation*: either the risk source (such as a technology, chemical, etc.) needs to be abandoned or replaced, or, in cases where that is not possible (e.g. natural hazards), vulnerabilities need to be reduced and exposure restricted.
- *Tolerable situation*: the risks need to be reduced or handled in some other way within the limits of reasonable resource investments (ALARP, including best practice). This can be performed by private actors (such as corporate risk managers), public actors (such as regulatory agencies) or both (public–private partnerships).
- *Acceptable situation*: the risks are so small – perhaps even regarded as negligible – that any risk reduction effort is unnecessary. However, risk-sharing via insurance and/or further risk reduction on a voluntary basis presents options for action that can be worthwhile pursuing even in the case of an acceptable risk.

3.3 Quantitative Risk Analysis (QRA)

Risk analysis is the structured use of available information to identify hazards and to describe risk. Risk analysis involves developing an understanding of the risk. Risk analysis involves the consideration of the causes and sources of risk, their positive and negative consequences and the likelihood that those consequences may occur. Risk is analysed by determining consequences and their likelihood, and other attributes of the risk. An event can have multiple consequences and can affect multiple objectives. Existing controls and their effectiveness and efficiency should also be taken into account (ISO, 2009b).

Risk analysis methodology is about establishing good principles, methods and models for analysing and describing risk. QRA is used as an abbreviation for ‘Quantified Risk Assessment’ or ‘Quantitative Risk Analysis’. The context usually has to be considered in order to determine which of these two terms is applicable. Risk assessment involves risk analysis as well as an evaluation of the results. The technique is also referred to as Probabilistic Risk Assessment, Probabilistic Safety Assessment, Concept Safety Evaluation and Total Risk Analysis. In spite of more than two decades of use and development, no convergence towards a universally accepted term has been seen (Vinnem, 2007). In this thesis, the term QRA refers to all the different techniques. The QRA process shall (Norsok, 2010):

a) identify hazardous situations and potential accidental events,
b) identify initiating events and describe their potential causes,
c) analyse accidental sequences and their possible consequences,
d) identify and assess risk reducing measures,
e) provide a nuanced and overall picture of the risk, presented in a way suitable for the various target groups/users and their specific needs and use.

Some companies have developed their own standards and guidelines of what a QRA should include. Especially related to barrier performance, there are separate studies preformed. These studies can be viewed as part of the QRA process if they are closely linked.

As the objective and scope of a risk assessment may vary, the way to perform the analysis of potential consequences may range from detailed modelling to coarse judgemental assessment. Analysis of the potential consequences may therefore be qualitative, semi-quantitative or quantitative, depending on the context (Norsok, 2010). In the process of updating the QRA it is important to ensure that former relevant studies and experience are included.

Authorities base their regulations and operators base their designs on the use of QRA. The use of QRA is central in the O&G industry to identify, analyse and evaluate risk. Establishing or maintaining safety barriers is essential in the risk treatment process. The use of indicators and feedback through precursor incidents and/or accidents is an important part of the monitoring and review process.

Historically, an important role of QRAs was to improve the incorporation of safety in design because a high number of accidents had their roots in the design process. Focus was mainly on the engineering phases (i.e. after the installation type and concept had been decided). QRAs were not commonly used during the initial choice of the high-level concept for fulfilling the system’s objectives. A issue that followed defining the boundaries for design was the inclusion of the operation phase where HOFs played an important role (Hale et al., 2007). For instance, statistics from the period 2001-2005 showed that half of the leaks from hydrocarbon systems on the Norwegian Continental Shelf were caused by manual interventions in the system

(Vinnem, 2008b; Vinnem et al., 2007). Engineered defences were often partially deactivated during these operations to avoid the disruption of stable production. These occurrences indicated that safety barriers relating to the containment of leaks did not function sufficiently (Vinnem, 2008b).

According to Bea (2002a), experience has shown that the primary hazard is not the ocean environment itself; the industry has learned how to engineer, build, operate and maintain structures that can survive the extreme storms, earthquakes, ice and sea floor soil movements that frequent the offshore environment. The primary hazard is associated with HOFs that develop during an installation's lifecycles. Studies have shown that while the majority of structural failures occur during operations and maintenance, most of these failures had sources that were founded during the design phase. Structures were engineered and designed that had inherent flaws; they could not be built as intended and were difficult to operate and maintain. While they may have the requested strength or capacity, they lacked the required durability, serviceability and compatibility (Bea, 2002b). The design and operation phases of a structure are carried out by two separate organisations. Decisions taken in the design phase influence the later phases where HOFs largely influence the major hazards. The need for understanding HOFs in all phases has been pointed out by the Health and Safety Executive (HSE) in the UK (HSE, 2003):

''*Management of human factors is increasingly recognised as having a vital role to play in the control of risk …. Successful management of human factors and control of risk involves the development of systems designed to take proper account of human capabilities and fallibilities …. It is now widely accepted that the majority of accidents in industry generally are in some way attributable to human as well as technical factors in the sense that actions by people initiated or contributed to accidents, or people could have acted better to avert them*".

3.4 Human and organizational factors (HOFs)

There are three areas of influence on people at work, namely: (a) the organisation; (b) the job and (c) personal factors. These are directly affected by: (a) the system for communication within the organisation and (b) the training systems and procedures in operation, all of which are directed at preventing human error (Stranks, 2006). Human factors are understood as the branch of science and technology that includes what is known and theorised about human behavioural and the biological characteristics that can be applied validly to the specification, design, evaluation, operation and maintenance of products and systems to enhance safe, effective and satisfactory use by individuals, groups and organisations (Goodwin, 2007).

The terms 'human factors' and 'human error' are often used interchangeably but, as pointed out by Gordon (1998), it is important to distinguish between the underlying causes of accidents (human factors) and their immediate causes (human errors). Human error can be defined as 'the failure of planned actions to achieve their desired ends – without the intervention of some unforeseeable event' (Schönbeck et al., 2010). According to Jacobs and Haber (1994), human errors may be of various origins and part of larger, organisational processes that encourage unsafe acts, which ultimately produce system failures.

Organisational factors are characterised by the division of tasks, the design of job positions including selection, training and cultural indoctrination and their coordination to accomplish activities. The main issues of an organisation that affects safety include factors such as complexity (chemical/process, physical, control and task), the size and age of the plant, organisational safety performance shaping factors such as leadership, culture, rewards, manning, communications and coordination and social norms and pressures (Bellamy et al., 2006).

The word "operational" is often used without explanations and has different meanings depending on the context. Combined with the word risk, it becomes a field of science. Even so, defining operational risk is easier said than done, and this is perhaps why it is dubbed "Risk X" by Metcalfe (2003). Likewise, Crouhy et al. (2001) stated that operational risk is a fuzzy concept because it is hard to make a clear-cut distinction between operational risk and the normal uncertainties faced by the organization in its daily operations. The most common (and reasonable) definition of operational risk first appeared in Wills et al. (1999) who defined operational risk as "*the direct or indirect loss resulting from inadequate or failed internal processes, people and systems, or from external events*". The trend towards a greater dependence on technology, more intensive competition and globalisation have left the corporate world more exposed to operational risk than ever before (Moosa, 2007).

Within safety engineering the term 'operational risk' has been mostly linked to the complexity and framework for processes and systems, and it is often overlapped by the definitions of HOFs. Operations are performed by humans as part of an organisation. They can all be described by factors that are not easily to distinct.

3.5 Safety barriers

Defining and modelling safety barriers is important when analysing the influence of HOFs in risk assessments. The concept of safety barriers is applied in practice, discussed in the literature and required in legislation and standards within different industries. In this thesis safety barriers are understood as being physical or non-physical means that are planned to prevent, control or mitigate undesired events or accidents. The means may range from a single technical unit or human action to a complex socio-technical system. The term "planned" implies that at least one of the intentions of the means is to reduce the risk. In line with ISO 13702 (ISO, 1999), the term "prevention" means the reduction of the likelihood of a hazardous event, "control" means limiting the extent and/or duration of a hazardous event to prevent escalation, while "mitigation" means the reduction of the effects of a hazardous event. Undesired events include technical failures, human errors, external events or a combination of these occurrences that may realise potential hazards. Accidents are undesired and unplanned events that lead to the loss of human lives, occupational injuries, environmental damage and/or material damage (Sklet, 2006).

Barrier systems can be classified according to several dimensions, for example as passive or active barrier systems and as physical, technical or human/operational barrier systems. Several attributes are necessary in order to characterise the performance of safety barriers: functionality/effectiveness, reliability/availability, response time, robustness and, finally, a description of the triggering event or condition. For some types of barriers, not all attributes are relevant or necessary in order to describe barrier performance (Sklet, 2006). The following definitions are extracted from Sklet (2005, 2006):

- Barrier function: A function planned to prevent, control or mitigate undesired events or accidents.
- Barrier element: Part of a barrier, but not sufficient alone to achieve the required overall function.
- Barrier influencing factor: Factor that influences the performances of barriers.

QRAs in the O&G industry have traditionally had a rather narrow analysis of barrier performance. The nuclear industry, by contrast, has carried out extensive studies on barrier performance (Aven et al., 2006; Sklet et al., 2006; Vinnem, 2008b; Vinnem et al., 2007).

