UiT THE ARCTIC UNIVERSITY OF NORWAY

Faculty of Science and Technology
Department of Engineering and Safety

Risk-Based Analysis of Drilling Waste Handling Operations

Bayesian Network, Cost-effectiveness, and Operational Conditions

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Yonas Zewdu Ayele

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Risk-Based Analysis of Drilling Waste Handling Operations

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By
Yonas Zewdu Ayele

Thesis submitted in fulfilment of
the requirements for the degree of
PHILOSOPHIAE DOCTOR
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. . . dedicated to my parents, Zafu and Zewdu

in love and gratitude.

" ነገር ግን አስቀድማችሁ የእግዚአብሔርን መንግሥት ጽድቁንም ፈልጉ፥ ይህም ሁሉ ይጨመርላችኋል።"

(የማቴዎስ ወንጌል 6:33)

"A RISK is a potential for a LOSS. The LOSS is the realisation of that negative potential. A RISK is running across a busy street blindfolded. A LOSS is getting hit by a car while doing that."

Riskviews

"Risk comes from not knowing what you`re doing."

Warren Buffett

"If we listened to our intellect, we'd never have a love affair. We'd never have a friendship. We'd never go into business. Well, that's nonsense. You've got to jump off cliffs all the time and build your wings on the way down."

Ray Bradbury

"Så snart du har lært deg å sykle er det vanskelig å forstå hvordan det var mulig å ikke kunne det. "

Abstract

As the offshore industry expands into the Arctic and sub-Arctic areas, the oil and gas exploration activities generate all kinds of waste, varying from contaminated runoff water to material packaging; however, the majority of the waste is associated with the drilling cuttings from drilling activities. Offshore Arctic projects have a high degree of technical and social complexity. The technological challenges of drilling at remote location coupled with the extreme weather conditions makes the operation of drilling waste handling in this environment very demanding and risky. Hence, the competence to reduce the adverse impacts of undesirable events during the drilling waste handling activities depends in part upon the effectiveness of our rigorous risk management plan and clear understanding of the effect of the Arctic operating environment on the drilling waste handling systems.

The aim of this research study is to evaluate, identify, and propose a methodology for drilling waste handling practices by considering the complex and fast-changing nature of the Arctic operational conditions. Moreover, the study seeks to foster an integrated interdisciplinary understanding of technical and operational risks associated with drilling wastes and their management by implementing the risk-based analysis. This includes identifying and assessing risks throughout the logistical chain of handling of petroleum related waste. Furthermore, to assure the operational performance of waste handling systems, the study focuses on developing and introducing the concept of a dynamic model for spare parts transportation in Arctic conditions by considering the time-independent and time-dependent covariates.

The first part of the study describes the main factors that may influence the operation and performance of the waste handling technologies and processes under Arctic conditions. Then, the current industry practice for managing and disposing of drilling waste are studied. Afterwards, the pros and cons of the common offshore and onshore disposal options are reviewed. Thereafter, a step-by-step methodology is developed for the identification of suitable drilling waste handling systems for Arctic offshore drilling. The application of the methodology is demonstrated by a case study of drilling waste handling practices of an oil field in the Barents Sea (part of Norwegian and Russian Arctic).

In the second part of this research study, a risk-based cost-effectiveness analysis model is developed. This model seeks to identify the drilling waste handling practice that is expected to provide the highest level of benefit for a given level of cost, and which has a minimal impact on the HSE (health, safety and environment). Moreover, to avoid inadequacies of the traditional risk assessment approaches and manage the major risk elements connected with handling of drilling wastes, a dynamic Bayesian network (DBN) based risk assessment model is developed. The proposed DBN based risk model combines prior operating environment information with actual observed data from weather forecasting to predict the future potential hazards and/or risks. Furthermore, to assure the availability of production facilities, including waste handling systems, a dynamic model for spare parts transportation called Dynamic Spare Parts Transportation Block Diagram (DSTBD) is described and introduced. The DSTBD model analysed the effect of the time-independent and time-dependent covariates on the spare parts transportation operation.

The result of the study shows that working in the cold Arctic environments has the potential if not managed properly to cause a significant negative effect on the cost elements and the risk of events. Moreover, the result from the temporal link or dynamic Bayesian network based risk analysis demonstrates that these negative impacts of the peculiar Arctic risk influencing factors on the reliability of the waste handling system and the risk of marine pollutions, is more significant with time. Furthermore, the DSTBD analysis results demonstrate that the operating environment of the Arctic region increases the spare parts transportation time significantly, particularly, during winter season, when transporting the spare parts from the south-western part of Norway to northern Norway.