3.6 HOFs and QRA

To predict human reliability in the QRA processes, human reliability analysis (HRA) is often used. The following list of high-level requirements captures the essence of HRA. The HRA method should (Mosleh and Chang, 2004):

- Identify human response (errors are the main focus) in the QRA context,
- Estimate response probabilities,
- Identify causes of errors to support the development of preventive or mitigating measures,
- Include a systematic procedure for generating reproducible qualitative and quantitative results,
- Have a causal model of human response with roots in cognitive and behavioural sciences, and with:
  - elements (e.g. Personal Shaping Factors') that are directly or indirectly observable, and
  - a structure that provides unambiguous and traceable links between its input and output
- Be detailed enough to support data collection, experimental validation and various applications of QRA. Data and model are two tightly coupled entities.

The model in the HRA should be data-informed. Conversely, the data collocation and analysis must be model-informed. A coordinated model-based collection and analysis of experimental and filed data should support the development and application of the model, and the quantification of its parameters (Mosleh and Chang, 2004).

There have been several efforts to develop methods for the formal inclusion of HOFs into risk analysis. Examples from the nuclear and airline industry include the Model of Accident Causation using Hierarchical Influence Networks (MACHINE) (Embrey, 1992), the work process analysis model (Davoudian et al., 1994a, b), System-Action-Management (SAM) (Paté-Cornell and Murphy, 1996), Omega Factor Model (Mosleh and Golfeiz, 1999), I-RISK (Oh et al., 1998; Papazoglou et al., 2003), the integrated safety model (Wreathall et al., 1992) and Causal Modelling of Air Safety (Ale et al., 2006). With respect to QRAs in the O&G industry; the Organisational Risk Influence Model (Øien, 2001a), Barrier and Operational Risk Analysis (BORA) (Aven et al., 2006; Sklet et al., 2006) and Operational Conditional Safety (OTS) (Vinnem, 2008b; Vinnem et al., 2007) are relevant. Common among these methods are the following parts:

- A set of organisational factors,
- A link to the system risk model,
- A set of modelling techniques, and
- A set of measurement methods.

The existing frameworks and methods have some similar steps and features, but they also have many unique features as well. The key questions can be summarised as follows:

- What are the organisational factors that affect risk?
- How do these factors influence risk?
- How much do they contribute to risk?

Each method answers these questions differently (Mohaghegh and Mosleh, 2009). Many proposed methods still lack a sufficient theoretical and/or experimental basis for their key ingredients. Missing from all methods is a fully implemented model of the underlying causal mechanisms linking measurable personal shaping factors or other characteristics of the context of operator response. The problem extends to the quantification of HOFs where the majority of the proposed approaches still rely on implicit functions relating personal shaping factors to probabilities. Again, often only limited theoretical or empirical bases are provided for such relations. In many cases, the numbers are the result of expert elicitation using arbitrary scales (Mosleh and Chang, 2004).

3.7 Safety indicators

The main purposes of safety indicators are to monitor the level of safety in a system, to motivate action and to provide the necessary information for decision-makers about where and how to act (Hale, 2009b). Often, hindsight shows that if early warnings had been revealed and managed in advance, the undesired event could have been prevented (Øien et al., 2011). The main challenge is to identify indicators that give management an opportunity to act upon the early warnings and that show responses within a suitable timeframe (Hale, 2009a). The indicators should also address operations close to the precursor zone, which is characterised by unknown conditions that challenge operator skills and lay the groundwork for more fundamental error or failure. In the precursor zone, operators encounter situations not informed by their prior experience (Roe and Schulman, 2008).

Safety indicators were addressed in a special issue of *Safety Science* (Volume 47, 2009) as well as in several research articles (Duijm et al., 2008; Hale, 2009a, b; Hopkins, 2009; HSE, 2006; Osmundsen et al., 2008; Saqib and Tahir Siddiqi, 2008; Sonnemans and Körvers, 2006; Vinnem, 2010; Øien et al., 2011; Øien et al., 2010). These articles mainly discuss two dimensions of safety indicators: occupational safety versus process safety and leading versus lagging indicators.

3.8 Feedback through accidents

The theory of incident learning relies on the observation made by Turner (1978) that disasters have long incubation periods during which warning signals (or incidents) are not detected or are ignored. Thus, while the occurrence of incidents may be normal, only an organisation with an effective incident learning system can respond to these incidents to prevent serious accidents from occurring in the future. Phimister et al., (2003) discuss the importance of identification, without which incident learning is impossible. Unless the organisation is sensitised to learning from incidents, deviations from normal behaviour will go unnoticed. According to Cooke and Rohleder (2006) an organisation that effectively implements a formal incident learning system can evolve into a high-reliability organisation.

Human errors were for a long time judged to be the root causes of major accidents, for example in the case of the accident at Esso Australia's gas plant at Longford in Victoria in September 1998 (Dawson and Brooks, 1999). This was the position taken by Esso at the Royal Commission. The company argued that operators and their supervisors on duty at the time should have known that the attempt to reintroduce a warm liquid into a cold pipe could result in brittle fracture. The company claimed that operators had been trained to be aware of the problem and Esso even produced the training records of one operator in an attempt to show that he should have known better. However, the investigation commission took the view that none of those on duty understood just how dangerous the situation was, which indicated a systematic training failure. Not even the plant manager, who was away from the plant at the time of the accident, understood the dangers of cold metal embrittlement. The investigation commission concluded that the inadequate training of operators and supervisors was the "real cause" of the accident. It is clear that operator error does not adequately account for the Longford incident (Hopkins, 2000). This is a general finding of inquiries into major accidents (Reason, 1997).

An accident investigation is the determination of the facts of an accident by inquiry, observation and examination and an analysis of these facts to establish the causes of the accident and the measures that must be adopted to prevent its recurrence (TBCS, 1992). The Center for Chemical Process Safety describes three main purposes for accident investigation. The first purpose is to organise information about the accident once evidence has been collected. The second is to help in describing the accident causation and developing a hypothesis for further examination by experts, and the last is to help with the assessment of proposed corrective actions (AICE, 2003; CCPS, 1992). In addition, the analytical techniques may also ensure that the results are transparent and verifiable. Accident and incident investigations are often aimed at finding the root causes of an accident. According to the Health and Safety Executive, a root cause is the most fundamental and direct cause of an accident or incident that can be reasonably identified, and that management has control to fix. A root cause contains the following three key elements (HSE, 2001):

- *Basic Cause.* Specific reasons as to why an incident occurred that enable recommendations to be made that will prevent the recurrence of the events leading up to the incident.
- *Reasonably Identified.* Incident investigation must be completed in a reasonable timeframe. Root cause analysis, to be effective, must help investigators get the most out of the time allotted for the investigation.
- *Control to Fix.* General cause classifications such as ‘operator error’ should be avoided. Such causes are not specific enough to allow those in charge to rectify the situation.

Experiences from major offshore accidents are important sources of information to prevent the occurrences of similar accidents in the future. A number of major accidents in the North Sea occurred in the second half of the 20th century, including Alexander Kielland (Næsheim, 1981), the Ekofisk Bravo Blowout (PSA, 2010a) and Piper Alfa (Cullen, 1990). All these accidents led to significant changes in technology, operations, supervision and regulation. There has been a positive safety trend during the past 15–20 years, resulting in fewer major accidents. This is a step in the right direction, but it has one challenge in the sense that experiences from major accident investigations have to be complemented by new or improved tools to ensure further progress in risk management. More knowledge related to how to risk analyze human, organisational and technical factors, is important. This includes identify and describe human and organisational safety barriers, and develop indicators on how to measure their level.

4 MAIN RESULTS

Risk assessment is a part of the risk management framework. Risk assessments help decision-makers make informed choices and thereby prioritise actions and distinguish among alternative courses of action (ISO, 2009b). A central part of this process is that the risk analysis identifies and describes HOFs and their influence on safety barriers. How and to what level this is done for QRAs performed for installations in the North Sea i is briefly described in chapter 4.1.1. The use of historical data and HOFs for risk analyzing offshore O&G blowout is described in chapter 4.1.2.

A review of experiences related to offshore EER operations is described in chapter 4.2.1. A review of stakeholder feedback related to offshore safety is the basis for article is described in chapter 4.2.2.

Adopting valid, reliable and adequate safety indicators for major accidents are of high importance and are relevant for monitoring and reviewing as well as ensuring continual improvement. Developing safety indicators for deepwater drilling is presented in chapter 4.3. Two different approaches for risk assessment are described in chapter 4.4.1. The causes for potential major accidents (precursor incidents) and how these can be analysed by combining accident investigation and QRAs are described in chapter 4.4.2.

4.1 Human and organisational barriers in risk analyses

The first sub-goal for this thesis was to identify and describe human and organisational barriers in risk analysis. This sub-goal was the basis for two articles that both focused on QRA offshore. The first article (Skogdalen and Vinnem, 2011b) focused on HOFs that were reflected in QRAs.