Keywords: Arctic, Bayesian networks, cost-effectiveness, drill cuttings, drilling waste, dynamic Bayesian network, oil and gas industry, offshore drilling, production facility, risk analysis, risk based, risk influencing factors, spare parts, time-independent covariate, time-dependent covariate, transportation, waste handling, waste management

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Standing on the Shoulders of the Giants…

I have gotten this far, in part, because of the efforts of my giants!! As Isaac Newton used to say, in his letters, if I have seen any further, it is by standing on the shoulders of my giants. My gratitude and deepest appreciation go to all of my giants who have helped and inspired me during my PhD studies.

I praised God for the wisdom and perseverance that he has been bestowed upon me during this research study, and indeed, throughout my life: ''*The Lord God is my strength, and he will make my feet like hinds' feet, and he will make me to walk upon mine high places.*'' (Habakkuk 3:19)

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Yonas Zewdu Ayele
Tromsø, Norway
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Paper II **Ayele, Y. Z.,** Barabady, J., Droguett, E. L. 2015. Dynamic Bayesian network based risk assessment for Arctic offshore drilling waste handling practices. *Submitted to Journal of Offshore Mechanics and Arctic Engineering. Under review.*

Paper III **Ayele, Y. Z.,** Barabadi, A., Droguett, E. L. 2015. Risk-based cost-effectiveness analysis of waste handling practices in the Arctic drilling operation. *Journal of Offshore Mechanics and Arctic Engineering. In Press. DOI:10.1115/1.4032707.*

Paper IV **Ayele, Y. Z.,** Barabadi, A., Barabady, J. 2015. Dynamic spare parts transportation model for Arctic production facility. *International Journal of System Assurance Engineering and Management.* Vol. 7, Issue 1, pp. 84 – 98.

Paper V **Ayele, Y. Z.,** Barabadi, A., Barabady, J. 2014. A risk-based approach to manage the Occupational Hazards in the Arctic drilling waste handling practices. *CRC Press 2014 ISBN 9781138026810.s. pp. 1329 – 1334. DOI: 10.1201/b17399-183.*

Additional papers, not included

Paper VI **Ayele, Y. Z.,** Barabady, J., Droguett, E. L. 2015. Risk assessment of Arctic drilling waste management operations based on Bayesian Networks. *European Safety and Reliability Conference ESREL 2015, 7 – 10 September, 2015, Zurich, Switzerland, CRC Press 2015, ISBN 9781138028791.s, pp. 1907 – 1915.*

Paper VII **Ayele, Y. Z.,** Løset, S. 2015. Drilling waste handling practices in low temperature operations: A risk perspective. *Proceedings of International Conference on Port and Ocean Engineering under Arctic Conditions 2015. ISSN 0376-6756.*

Paper VIII **Ayele, Y. Z.,** Barabadi, A., Barabady, J. 2015. Performance-based risk management systems (PBRMS) in the Arctic drilling waste handling operation. *Proceeding of IEEE International Conference on Industrial Engineering and Engineering Management (IEEM) 2015. pp. 1623 - 1628, DOI: 10.1109/IEEM.2015.7385922.*

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Paper XI **Ayele, Y.Z.,** Barabadi, A., Barabady, J. 2014. Effectiveness assessment for waste management decision-support in the Arctic drilling. *Proceeding of IEEE International Conference on Industrial Engineering and Engineering Management 2014. pp. 559 – 564, DOI: 10.1109/IEEM.2014.7058700.*

Paper XII **Ayele, Y. Z.,** Barabadi, A., Barabady, J. 2013. Drilling waste handling and management in the High North. *Proceeding of IEEE International Conference on Industrial Engineering and Engineering Management 2013. pp. 673 – 678, DOI: 10.1109/IEEM.2013.6962496.*

Paper XIII **Ayele, Y. Z.,** Barabadi, A., Markeset, T. 2013. Spare parts transportation management in the High North. *Proceedings of International Conference on Port and Ocean Engineering under Arctic Conditions 2013. ISSN 0376-6756.*

Part I – Thesis Summary

1. Introduction and background

Oil and gas producers continue to push offshore projects into the arduous and colder Arctic frontiers, driven primarily by the need to secure future oil and gas reserves (Martin, 2012; Paulsen et al., 2002). As the offshore industry expands into the Arctic and sub-Arctic, the oil and gas exploration activities generate all kinds of wastes, varying from contaminated runoff water to material packaging; however, the majority of the waste is associated with the drilling cuttings, from the drilling activities (Geehan et al., 2007). To maximise the value of each project and optimise their portfolio of investment opportunities, oil and gas companies operating in the region are attempting to properly identify suitable methods of handling the drilling waste. Current industry practice for managing and disposing of drilling waste is broadly classified into three major categories: *i)* offshore discharge – treating and discharging the drilling waste to the ocean (sea), *ii)* offshore re-injection – re-injecting the drilling waste offshore both in a dedicated re-injection well and/or in a dry (dead) well, and *iii)* skip-and-ship – hauling the drilling waste back to shore for further treatment and disposal (Veil, 2002).

Drilling wastes handling practices pose health, safety and environmental (HSE) risks due to the potential for releases or spills of drilling fluids and cuttings during operation on the well pad or off-site during transporting of drilling fluid additives or waste drilling fluids and cuttings (Valeur, 2010; Sadiq et al., 2004; Ayele et al., 2015a). The releases or spills of drilling fluids to the Arctic marine environment is of major concern for two main reasons: economical loss associated with expensive drilling fluid discharge and potential adverse environmental impacts or marine pollutions (Sadiq et al., 2004). Moreover, the peculiar challenge and an overriding factor that must be accommodated in the analysis of the potential hazards and HSE risks, in the Arctic offshore drilling waste handling activities, is an extreme cold climate with a significant variations in temperature within a short period of time (Svensen and Taugbol, 2011; Paulsen et al., 2005; Guo et al., 2005) (Freitag and McFadden, 1997). The other predominant factor that have negative impact on drilling waste handling activities in the region is icing condition. Sea ice and atmospheric icing potentially lead to accretion of ice on the waste handling systems and structures (Battisti et al., 2006). The process of accretion of ice have significant impact on the performance of offshore waste handling system, the safety of personnel, and the overall economics of waste management operation (Gudmestad et al., 2007; Jacobsen and Gudmestad, 2012; Gudmestad and Strass, 1994). Typically, the hazards and risks associated with Arctic offshore operation will differ vastly depending on the ice conditions, very low temperatures, water depths, and proximity to existing support infrastructure of the specific area and region (Øien, 2013; Martin, 2012; Louis, 1983).

In addition, when deciding on the type of drilling waste handling technologies to use for work in cold Arctic environments, the operators need to conduct comprehensive occupational hazard assessments of the drilling waste streams. This is especially due to the negative impact of cold on human health and performance, as well as on work productivity, quality and safety (ISO 15743, 2008). The rigorous hazards assessment can be done by considering the HSE aspects, and by striking an appropriate balance between their potentially conflicting requirements (IPIECA and OGP, 2009).

Furthermore, the prevailing low temperatures magnifies the embrittlement of waste handling systems causing failures at loads that are routinely imposed without damage in warmer climate; and it also amplifies the system wear rates as a result of lubricants failure (Larsen and Markeset, 2007). In addition, the cold temperatures reduce the performance of components of the waste handling systems; especially the solids-control system – a system that separates drill solids from the drilling fluid, thereby allowing it to be recirculated down the drill pipe. Hence, to meet the drilling-performance demands and reduce the consequences from component failure, effective spare parts and logistic support is essential. However, spare parts logistics is affected in complex ways while operating in the Arctic, since the area is sparsely populated and has insufficient infrastructure. It is also greatly affected by the distinctive operational environment of the region. Therefore, in order to have an effective logistic plan, the effect of all influencing factors, called covariates, on the transportation of the spare parts need to be identified, modelled and quantified by the use of an appropriate dynamic model.

To addresses the above-mentioned issues, assessing and understanding of the peculiar Arctic risks can provide the knowledge and competence for measuring as well as managing the HSE risks related to drilling waste handling activities. Further, based on the above discussion, it is an important requirement to consider the impact of the operating environment, when identifying those cost-effective drilling waste handling practices with a low level of risk for oil and gas companies operating under Arctic conditions. In addition, a risk-based approach that models a complex time-dependent and uncertain variables have a key role to play in ensuring the safety standards and regulation associated with handling and transporting of the drilling wastes in the Arctic offshore (Hasle et al., 2009). The risk-based model ensures a better perceptive of the inherited hazards, mitigation measures, and inbuilt risks in the waste handling practices (Aven et al., 2006; Øien, 2013). Further, employing risk-based approaches encourage a deeper understanding of the unique Arctic risks related with waste handling system failures, than what would be possible under generic approaches.