4.1.1 Quantitative risk analysis - human and organizational factors

Much criticism has been associated to the limitations related to QRA models, especially that QRAs do not include HOFs. A study of 15 QRAs (Skogdalen and Vinnem, 2011b) showed that the factors were to some extent included, but also that there were large differences between the QRAs. In the study, the QRAs were categorised into four levels according to how HOFs were included in the analyses. The levels are shown in Table 2.

Table 2 - Level and characteristics

Level	Characteristics
Level 4	- The QRA is an integrated part of the safety and risk management system. - Results from the QRA form the basis for daily risk management. - The QRA is known and accepted at all levels of the organisation. - The QRA is combined with risk indicators to reveal the status of the safety barriers.
Level 3	- Systematic collection of data is related to HOFs. - QRA models are adjusted according to the findings from HOFs. - Identifies the causes of errors to support the development of preventive or mitigating measures. - Includes a systematic procedure for generating reproducible qualitative and quantitative results (e.g. BORA, OTS …).
Level 2	- Explains the importance of HOFs - How the HOF factors' influence on different part of the system are partly described. - Human error is calculated separately. - Includes interviews with some of the crew. The results are revealed but the models and calculation are not adjusted.
Level 1	- Analysis of technical and operational factors. Technical factors are valves, flanges, bends, instrument connections, water depth, pressure and hydrocarbon composition. Operational factors are number of flights, number of shipping arrivals, etc. - Risk-reducing measures are technical; for example, passive fire protection and riser bumper protection. They can also be operational, such as fewer shipping arrivals.

None of the QRAs fulfilled the requirements to include HOFs such that they could be considered a level 4 analysis. Relevant research projects have been conducted to fulfil the requirements of level 3 analysis. Further research needs to be carried out and the different scientific disciplines need to be further united for being able to fulfil the requirements to a level 4 analysis. Safety audits by regulatory authorities are probably necessary to point out the direction for QRA and speed up development. (Skogdalen and Vinnem, 2011b). Research on QRA and HOFs should include a broader understanding of precursor incidents and safety indicators.

4.1.2 Quantitative Risk Analysis of offshore drilling

A second article (Skogdalen and Vinnem, 2011a) focused on how QRAs reflect the technical, human and organisational barriers related to deepwater drilling. According to the Commission, the Deepwater Horizon accident requires a reassessment of the risks associated with offshore drilling worldwide. The Commission recommended a proactive, risk-based performance approach specific to individual facilities, operations and environments, similar to the safety case/QRA approach in the North Sea. A review of 15 QRAs revealed that the RIFs for the individual facilities, operations and environments were hardly discussed and not calculated. The QRAs did not include HOFs related to drilling operations. As seen in the Macondo blowout, most of the findings were related to HOFs such as work practice, competence, communication, procedures and management. The multiple RIFs related to environment, geology, technology and operation when drilling deepwater, have to be controlled by safety barriers depending on HOFs. An example related to hydrocarbons in well and kill operations is shown in Figure 3.

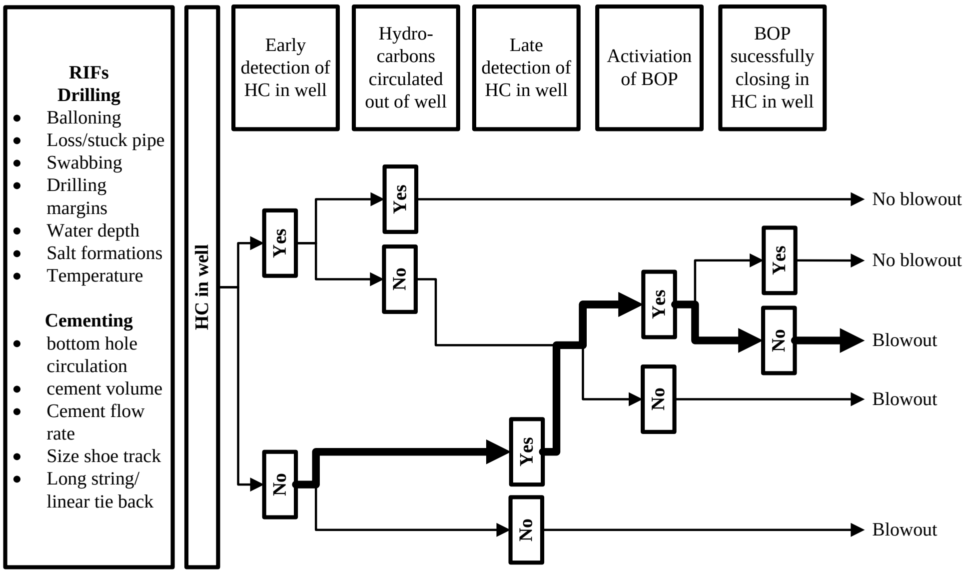


Figure 3 Hydrocarbons in well and kill operations

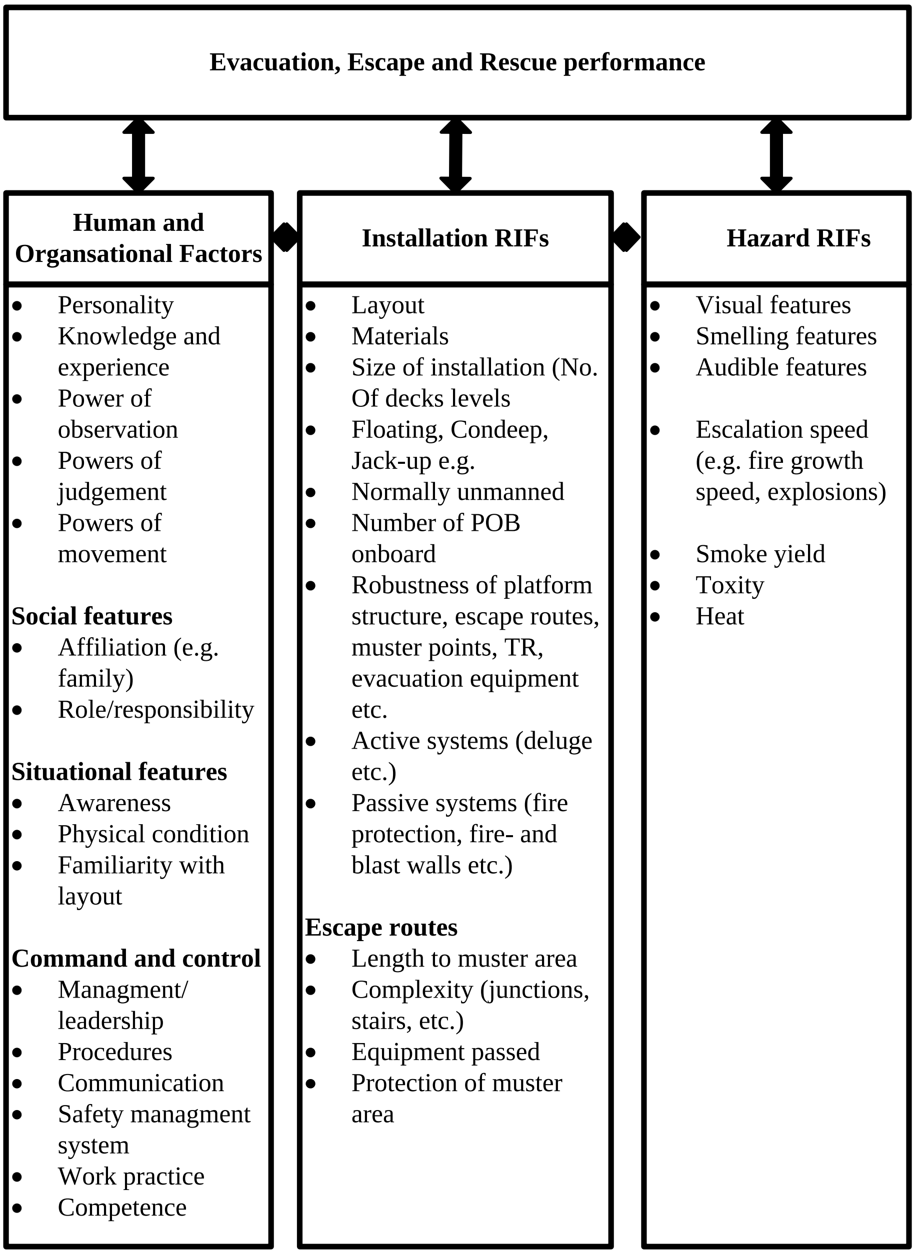
HOFs are of high importance to ensure well control (barriers) and to act when well integrity is threatened. Early kick detection is a barrier of high importance, which failed in at the Deepwater Horizon rig.

4.2 Organisational, human and technical factors that influence safety barriers

The second sub-goal of this thesis was to provide knowledge regarding human, organisational and technical factors that influence safety barriers. The sub-goal was the basis for two articles (Skogdalen et al., 2011a; Skogdalen and Tveiten, 2011).

4.2.1 Evacuation, escape, and rescue experiences from offshore accidents

EER operations play a vital role in safeguarding the lives of personnel on board when a major hazard occurs on an installation. The majority of the casualties from the Alexander Kielland, Ocean Ranger, Piper Alpha and Usumacinta offshore accidents occurred during EER attempts. EER operations can be divided into three categories depending on the hazards, time pressure and RIFs (Skogdalen et al., 2011a). The RIFs can also be categorised into human elements, the installation and hazards, as shown in figure 4.



Evacuation, Escape and Rescue performance

Human and Organsational Factors

- Personality
- Knowledge and experience
- Power of observation
- Powers of judgement
- Powers of movement

Social features

- Affiliation (e.g. family)
- Role/responsibility

Situational features

- Awareness
- Physical condition
- Familiarity with layout

Command and control

- Managment/ leadership
- Procedures
- Communication
- Safety managment system
- Work practice
- Competence

Installation RIFs

- Layout
- Materials
- Size of installation (No. Of decks levels
- Floating, Condeep, Jack-up e.g.
- Normally unmanned
- Number of POB onboard
- Robustness of platform structure, escape routes, muster points, TR, evacuation equipment etc.
- Active systems (deluge etc.)
- Passive systems (fire protection, fire- and blast walls etc.)

Escape routes

- Length to muster area
- Complexity (junctions, stairs, etc.)
- Equipment passed
- Protection of muster area

Hazard RIFs

- Visual features
- Smelling features
- Audible features

- Escalation speed (e.g. fire growth speed, explosions)

- Smoke yield
- Toxity
- Heat

Figure 4 EER performance, partly based on (Kobes et al., 2010)

The EER operations from the Deepwater Horizon rig was reviewed based on testimonies from the survivors. No casualties were reported as a result of the EER operations, however the number of survivors offered a limited insight into the level of success of the EER operations. Testimonies revealed that several of the barriers on the Deepwater Horizon failed partially or totally. These systems included the general alarm, the blowout preventer, the emergency disconnect system (EDS) and the power supply. Several technical and non-technical improvements were suggested to improve EER operations (Skogdalen et al., 2011a).

4.2.2 The perception and comprehension of safety

The perception and comprehension among offshore workers related to human, organisational and technical factors that influence on safety barriers, is often measured by surveys. Developing and maintaining a positive safety culture is important for improving safety within any organisation. One element of safety culture is what has been called the safety climate, which is normally measured by surveys based on levels of agreement with pre-developed statements.

One study presented in the article (Skogdalen and Tveiten, 2011) showed that the perception and comprehension of safety differed significantly at Norwegian offshore installations between the offshore installation managers (OIMs), and the rest of the organisation. The basis for the analysis was a safety climate survey answered by 6850 offshore petroleum employees in 2007. The OIMs had the most positive perceptions of the following categories of questions: safety prioritisation, safety management and involvement, safety versus production, individual motivation and system comprehension. The article contributed to obtaining knowledge about the understanding of the safety climate at different levels of an offshore organisation.

The findings resemble previous studies, that generally the managers, who are closer to the planning and strategy of operations, express a more positive view of the safety level. Although the findings correspond to previous research, OIMs have not been isolated as group in such studies. Working offshore is special in the sense that all levels of the organisation work, eat, have their time off and sleep in a very limited space far away from family. This creates a unique work environment in comparison to most other workplaces. Offshore workers often refer to the organisation as “one big family” and state that there is a low level of hierarchy. It is thus of interest to see how this close interaction influences safety perceptions.

Group identity, different knowledge and control and issues of power and conflict may influence the different safety perceptions and comprehensions. The phenomenon of different safety perceptions and comprehensions between these groups is important to bear in mind when planning surveys as well as planning and implementing safety measures.

4.3 Indicators for safety barriers

The third sub-goal for this thesis was to define indicators that are suitable for the measurement of barrier performance. The Deepwater Horizon accident was a result of failures in multiple barriers consisting of human, organisational and technical barrier elements. Barriers planned and included in design often degrade over time. Serious blowouts are rare events, and the rationale for many safeguards may be lost over time and the maintenance to keep them functional may not occur. Normalization of deviation, and a proper definition of deviation, is an important issue in this regard. A first step when developing indicators is therefore often to define what deviations are, and thereafter define how they should be monitored (Skogdalen et al., 2011b).

Currently, the development and monitoring of safety indicators in the O&G industry seems to be limited to a shortlist of “accepted” indicators. The Deepwater Horizon accident shows that there is a need for more extensive monitoring and understanding of safety indicators. This demands a multidisciplinary approach and cooperation across the industry.

The Risk Level Project (RNNP) aims to monitor safety performance in the O&G industry on the Norwegian Shelf through the use of different statistical, engineering and social sciences methods. The result is mainly summarised as safety indicators that contribute to the understanding of the causes of precursor incidents and accidents and their relative significances in the context of risk. As a tool, the RNNP has undergone substantial development since 1999/2000. This development has taken place in the context of collaboration between the partners in the industry, and a consensus that the chosen approach is a sensible and rational basis for a common understanding of the level of HSE and its trends from an industrial perspective (PSA, 2010c).

The RNNP is an important tool for risk management across the different levels of the socio-technical system. Therefore, it should not only be studied in relation to its indicators but also be viewed as a framework that can be adopted by other nations or industries. More indicators related to well incidents and well integrity can easily be added (Skogdalen et al., 2011b). Figure 5 summarizes the suggested indicators.

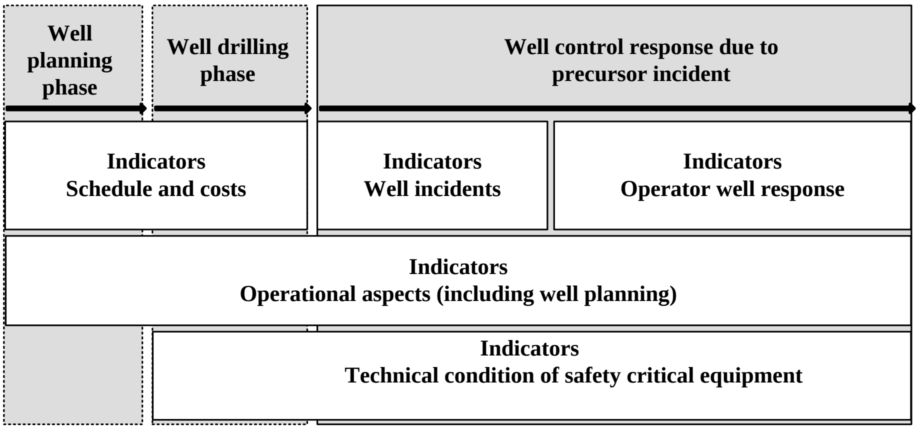


Figure 5. Summary of suggested indicators related to deepwater drilling

All the suggested areas for indicators are based on available data, which in several cases the data have been recorded for years by the regulatory authorities in Norway, research communities, companies and/or rigs. The data have not been used as the basis for indicators. Even though there seems to be agreement among the parties involved in the O&G industry that safety culture, operational aspects, technical conditions and the number of precursor incidents influence each other, there is a lack of understanding on how and why. This understanding can only be achieved by combining methods for risk management, such as different risk analysis methods, safety monitoring using indicators, the investigation of precursor incidents, revisions and inspections and accident investigations. In this way, a precursor incident, for example a kick, will not only form the basis as an input into an indicator related to “well incidents”, but also its causes and follow-up actions can be used as the basis for indicators related to “operator well response” and “well integrity”.

New and more extensive data can improve understanding related to questions like: Does low costs and tight schedules lead to degraded conditions for safety critical equipment and/or more precursor incidents? Does a tight schedule lead to more well incidents (e.g. kicks)? The indicators need to be specific for the rig and operation. Data about schedule, cost and operational aspects are available in the well planning phase and are thereby the first possible early warning indicators. Knowledge about the factors that influence risk, their interaction and status, is essential for managing risk and ensuring value for the money invested.

4.4 Models for barrier performance reflecting human, organisational and technical factors

The last sub-goal of this thesis was to develop models for barrier performance reflecting human, organisational and technical factors. The sub-goal was examined in two articles. In the first article (Skogdalen, 2010), two different approaches for improvements within safety engineering were reviewed, including their approaches towards modelling.

4.4.1 Safety engineering and different approaches

New methods for safety engineering are constantly being developed. In recent years, several scientists have stressed the need for a different approach within safety engineering that includes studying normal performance rather than failure. This has become known as resilience engineering. According to its followers, the term resilience engineering represents a new way of thinking about safety. According to Woods (2006) resilience engineering is a paradigm for safety management that focuses on how to help people cope with complexity under pressure to achieve success. Rather than view past success as a reason to ramp down investments, resilient organisations continue to invest in anticipating the changing potential for failure because they appreciate that their knowledge of the gaps is imperfect and that their environments constantly change. One measure of resilience is therefore the ability to create foresight, namely to anticipate the changing shape of risk before failure and harm occurs (Hollnagel et al., 2006).