For the purpose of this study, ‘‘the Arctic’’ is taken simply to mean the Norwegian Arctic and the starting point of our discussion is the Barents Sea.

1.1. Problem statement

When planning and performing drilling operations in harsh, cold climates and ice-infested waters such as Arctic offshore, it is essential to identify the main risk factors that may influence the operations and the chosen waste handling technology (Sadiq et al., 2004; Melton et al., 2004; Neff et al., 1987). Proper risk assessment will result in more advanced design, more efficient operations, and improved environmental protection (Northcott et al., 2005; Abdalla et al., 2008). Moreover, it can be used to identify weaknesses or strengths of existing or new waste handling systems in a structured way and hereby highlight factors of success and failure (Zurbrügg et al., 2014). It is also a core element in examining the overall quality of the drilling waste handling solutions before deploying the waste handling equipment and work force.

To examine the potential hazards associated with offshore drilling waste handling activities in the cold region, a number of safety and risk assessment models have been developed; see e.g. Veil (2002), Maunder et al. (1990), Boesch and Rabalais (2003), McKay et al. (1991), Schumacher et al. (1991), Cohrssen and Covello (1999), Risikko et al. (2003), Sadiq and Husain (2005), Lindøe et al. (2006), and Broni-Bediako and Amorin (2010) and Hoehn et al. (2000). In addition, to identify the occupational hazards and assess the level of risk associated with those hazards, during handling and managing of the drilling wastes in cold regions, several studies have been carried out; see e.g. Giedraitytė (2005), Holmér (1999), Risikko et al. (2003), Geller (2005), Robson et al. (2007), and Lindøe et al. (2006). Furthermore, the application of Bayesian Network (BN) to risk assessment and decision-making in the offshore operation, are getting popularity and have been discussed in several literatures; see e.g. Aven and Rettedal (1998), Røed et al. (2009), Pollino et al. (2007), and Lee and Lee (2006).

However, most of the available qualitative, quantitative and BN based risk and occupational hazard assessment models, suffers limitation as they fail to capture and model the time variant operating environment. Robust waste management practices, especially in the Arctic offshore, requires understanding of the unique risks due to icing, ice loading, remoteness, very low temperatures, wind-chill effects, and etc., in addition to the ‘‘conventional’’ or ‘‘tolerable’’ risks. Hence, in order to minimise and manage the potential hazards and risks, during handling of drilling wastes in Arctic regions, it is important to model the complex and time-dependent operating environment.

Moreover, cost factors will most often decide the acceptable level of system (including waste handling systems) performance with respect to capacity and availability (Kayrbekova et al., 2011). To identify cost-effective and efficient waste handling practices, for Arctic offshore drilling, it has been argued that two questions are fundamental (Sculpher and Claxton, 2005; Cantor, 1994; Barton et al., 2008). Firstly, which drilling waste handling practice is estimated to be cost-effective and environmentally sustainable, based on the prevailing evidence? Secondly, should further research be carried out in order to minimise the level of uncertainty related to the decision? To answer these questions and determine the cost-effectiveness of the waste handling practices, a number of studies have been carried out, see e.g. Gentil et al. (2010), Kazanowski (1966), Kazanowski (1968), Barton et al. (2008), Cellini and Kee (2010), Levin and McEwan (2001), Clift et al. (2000), Finnveden et al. (2007), Morrissey and Browne (2004), Popovich et al. (1973), Matthies et al. (2007), Curran (1996), Kiker et al. (2005) and Finnveden (2000).

However, in most of the available cost-effectiveness literatures, there is a lack of consideration of the impact of the operating environment on the cost profile. This is considered as a significant shortcoming, especially, in an industry with high level of investment, such as the Arctic offshore operations. For instance, the offshore industry in the region is experiencing longer lead times due to frozen drilling cuttings being stuck in skips while waiting to get emptied onshore for further treatment (Svensen and Taugbol, 2011). This means that the longer the lead-time, the higher the cost of the waste handling practice will become. Hence, it is essential to assess the cost-effectiveness of each waste handling alternatives by identifying those costs that will have the most significant implications on the strategic decision.