In the same period, several research projects have worked to improve traditional risk assessments. This involves risk analysis as well as an evaluation of the results. The OMT project (Vinnem, 2008a), of which this PhD is a part, summarises earlier projects and focuses on HOFs. The approach to safety engineering is different to resilience engineering since resilience engineering focuses on success, whereas the OMT method focuses on failure. The OMT method is based on the idea that by combining existing knowledge on a multidisciplinary level, further improvement can be achieved. Existing safety models need adjustments and new combinations based on multidisciplinary knowledge, and thereby it is not about a new paradigm within safety (Skogdalen, 2010). In the OMT method, research related to barriers and modelling is central. Barriers and modelling are also important elements in resilience engineering. The OMT method and resilience engineering share the principle that new knowledge is needed for further improvement within safety engineering. The approach for achieving this knowledge differs, however the central elements such as modelling, barriers and a multidisciplinary approach are shared (Skogdalen, 2010).

In the second article (Skogdalen and Vinnem, 2011), traditional methods within risk management were combined in order to obtain further knowledge from precursor incidents.

4.4.2 Combining precursor incidents investigations and QRA

In several accident investigation reports, the Petroleum Safety Authority Norway (PSA) has concluded that under slightly different circumstances, the incidents could have developed into major accidents, with extensive pollution and the potential loss of multiple lives (PSA, 2010b). Central questions are then:

- What circumstances?
- How probable were these circumstances?
- What were the possible harm/consequences?

These questions are only superficially answered, if they are answered at all, in the accident investigation reports. Let us say that the Piper Alpha or the Deepwater Horizon accidents were prevented by the gas cloud not being ignited because of a fortunate wind direction. In that case, should they not have been taken just as seriously?

The frequency and nature of catastrophic accidents make them unsuitable as measures of health and safety performance. There are over a hundred precursor incidents every year on the Norwegian Continental Shelf (PSA, 2009). These precursor incidents, or unwanted incidents as they are often called, are usually superficially judged in investigation reports using risk matrices. The consequences of major accidents are unacceptable in our society, and therefore precursor incidents with the potential to cause major accidents should be thoroughly investigated to prevent them from reoccurring (Skogdalen and Vinnem, 2011).

Accident investigation is the collection and examination of facts related to a specific event. Risk analysis is the systematic use of available information to identify hazards and to estimate risk. Both methods are about describing hazards in a methodical structure. They share the same elements. The extensive research conducted related to the inclusion of human and organisational factors in QRA bring accident investigation and QRA closer together.

Figure 6 illustrates how the different elements can be combined in a bow-tie illustration. QRA includes the modelling of engineering, operational and maintenance activities. It covers the initiating events as well as their consequences. A typical precursor investigation does not cover the modelling of the potential consequences and related probabilities. Therefore, the status of most of the barriers related to consequence reduction is not analysed.

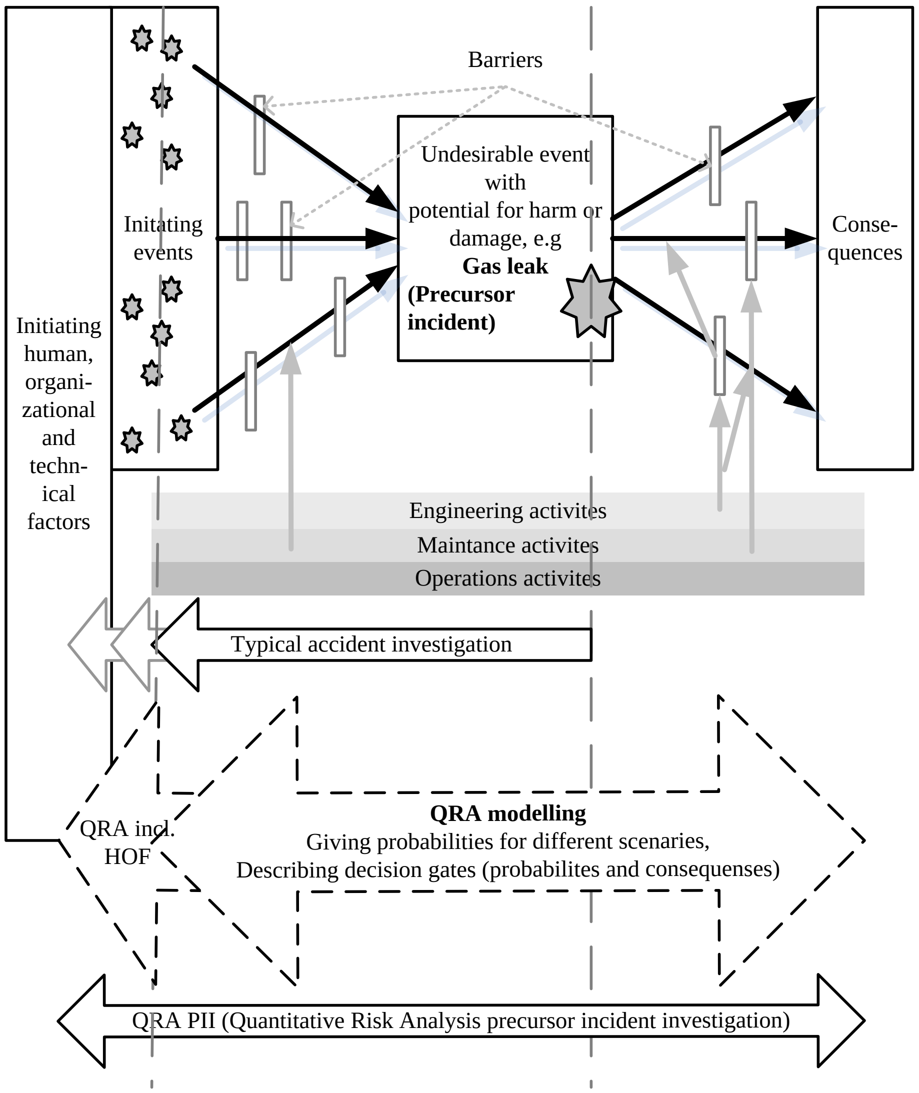


Figure 6 Bow tie, QRA and precursor incident investigation

The O&G industry consists of complex systems that are hard to specify completely. Even so, it is important that we use the available scientific methods and combine these to ensure as much understanding and specification as possible. Precursor incidents rarely lead to major accidents, and in turn this reduces the fear of an occurrence as well as the visible benefits of safety investments. By describing precursor incidents with related probabilities and consequences, proactive management can be mobilised. Parts of QRA modelling have been applied to accident investigations in the past. Especially modelling of gas clouds and explosion forces have been done, both to verify software tools as well as understanding the sequence in the accident. However, this has rarely been done for precursor incidents. Any conclusion of an investigation should be based on an understanding of the events leading up to the event as well as its potential consequences. Combining precursor incident/accident investigation and QRAs can contribute to this understanding (Skogdalen and Vinnem, 2011).

5 CONCLUSION AND FURTHER WORK

The overall objective of this thesis was to provide knowledge and tools for major hazard risk management for offshore installations (and onshore plants) based on an improved understanding of the influence of organizational, human and technical factors. The thesis focused mainly on risk assessment related to the process of risk management. The Deepwater Horizon accident forms the basis for several of the articles in part two of this thesis. The rig was considered a safe drilling vessel based on a low number of lost time incidents often summarised as “slips, trips and falls”.

The risk management framework treated in ISO 31000 is a skeleton of principles and guidelines that needs flesh and blood to become a meaningful system. One important acknowledgement is that risk management of major hazards differs from managing occupational safety. Another is that managing risk in the O&G industry demands a high level due to the potential severe consequences. The hazards introduced by deepwater drilling have been demonstrated by the Deepwater Horizon accident, and the consequences of loss of well control are unacceptable.

The consequences of the Deepwater Horizon accident extend far beyond the possibility that drilling operations could become more expensive. Based on extensive information about and analyses of the accident, as well as the companies, the industry, the authorities and so forth over a long period (back to the 1970s), the Commission concluded that the errors in managing major accident risk are symptomatic of the prevailing safety culture throughout the industry (Graham et al., 2011). The PSA takes the view that the lessons drawn from the Deepwater Horizon accident must not be limited to the well control system that was in use on the rig, but must apply to all types of barrier systems (PSA, 2011).

Complex systems fail in complex ways. Major accidents cannot be explained by simple models and cannot be prevented by simple solutions. While it is important to simplify reality in order to deal with it in practice, it is also important to be able to deal with complexity. This is a fundamental requirement for developing the necessary respect for the uncertainty that underlies most decisions, and thereby being able to choose more robust solutions (PSA, 2011). Integration of human, organisational and technical factors in risk assessments is a challenge that adds complexity to the existing models, but can also reduce the uncertainty. The more extensive use of indicators can support the monitoring and review process. This is important to ensure that a greater diversity of risk analysis tools actually support the improved management of risk.

The word “culture” is mentioned 69 times in the Commission’s Deepwater Horizon accident investigation report. The Commission concluded that the errors, mistakes and management failures that caused the disaster were not the product of a single, rogue company, but instead revealed both the failures and inadequate safety procedures by three key industry players that all have a large presence in offshore oil and gas drilling throughout the world. What the men and women who worked on the Deepwater Horizon lacked—and what every drilling operation requires—is a culture of leadership responsibility (Bartlit et al., 2011). According to the Commission, the lessons learned from the Deepwater Horizon accident were not confined to only the US government and industry, but were relevant to the rest of the world. The Commission demanded no less than a fundamental transformation of the industry's safety culture. The PSA stated that the Deepwater Horizon accident must be seen as a wake-up call to the Norwegian petroleum sector, that it must lead to a big improvement in managing major accident risk and that the conclusion that the safety culture needs developing throughout the industry must also be considered relevant for Norway's petroleum activities (PSA, 2011).

The term "culture" seems to be a buzzword in the Commission's report, and their understanding of the word is difficult to comprehend precisely. It seems to be more a summary of feelings about a culture after an accident than a well-argued statement based on historical data and analyses within and outside the O&G industry. In the same way, it is a challenge for the industry to respond to the request for a cultural change. The elements and factors of an acceptable safety culture need to be further sorted out. The elements and factors must be specific related to major hazard risk management and should be specified for each industry as the risk level differs largely between industries.

Through the examination and understanding of accidents, it is clear that revealing, analyzing, monitoring and treating HOFs are essential for managing risk and thereby improving elements of the safety culture. The complex technical systems used in the O&G industry require human actions for tasks such as set-up, maintenance, monitoring as well as any necessary corrective actions or interventions. The results presented in this thesis demonstrate that one of the most important tools for managing risk, namely the QRA, does not reflect HOFs. For risk management to be effective it should take human and cultural factors into account, and thereby recognize the capabilities, perceptions and intentions of external and internal people that can facilitate or hinder the achievement of the organisation's objectives. This is an important but often undervalued principle in ISO 31000 (ISO, 2009b).

The Deepwater Horizon accident was a result of a loss of well control. The data and methods used in QRA for offshore deepwater drilling have essential shortcomings. The narrow drilling window related to deepwater drilling has to be controlled by safety barriers that are dependent on HOFs. There is a lack of data related to how to take HOFs into account. Furthermore, the data related to technical reliability can be questioned when analysing the risk of deepwater drilling.

One of the main findings in this thesis is that more data (e.g. operator well response and operational aspects) need to be collected and analysed. The data are important both for being able to assess the risk level and monitor the trends in risk levels. The data need to include human, organisational, operational and technical factors. A research project using the RNNP data has demonstrated a statistical correlation among safety climate surveys with major hazard precursor incidents (Vinnem et al., 2010). A separate study using data from a large offshore operator supports these findings (Kongsvik et al., 2011). These are important contributions to the process of modelling the interactions between the factors. The data and understanding of the interactions are essential both for risk assessments and for monitoring.

The RNNP needs to be supported by more data as basis for indicators. Time pressure, cost increases and an exceeded schedule were all pointed as root causes for the Deepwater Horizon accident. Even so, hardly any data or research exist that supports that there is any coherence between schedule and cost factors, and safety levels. The Chief Counsel argued in one of the final meetings with the Commission that there was no indication that any individual purposely had made decisions that he or she knew increased risk and saved money (Commission, 2010b). This is in contradiction to the Commission's final conclusion. This disagreement demonstrates the challenge of sorting out the RIFs, and thereby how to improve safety culture. More money, employees or extended time limits do not necessary lead to safer operations. More safety and risk indicators are necessary to ensure improved risk management.

The data need to be gathered across the O&G industry worldwide. Examples of data are unwanted events, precursor incidents, operational aspects and the technical conditions of safety critical equipment. Knowledge about the factors that influence risk as well as their interaction and status is essential for managing risk. Different disciplines such as social sciences, economics, psychology, sociology and engineering need improved cooperation as they all provide different bases for analyzing risk.

There are several competing actors within deepwater drilling. The data requested might by some companies be considered trade secrets. It is thus necessary that regulators and authorities take the lead in the process of gathering data. The increased amount of data needs to be assisted by improved models and techniques for assessing, communicating, monitoring and reviewing hazards.

The focus on and efforts to improve major hazard risk management can be sacrificed over time due to the absence of accidents. This is a paradox as long as the absence of major accidents indicates that the management of risk is according to intentions. The number of precursor incidents is an important safety indicator. In several accident investigation reports, the PSA has concluded that under slightly different circumstances, the precursor incidents could have developed into major accidents, with extensive pollution and the potential loss of multiple lives (PSA, 2010b). This thesis argues for extended and multidisciplinary investigations of precursor incidents. Risk is managed at all levels of an organisation and in a socio-technical system. Communication between the stakeholders is essential, and unfortunately it often fails. More extensive analyses of precursor incidents can be the basis for improving the communication, management of change and understanding of potential accidents.

Deepwater drilling was made possible through the technical developments within various scientific fields, e.g., metallurgy, seismology, directional drilling, drilling control systems, positioning systems and power management among others. The level of automation has rapidly increased over several decades. These automation systems are essential for the safety, reliability and performance of the systems. Even though the systems are often described as automatic, they require human actions for tasks such as set-up, maintenance, monitoring as well as any necessary corrective actions or interventions. The technological development, complexity and the systems' prompt and major impact on each other demand a multidisciplinary approach towards managing risk.

Deepwater drilling introduces new challenges to the O&G industry (e.g. casing wear and remote operation on the seabed). The risks related to large reservoirs with extreme temperatures and pressures demands improvements within risk management. The Deepwater Horizon accident demonstrated some of the potential consequences if risk management does not keep pace with technology. Upcoming exploration in Arctic areas may increase the risks further because of the long distances from shore and harsh weather conditions. More data related to technical, human and organisational factors are needed. These data will form the basis for improved knowledge about how to integrate the factors into risk assessments of major hazards. This is crucial to ensure that risk management follows the technological pace.

There seems to be agreement among the parties involved in the O&G industry that safety culture, operational aspects, technical conditions and the number of precursor incidents influence each other, but there is a need for more knowledge related to how and why. This understanding can be achieved by combining and improving methods for risk management, such as different risk analysis methods, safety monitoring using indicators, the investigation of precursor incidents, revisions and inspections and accident investigations. The suggestions made in this thesis are small steps in the process, and further research is necessary to:

- Improve methods for precursor incident reporting,
- Improve methods for precursor investigation,
- Extend the collection of safety indicators,
- Analyse the correlation between safety indicators,
- Improve the understanding of correlations, and the possible use of safety indicators,
- Improve the data sets used in QRAs, and
- Establish an industry standard for how HOFs should be incorporated in QRAs.

6 REFERENCES

AICE, (2003). American Institute of Chemical Engineers. *Guidelines for investigating chemical process incidents*. 2nd ed.

Ale, B., (2002). Risk assessment practices in The Netherlands. *Safety Science*, 40: 105-126.

Ale, B.J.M., Bellamy, L.J., Cooke, R.M., Goossens, L.H.J., Hale, A.R., Roelen, A.L.C., Smith, E., (2006). Towards a causal model for air transport safety - an ongoing research project. *Safety Science*, 44: 657-673.

Apostolakis, G., (1990). The concept of probability in safety assessments of technological systems. *Science*, 250: 1359-1364.

Apostolakis, G.E., (2004). How Useful Is Quantitative Risk Assessment? *Risk Analysis*, 24: 515-520.

Aven, T., (2007). A unified framework for risk and vulnerability analysis covering both safety and security. *Reliability Engineering & System Safety*, 92: 745-754.

Aven, T., (2008). Risk analysis: assessing uncertainties beyond expected values and probabilites. John Wiley, Chichester.

Aven, T., (2009). Perspectives on risk in a decision-making context - Review and discussion. *Safety Science*, 47: 798-806.

Aven, T., (2010). On how to define, understand and describe risk. *Reliability Engineering and System Safety*, 95: 623-631.

Aven, T., (2011a). Interpretations of alternative uncertainty representations in a reliability and risk analysis context. *Reliability Engineering & System Safety*, 96: 353-360.

Aven, T., (2011b). On the new ISO guide on risk management terminology. *Reliability Engineering & System Safety*, 96: 719-726.

Aven, T., (2011c). Response. *Risk Analysis*, 35: 693-697.

Aven, T., Kristensen, V., (2005). Perspectives on risk: review and discussion of the basis for establishing a unified and holistic approach. *Reliability Engineering & System Safety*, 90: 1-14.

Aven, T., Renn, O., (2009). On risk defined as an event where the outcome is uncertain. *Journal of Risk Research*, 12: 1-11.

Aven, T., Renn, O., (2010). Risk Management and Governance: Concepts, Guidelines and Applications. Springer, Heidelberg.

Aven, T., Sklet, S., Vinnem, J.E., (2006). Barrier and operational risk analysis of hydrocarbon releases (BORA-Release): Part I. Method description. *Journal of Hazardous Materials*, 137: 681-691.

Aven, T., Vinnem, J.E., Wiencke, H.S., (2007). A decision framework for risk management, with application to the offshore oil and gas industry. *Reliability Engineering & System Safety*, 92: 433-448.

Baker, J., Bowman, F., Erwin, G., Gorton, S., Hendershot, D., Leveson, N., (2007). *The report of the BP U.S. Refineries independent safety review panel*, Washington DC, USA.