Furthermore, to assure effective logistic support and, consequently meet the drilling-performance demands, precise estimation of the spare parts transportation time and its associated probability plays a crucial role (Ghodrati et al., 2007; Ayele et al., 2013b). Hence, several models have been studied in the literature to estimate transportation time and analyse the dynamic behaviour of the transportation network; see e.g. Kaufman and Smith (1993), Lo and Szeto (2009), Wong et al. (2007), Pretolani (2000), Pfohl and Ester (1999), Haghani and Jung (2005), Lemp et al. (2010), Ran and Boyce (1994),Wong et al. (2005), Huiskonen (2001) and Späth (2000). The traditional models, however, lack the comprehensive integration of the effect of time-independent and time-dependent covariates on the spare parts transportation. Hence, it is essential to develop a dynamic model that is used for prediction of the spare parts transportation time by considering the time-independent and time-dependent covariates.

1.2. Research questions

Based on the above discussion, the main problem of the research study is to assess the HSE risks related to the operational performance and cost-effectiveness of drilling waste handling alternative, which includes identifying, and assessing risks throughout the logistical chain of handling of petroleum related waste. The following research questions are posed based on the research problem:

1. How to develop a methodology for the identification of suitable drilling waste handling systems that supports and facilitates the decision-making process, by considering the Arctic operating conditions?
2. What are the major risks related to the design, operation and management of various alternative waste handling systems in the Arctic?
3. How can the most cost-effective waste handling system with low level of risk be identified for oil and gas industry operated in the Arctic?
4. How to consider the dynamic operational conditions of the Arctic in spare parts transportation time estimation, in order to meet the drilling waste handling system performance?

1.3. Research purpose and objectives

The purpose of this research is to study, identify, and propose a methodology for Arctic offshore drilling waste handling operations by considering the complex and fast-changing nature of the Arctic operational conditions. Moreover, the study seeks to foster an integrated interdisciplinary understanding of technical and operational risks associated with drilling wastes and their management by implementing the risk-based analysis. More specifically, the sub-objectives of the research are:

- To propose a step-by-step methodology for the identification of suitable drilling waste handling systems for Arctic offshore drilling, which can offer the solution to filling the gaps that exist in the present system identification practices.
- To evaluate and assess HSE risks peculiar to the Arctic offshore drilling waste handling activities and develop a risk assessment model by considering the complex and time-dependent operating environment.
- To identify the most cost-effective available drilling waste handling system with low level of risk for oil and gas industries operated in the Arctic.
- To develop a dynamic model for spare parts transportation by considering the effect of the time-independent and time-dependent covariates on the spare parts transportation operation.

1.4. Scope and limitation of the research

The limitation of the findings are outlined below.

- In the Arctic offshore waste handling operations, especially in the Barents Sea, there is a lack of historical system failure rate data. Hence, judgements provided by those people with expertise in identifying potential hazards and risks of undesirable events are utilised at various stages of the risk analysis in order to perform effective risk identification and quantification. The estimated risk results presented in the case studies should be updated as new data/evidence becomes available, preferably in the form of field (hard) data reflecting the actual operational experience in this Arctic region and therefore gradually supplanting the opinions elicited from experts.

- A shortage of time to delivery and weather-related data in the Arctic environment was a challenge during the computation of the probabilities and spare parts deliverability. The estimated results presented in the case study may thus need to be tested through replication of findings in more case studies.

- In the case study analysis the basic assumptions are a year-round operational window and there is no winterisation or enclosure of the waste handling systems to protect the vulnerable areas.

2. Research Methodology

The purpose of this chapter is to provide a brief description of the research methodology, approaches, and methods for data collection and data analysis, which are used in this study in order to achieve the research objectives. Research has been defined in a number of different ways. A broad definition of research is given by Shuttleworth (2008) - "In the broadest sense of the word, the definition of research includes any gathering of data, information and facts for the advancement of knowledge". Creswell (2008) gives another definition of research – “Research is a process of steps used to collect and analyse information to increase our understanding of a topic or issue". In general research consists of three steps: Pose a question, collect data to answer the question, and present an answer to the question (Creswell, 2008). The research methodology is the link between thinking and evidence (Sumser, 2000). Research can broadly be classified into two: basic research and applied research. Basic research is carried out to understand the fundamental nature of a subject or topic which can generate a new idea or fundamental knowledge (Young and Schmid, 1966). Applied research conducts a study to address a specific concern or to offer solutions to a problem (Young and Schmid, 1966). Applied research usually means a quick, small-scale study that provides practical results that people can use in the short term (Neuman, 2003). The most and crucial step to do a research, is to choose a clear methodology. Further, research can be conceptualised as exhibiting one or more of the following four purposes: *i)* exploratory such as discovering, uncovering, and exploring; *ii)* descriptive such as summarising, gathering information, and mapping; *iii)* explanatory such as testing and understanding causal relations; *iv)* predictive such as predict what might happen in various scenarios.