Bartlit, J.F.H., Sankar, S.N., Grimsley, S.C., (2011). National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling. *Macondo - The Gulf Oil Disaster - Chief Counsel's Report*

Bea, R., (2002a). Human & Organizational Factors in Design and Operation of Deepwater Structures. *Offshore Technology Conference*, Houston, USA, 6-9th May 2002.

Bea, R., (2002b). Human and organizational factors in reliability assessment and management of offshore structures. *Risk Analysis*, 22: 29-45.

Bellamy, L.J., Geyer, T.A.W., Wilkinson, J., (2006). Development of a functional model which integrates human factors, safety management systems and wider organisational issues. *Safety Science*, 46: 461-492.

Campbell, S., (2005). Determining overall risk. *Journal of Risk Research*, 8: 569-581.

CCPS, (1992). *Guidelines for investigating chemical process incidents*. Center for Chemical Process Safety of the American Institute of Chemical Engineers, New York.

Commission, (2010a). National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling. *A Brief History of Offshore Oil Drilling*.

Commission, (2010b). National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling. *Meeting 5: November 8-9, 2010*. Washington DC, USA.

Cooke, D.L., Rohleder, T.R., (2006). Learning from incidents: from normal accidents to high reliability. *System Dynamics Review*, 22: 213-239.

Crouhy, M., Galai, D., Mark, R., (2001). *Risk management*. McGraw-Hill, New York.

Cullen, W.D., (1990). *The Public Inquiry into the Piper Alpha disaster*. Department of Energy, London.

Davoudian, K., Wu, J.-S., Apostolakis, G., (1994a). Incorporating organizational factors into risk assessment through the analysis of work processes. *Reliability Engineering & System Safety*, 45: 85-105.

Davoudian, K., Wu, J.-S., Apostolakis, G., (1994b). The work process analysis model (WPAM). *Reliability Engineering & System Safety*, 45: 107-125.

Dawson, D., Brooks, B., (1999). Esso Longford gas plant accident: Report of the Longford Royal Commission. Longford Royal Commission.

Dempsey, P., Wogalter, M., Hancock, P., (2006). Defining Ergonomics/Human Factors. *International encyclopedia of ergonomics and human factors*, 32.

DHJIT, (2010). USCG/BOEM Marine Board of investigation into the marine casualty, explosion, fire, pollution, and sinking of mobile offshore drilling unit Deepwater Horizon, with the loss of life in the Gulf of Mexico April 21-27, 2010. Deepwater Horizon Incident Joint Investigation Team, The U.S. Coast Guard (USCG) / Bureau of Ocean Energy Management, Regulation and Enforcement (BOEMRE) Joint Investigation Team (JIT).

DHSG, *Deepwater Horizon Study Group*.Access date on web: 01 August 2011. http://ccrm.berkeley.edu/deepwaterhorizonstudygroup/index.shtml

Duijm, N.J., Fiévez, C., Gerbec, M., Hauptmanns, U., Konstandinidou, M., (2008). Management of health, safety and environment in process industry. *Safety Science*, 46: 908-920.

EBO, (2008). *"safety."* Encyclopædia Britannica Online. Access date on web: 08 September 2010. http://www.britannica.com/

Embrey, D.E., (1992). Incorporating management and organisational factors into probabilistic safety assessment. *Reliability Engineering & System Safety*, 38: 199-208.

EPA/OSHA, (1998). United States Enviromental Protection Agency/United States Occupationonal Safety and Health Administration. *Joint Chemical Accident Investigation Report - Shell Chemical Company Deer Par, Texas*.

Fet, A.M., (1997). Systems Engineering methods and environmental life cycle performance within ship industry. PhD thesis, NTNU, Norway.

Flage, R., (2010). Contributions to the treatment of uncertainty in risk assessment and management. University of Stavanger, Norway.

Funtowicz, S.O., Ravetz, J.R., (1990). *Uncertainty and quality in science for policy*. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Goodwin, S., (2007). Det Norske Veritas Ltd. Human Factors in QRA. Report for Intl. Association of Oil & Gas Producers.

Gordon, R.P.E., (1998). The contribution of human factors to accidents in the offshore oil industry. *Reliability Engineering & System Safety*, 61: 95-108.

Graham, B., Reilly, W.K., Beinecke, F., Boesch, D.F., Garcia, T.D., Murray, C.A., Ulmer, F., (2011). the National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling. *Deep Water. The Gulf Oil Disaster and the Future of Offshore Drilling. Report to the President*. Washington DC, USA.

Graham, J.D., Wiener, J.B., (1997). Risk versus risk: Tradeoffs in protecting health and the environment. Harvard University Press.

Hale, A., (2009a). Editorial: Special Issue on Process Safety Indicators. *Safety Science*, 47: 459-459.

Hale, A., (2009b). Why safety performance indicators? *Safety Science*, 47: 479-480.

Hale, A., Kirwan, B., Kjellén, U., (2007). Safe by design: where are we now? *Safety Science*, 45: 305-327.

Hellevik, O., (1999). Research Methodology in Sociology and Political Science, (In Norwegian: Forskiningsmetode i sosiologi og statsvitenskap). Universitetsforlaget, Oslo, Norway.

Helton, J.C., Burmaster, D.E., (1996). Guest editorial: treatment of aleatory and epistemic uncertainty in performance assessments for complex systems. *Reliability Engineering and System Safety*, 54: 91-94.

Hollnagel, E., Woods, D., Leveson, N., (2006). *Resilience Engineering: Concepts and Precepts*. Ashgate Publishing, Ltd.

Hopkins, A., (2000). Lessons from Longford: the Esso gas plant explosion. CCH Australia Ltd, Sydney.

Hopkins, A., (2009). Thinking About Process Safety Indicators. *Safety Science*, 47: 460-465.

HSE, (2001). WS Atkins Consultants Ltd. *Root causes analysis: Literature review*. Contract research report 325/2001.

HSE, (2003). Organisational change and major hazards. HSE Books.

HSE, (2006). Developing process safety indicators. HSE Books.

HSE, (2010). *Major Hazards*.Strategies and plans Plans archive Business plan 04-05 Major hazards. Access date on web: 08. April 2010. http://www.hse.gov.uk/aboutus/strategiesandplans/hscplans/businessplans/0405/07.htm

IRGC, (2005). International Risk Governance Council. Risk governance: Towards an integrative approach. White Paper No. 1, O. Renn with an Annex by P. Graham. Geneva.

ISO, (1999). International Organization for Standardization. *ISO 13702:1999 - Petroleum and natural gas industries -- Control and mitigation of fires and explosions on offshore production installations -- Requirements and guidelines*.

ISO, (2009a). International Organization for Standardization. *Guide 73. Risk Management – Vocabulary*.

ISO, (2009b). International Organization for Standardization. *ISO 31000 Risk Management – Principles and guidelines*.

Jacobs, R., Haber, S., (1994). Organizational processes and nuclear power plant safety. *Reliability Engineering & System Safety*, 45: 75-83.

Kaplan, S., (1991). Risk assessment and risk management-Basic concepts and terminology. *Risk management: Expanding horizons in nuclear power and other industries*: 11-28.

Kaplan, S., (1997). The Words of Risk Analysis. *Risk Analysis*, 17: 407-417.

Kaplan, S., Garrick, B.J., (1981). On the quantitative definition of risk. *Risk Analysis*, 1: 11-27.

Kobes, M., Helsloot, I., de Vries, B., Post, J.G., (2010). Building safety and human behaviour in fire: A literature review. *Fire Safety Journal*, 45: 1-11.

Kongsvik, T., Kjøs Johnsen, S.Å., Sklet, S., (2011). Safety climate and hydrocarbon leaks: An empirical contribution to the leading-lagging indicator discussion. *Journal of Loss Prevention in the Process Industries*, 24: 405-411.

Lowrance, W.W., (1976). *Of Acceptable Risk: Science and the Determination of Safety*. William Kaufmann, Inc., Los Altos, USA.

Metcalfe, R., (2003). *Operational Risk: The Empiricists Strike Back*. In Field, London, UK.

Mohaghegh, Z., Mosleh, A., (2009). Incorporating organizational factors into probabilistic risk assessment of complex socio-technical systems: Principles and theoretical foundations. *Safety Science*, 47: 1139-1158.

Moosa, I.A., (2007). Operational Risk: A Survey. *Financial Markets, Institutions & Instruments*, 16: 167-200.

Mosleh, A., Chang, Y.H., (2004). Model-based human reliability analysis: Prospects and requirements. *Reliability Engineering and System Safety*, 83: 241-253.

Mosleh, A., Golfeiz, E., (1999). An approach for assessing the impact of organizational factors on risk. Technical Research Report. *Center for Technology Risk Studies, University of Maryland at College Park, MD, USA*.

NENT, (2008). The National Committee for Research Ethics in Science and Technology. *Guidelines for research ethics in science and technology*.

Norsok, (2010). Standards Norway. Norsok Standard: Risk and emergency preparedness analysis, Z-013 3ed. Oslo.

NRC, (2000). Norwegian Research Council. Quality in Norwegian Research. A summary of concepts, methods, and means (In Norwegian: Kvalitet i norsk forskning. En oversikt over begreper, metoder og virkemidler). Oslo, Norway.