This research study is a piece of applied research that is not only going to study and develop a methodology for identifying suitable and cost-effective drilling waste handling alternative with a low level of risk; but also, to develop a dynamic Bayesian network based risk assessment model and a dynamic model for spare parts transportation, taking into consideration the Arctic operational conditions. Hence, in order to fulfil the purpose of this research study, both explorative and explanatory methodologies are used. An explanatory research treats and maps the current state-of-the-art of drilling waste handling methods and identifies the gaps, which exist between the present waste handling practices and future needs. An exploratory research is intended to generate new knowledge and a model regarding the negative adverse effect of the operating environment of other Arctic conditions on drilling waste handling practices as well as on the transportation of the spare parts. The obtained results and knowledge can be used in both planning phases of well drilling program and operational phases of a drilling waste handling activities, such as drilling waste collection, processing, transporting as well as disposing.

2.1. Research approach

Research approach refers to the approach or the methodology that has been adopted to conduct the research (Creswell, 2008). It basically involves the selection of research questions, the conceptual framework that has to be adopted, the selection of appropriate research method such as primary research, secondary research, etc. (Creswell, 2008). Research approach can be one or a mix of the following three methods: inductive, deductive, and abductive. The aim of inductive approach is to establish descriptions of characteristics and patterns, and the approach starts by collecting data on characteristics and/or patterns, and finishes by relating these to the research questions (Blaikie, 2009). The aim of deductive approach is to test theories, to eliminate false ones and corroborate the survivor. It starts by constructing a theory and deduce hypotheses and ends by testing hypotheses by matching them with data explanation in that context (Blaikie, 2009). Abductive approach can be seen as a combination of deductive and inductive approach. In the abductive approach, research can be started with a deductive approach, and an empirical collection of data based on a theoretical framework can be made; this can then continue with the inductive approach in which theories based on the previously collected empirical data are developed (Neuman, 2003). To discover underlying mechanisms and to explain observed regularities are the main aims of reproductive approach. In general, abductive creates, deductive explains, and inductive verifies (Neuman, 2003).

In this research study both deductive and inductive research approaches are applied. The research started as a deductive approach with a literature review to gain a deeper understanding about the overall characteristics of drilling wastes, the available waste handling methods, operational and technological challenges of the Arctic, and sources and types of uncertainties. Results from the literature review shows that there is a lack of implementation of comprehensive as well as systematic waste handling system identification methodology, specifically intended for Arctic offshore drilling. Moreover, some of the available tools or methodologies are too cumbersome, time-consuming and generalised (Jonathan R. and Emma J., 2010; Sustainable and Ecological Management Working Group, 2014). Further, most of the literature did not consider the effects of the dynamic operating environment of the Arctic on the risk and cost profile as well as on the spare parts transportation. As a result, the conventional methodologies and models should be modified to consider the influence of the dynamic operating environment, when identifying suitable drilling waste handling systems for Arctic operation. Thereafter, some models have developed in order to analyse the impact of the dynamic operating environment, when identifying those cost-effective and environmentally friendly drilling waste handling system. The developed dynamic models were then applied in an inductive approach by studying the empirically obtained data. Afterwards, the validity of the model was studied, and conclusions were drawn based on the experience gained from empirical case studies.

Research approach can be also classified as quantitative, qualitative and/or mixed, see e.g. Given (2008), Sullivan (2001) and Creswell et al. (2004). Both qualitative and quantitative research methodologies have been applied in this research. Quantitative research deals with estimating the conditional and posterior probabilities of failure of the waste handling systems due to the predominant Arctic operating environment; predicting the environmental risks due to the release of untreated wastes; determining which cost variables affect the cost-effectiveness of the chosen drilling waste handling solution; and estimation of spare part transportation time as well as probabilistic estimation of spare part deliverability. Qualitative analysis covers a review of various alternatives of waste handling systems, guidelines, standards, regulations governing the process of waste management and handling, process of installation and operation in the Arctic region. As this research study tries to mix the best of qualitative and quantitative methods, and uses both deductive and inductive methods, it can be characterised as having an abductive-mixed research approach.

2.2. Research strategy

A research strategy is a procedure for achieving a particular intermediary research objective, such as sampling, data collection, or data analysis (Creswell, 2008). Thus, we can have sampling strategies or data analysis strategies. The use of multiple strategies to enhance construct validity (a form of methodological triangulation) is now routinely advocated by most methodologists (Creswell, 2008). In short, mixing or integrating research strategies (qualitative and/or quantitative) in any and all research undertaking is now considered a common feature of all good research (Brannen, 2005). The selection of a research strategy mostly depends on which kind of information the researcher is looking for (Yin, 2008), which is mostly based on the purpose of the study and the research questions. Yin (2008) describes five different research strategies to apply when collecting and analysing empirical evidence. These are archival analysis, history, experiment, survey, and case study. Archival analysis and history strategies refer to the past conditions of the case under study (Yin, 2008). The rest of the strategies (experiments, surveys and case studies) usually refer to the present situation (Yin, 2008). For instance, case studies emphasises detailed contextual analysis of a limited number of events or conditions and their relationships (Soy, 1997). Yin (1984) defines the case study research method as an empirical inquiry that investigates a contemporary phenomenon within its real-life context; when the boundaries between phenomenon and context are not clearly evident; and in which multiple sources of evidence are used. Case study research excels at bringing us to an understanding of a complex issue or object and can extend experience or add strength to what is already known through previous research (Soy, 1997).

The first, third and fourth research questions of this study includes ‘‘how’’, which is most likely to favour the use of case studies, experiment and history. Since the focus of this study are contemporary events and with reference to the different forms of research strategies as well as considering the objectives of the present research, the case study has been chosen as main research strategy. The second research questions of this study include ‘‘what’’. The questions are mainly of an explorative nature and are intended to develop relevant hypothesis and propositions for further investigation. To answer the research questions, waste handling activities in the Barents Sea, are selected as a case studies. The scientific logic and principles such as risk assessment, cost-effectiveness and reliability analysis and logistic support strategies have been used and their application in the real life waste handling activities have been evaluated. The case studies were supported by literature study, in order to gain knowledge about the research area.

2.3. Data collection

Within each one of the general research approaches, one or many data collection techniques may be used (Straub et al., 2004). Typically, a researcher will decide for one (or multiple) data collection techniques while considering its overall appropriateness to the research, along with other practical factors, such as: the expected quality of the collected data, estimated costs, predicted non-response rates, expected level of measurement errors, and length of the data collection period (Lyberg and Kasprzyk, 1991). It is of course possible that a given research question may not be satisfactorily studied because specific data collection techniques do not exist to collect the data needed to answer such a question (Kerlinger and Lee, 1986). The most popular data collection techniques include: surveys, secondary data sources or archival data, objective measures or tests, and interviews (Yin, 1984).

The data used in this study have been collected using different sources. Table 2-1 summarises the type of data collected and source of the data. The chemical consumption and waste generated data (Paper I and III) are based on the application for a permit report to drill appraisal and production wells by Statoil (2011) and by EniNorge (2012) as well as a permit report from the Norwegian Climate and Pollution Agency (2010). The cost-related data (Paper III) have been collected via meetings and discussions with drilling waste treatment plant operators; owners of waste containers, container trucks, and super-sucker trucks; and suppliers of offshore services. The minimum temperature (ºC) data (Paper II) were collected over a period of 10 years (from 2005 – 2014) on the monthly basis, from Norwegian Meteorological Institute database. Direct elicitation or expert judgment data (Paper II and III) were collected via interview of experts, which have expertise in risk analysis, reliability engineering, meteorology, cold-climate technology, and offshore engineering with 5 to 15 years of experience in their respective fields. Further, data on the time to delivery (Paper IV) for the summer and winter seasons was collected via interviews and meetings with the major shipping agents, suppliers, and manufacturers located in south-western and northern Norway.