Næsheim, T., (1981). NOU, The "Alexander L. Kielland"-accident (In Norwegian). Oslo.

OECD, (2002). Organisation for Economic Co-operation and Development. Frascati Manual: Proposed Standard Practice for Surveys on Research and Experimental Development.

Oh, J., Brouwer, W., Bellamy, L., Hale, A., Ale, B., Papazoglou, I., (1998). The I-Risk project: development of an integrated technical and management risk control and monitoring methodology for managing and quantifying on-site and off-site risks. *Probabilistic Safety Assessment and Management. Springer, London*: 2485–2491.

Osmundsen, P., Aven, T., Erik Vinnem, J., (2008). Safety, economic incentives and insurance in the Norwegian petroleum industry. *Reliability Engineering & System Safety*, 93: 137-143.

Papazoglou, I.A., Bellamy, L.J., Hale, A.R., Aneziris, O.N., Ale, B.J.M., Post, J.G., Oh, J.I.H., (2003). I-Risk: development of an integrated technical and management risk methodology for chemical installations. *Journal of Loss Prevention in the Process Industries*, 16: 575-591.

Paté-Cornell, M.E., Murphy, D.M., (1996). Human and management factors in probabilistic risk analysis: the SAM approach and observations from recent applications. *Reliability Engineering & System Safety*, 53: 115-126.

Pendery, D., (2009). Three top economists agree 2009 worst financial crisis since great depression; risks increase if right steps are not taken. *Business Wire News. http://www. Businesswire. com/portal/site/home/permalink*. Access date on web: 16 February 2010.

Phimister, J., Oktem, U., Kleindorfer, P., Kunreuther, H., (2003). Near-miss incident management in the chemical process industry. *Risk Analysis*, 23: 445-459.

PSA, (2009). Petroleum Safety Authority, Norway. Trends in risk level in the petroleum sector, Norwegian Shelf, 2008.

PSA, (2010a). Petroleum Safety Authority Norway. *From prescription to performance in petroleum supervision*. Access date on web: 16 February 2010. http://www.ptil.no/news/from-prescription-to-performance-in-petroleum-supervision-article6696-79.html?lang=en_US

PSA, (2010b). Petroleum Safety Authority Norway. *Investigations*. Access date on web: 09. April 2010. http://www.ptil.no/investigations/category157.html

PSA, (2010c). Petroleum Safety Authority Norway. Trends in risk level in the petroleum activity 2009.

PSA, (2011). Petroleum Safety Authority Norway. The Deepwater Horizon accident - assessments and recommendations for the Norwegian petroleum industry summary.

Rasmussen, J., (1997). Risk management in a dynamic society: a modelling problem. *Safety Science*, 27: 183-213.

Reason, J., (1997). *Managing the Risks of Organizational Accidents*. Ashgate Publishing Company, Aldershot, UK.

Roe, E., Schulman, P., (2008). *High reliability management: Operating on the edge*. Stanford University Press.

Rosa, E., (2003). The logical structure of the Social Amplication of Risk Framework (SARF): Metatheoretical foundations and policy implications. The Social Amplication of Risk. Cambridge University Press, UK.

Rosa, E.A., (1998). Metatheoretical foundations for post-normal risk. *Journal of Risk Research*, 1: 15-44.

Saqib, N., Tahir Siddiqi, M., (2008). Aggregation of safety performance indicators to higher-level indicators. *Reliability Engineering & System Safety*, 93: 307-315.

Schönbeck, M., Rausand, M., Rouvroye, J., (2010). Human and organisational factors in the operational phase of safety instrumented systems: A new approach. *Safety Science*, 48: 310-318.

Sklet, S., (2005). Safety Barriers on Oil and Gas Platforms. Means to Prevent Hydrocarbon Releases. PhD thesis, NTNU, Norway.

Sklet, S., (2006). Safety barriers: Definition, classification, and performance. *Journal of Loss Prevention in the Process Industries*, 19: 494-506.

Sklet, S., Vinnem, J.E., Aven, T., (2006). Barrier and operational risk analysis of hydrocarbon releases (BORA-Release): Part II: Results from a case study. *Journal of Hazardous Materials*, 137: 692-708.

Skogdalen, J.E., (2010). Safety engineering and different approaches *Safety Science Monitor*, 14.

Skogdalen, J.E., Khorsandi, J., Vinnem, J.E., (2011a). Evacuation, escape and rescue experiences from offshore accidents including the Deepwater Horizon. *Journal of Loss Prevention in the Process Industries*. doi: 10.1016/j.jlp.2011.08.005

Skogdalen, J.E., Tveiten, C., (2011). Safety perceptions and comprehensions among offshore installation managers on the Norwegian Continental Shelf. *Submitted for Journal of Safety Science. Accepted with revision 24 May 2011*.

Skogdalen, J.E., Utne, I.B., Vinnem, J.E., (2011b). Developing safety indicators for preventing offshore oil and gas deepwater drilling blowouts. *Safety Science*, 49: 1187-1199.

Skogdalen, J.E., Vinnem, J.E., (2011). Combining precursor incidents investigations and QRA in oil and gas industry *Submitted for Journal of Reliability Engineering & System Safety*. Accepted with revisions 06 September 2011.

Skogdalen, J.E., Vinnem, J.E., (2011a). Quantitative Risk Analysis of oil and gas drilling, using Deepwater Horizon as case. *Submitted for Journal of Reliability Engineering & System Safety 10 May 2011.*

Skogdalen, J.E., Vinnem, J.E., (2011b). Quantitative risk analysis offshore--Human and organizational factors. *Reliability Engineering & System Safety*, 96: 468-479.

Sonnemans, P.J.M., Körvers, P.M.W., (2006). Accidents in the chemical industry: are they foreseeable? *Journal of Loss Prevention in the Process Industries*, 19: 1-12.

Stranks, J., (2006). *The Manager`s Guide to Health & Safety at Work*. Kogan Page Ltd., London, UK.

SU, (2002). The Strategy Unit. Risk: Improving government's capability to handle risk and uncertainty. London, UK.

Taylor, J., (2009). Defining Systemic Risk Operationally. *Ending Government Bailouts As We Know Them",* Hoover Press, Stanford University.

TBCS, (1992). Treasury Board of Canada Secretariat, A Guide to Accident Investigation, Treasury Board of Canada Secretariat.

Turner, B.A., (1978). *Man-made disasters*. Wykeham, London, UK.

USDI, (2010). U.S. Department of the Interior. Increased Safety Measures for Energy Development on the Outer Continental Shelf.

Utne, I.B., (2007). Sustainable fishing fleet: a systems engineering approach. PhD thesis, NTNU, Norway.

Vinnem, J., (2010). Risk indicators for major hazards on offshore installations. *Safety Science*, 48: 770-787.

Vinnem, J.E., (2007). *Offshore Risk Assessment*, 2nd ed. Springer, London, UK.

Vinnem, J.E., (2008a). Project description Risk Modelling – Integration of Organisational, Human and Technical factors.

Vinnem, J.E., Haugen, S., Kongsvik, T., Seljelid, J., Steen, S., Sklet, S., Thomassen, O., (2007). *Operational Safety Condition - Concept Development*, ESREL. Taylor and Francis Group, London.

Vinnem, J.E., Hestad, J.A., Kvaløy, J.T., Skogdalen, J.E., (2010). Analysis of root causes of major hazard precursors (hydrocarbon leaks) in the Norwegian offshore petroleum industry. *Reliability Engineering & System Safety*, 95: 1142-1153.

Vinnem, J.E., Seljelid, J., Haugen, S., Aven, T. , (2008b). Generalized methodology for operational risk analysis of offshore installations. *Journal of Risk and Reliability*, 223: 87-98.

Willis, H.H., (2007). Guiding resource allocations based on terrorism risk. *Risk Analysis*, 27: 597-606.

Wills, S., Hinko, S., Haubenstock, M., Leibfried, K., Pozzi, A., Hayes, N., (1999). *Operational Risk—The Next Frontier*. British Bankers' Association/International Swaps and Derivatives Association (ISDA)/Pricewaterhouse Coopers/RMA, ISBN.

Woods, D., (2006). Essential characteristics of resilience. *Resilience engineering: Concepts and precepts*: Ashgate Publishing. Hampshire.

Wreathall, J., Schurman, D., Modarres, M., Anderson, N., Roush, M., Mosleh, A., (1992). Vol. 1 and 2. US Nuclear Regulatory Commission, Washington DC, USA. *US Nuclear Regulatory Commission: A framework and method for the amalgamation of performance indicators at nuclear power plants*.

Øien, K., (2001a). A framework for the establishment of organizational risk indicators. *Reliability Engineering & System Safety*, 74: 147-167.

Øien, K., (2001b). Risk indicators as a tool for risk control. *Reliability Engineering and System Safety*, 74: 129-145.

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

Øien, K., Utne, I.B., Tinmannsvik, R.K., Massaiu, S., (2010). Building Safety Indicators Part 2: - Application, practises and results. *Safety Science*, 49: 162-171.