Table 2-1. Data used in this research study

Paper No.	***Industry***	***Type of data***	***Covariates***	***Source of data***
Paper I	Oil &gas	- Total chemical consumption - Total amount of discharge of drilling waste		- Reports - Documentation - Archival records
Paper II	Oil &gas	- Expected subjective probabilities of risk of events - Operation costs per day - Cost for unit ton/kilo of drilling waste - Total amount of waste generated		- Expert judgement - Reports - Meetings and interviews
Paper II and III	Oil &gas	- The temperature data - Expected subjective probabilities of risk of events - Waste handling system failure rate data	- Temperature, - Snowstorm, Icing - Icicles	- Norwegian meteorological institute database - Expert judgement - Documentation - Archival records
Paper IV	Oil &gas	- Time to delivery (*TTD*)	- Blizzards - Fogginess - Atmospheric icing - Sea spray icing - Heavy rain	- Interviews and meetings - Norwegian Public Roads Administration route planner

2.4. Data analysis

Data analysis usually involves inspecting, transforming and modelling data with the goal of highlighting useful information, suggesting conclusions, and supporting decision making (Adèr, 2008). Data analysis can be divided into two groups, exploratory and confirmatory data analysis. Exploratory focuses on discovering new features in the data and confirmatory on confirming or falsifying existing hypotheses (Adèr, 2008). In this research, both techniques have been employed.

To analyse the mud formulation data and assess the impact of the discharge of the generated waste, an environmental impact assessment for the planned drilling and waste handling activity has been carried out (Paper I). To evaluate the cost-related data and assess the expected cost of the given waste handling alternatives and estimate the relative effect of the Arctic on the total cost, the ex-ante cost-effectiveness analysis has been applied (Paper III). Further, the cost-effectiveness ratios for each waste handling systems have been estimated. To describe the multiplication of the risk of events that occurs due to the operating environment of the Arctic region, risk ratios have been defined and estimated (Paper III). In addition, experts' judgements data provided by those people with expertise in identifying potential hazards and risks of undesirable events are utilised at various stages of the risk analysis in order to perform effective risk identification and quantification (Paper III).

Moreover, once the marginal subjective probabilities are elicited (Paper II), thereafter, a DBN learning and probabilistic inference are carried out by employing AgenaRisk (2015) – a commercial general-purpose (D)BN software tool. In addition, in order to capture the time dimension in our DBN model so that we can reason about how changes in the air temperature, snowstorm, icing, etc. each day affect the level of posterior environmental risk, the DBN fragments are arranged in the chronological order, as Time-slice 1, 2 ,…, *T*. Then, the link between the DBN fragments is introduced. Afterwards, the actual observed data from weather forecasting has been used to estimate the posterior reliability of the waste handling system and environmental risks (Paper II).

Furthermore, the analysis of time to delivery (*TTD*) data for spare parts transportation was carried out (Paper IV). In order to consider the effect of dynamic operational conditions on the spare parts deliverability function, the data have been categorised into two groups, i.e. for summer and winter season. In the next stage using some goodness of fit test, the best fit distribution of the data was found. Then the distribution parameter is calculated using available methods such as maximum likelihood (MLE) methods (Kumar et al., 2000). In this research study (i.e. Paper IV), Weibull ++7 distribution wizard is used as a tool to estimate the best fit distribution for the given time to delivery data (ReliaSoft, 2007). Then, by implementing the best-fit distribution for the given data using MLE, mean time to delivery (*MTTD*) are estimated. Afterwards, to estimate the probabilities of using transport mode *i*, being used from *N* available alternatives, the best-fit distribution results from Weibull ++7 distribution wizard have been used. Moreover, in order to obtain the spare parts transportation deliverability, the common distributions have been used distributions such as normal, lognormal or Weibull was nominated for the data, and the dynamic spare parts transportation block diagram (DSTBD) is employed to obtain the network deliverability.

2.5. Reliability and validity of research

The principles of validity and reliability are fundamental cornerstones of the research method (Shuttleworth, 2008). In general, reliability means dependability or consistency (Neuman, 2003). Reliability can be also defined as the extent to which a questionnaire, test, observation or any measurement procedure produces the same results on repeated trials (Miller, 2012). In short, it is the stability or consistency of scores over time or across raters' (Miller, 2012). With high reliability, it is possible for another researcher to achieve the same results on condition that the same methodology is used. In this study, the empirical data is used as case studies for risk and cost-effectiveness analysis, system reliability as well as logistic analysis. To meet the reliability requirement, the data collection, sorting and classification process are done as per established standard and methodology, described in literature. Furthermore, the source of data (reports) is available for recollection and reanalysis.

Validity is concerned with how well an idea about reality fits with the actual reality (Neuman, 2003). In general, there are two types of validity: internal and external validity. This research study possess internal validity since the findings of the study are relevant and logically connected to the existing theory. However, in order to generalise the results and findings to theoretical propositions, the proposed methodology, a dynamic models must be tested through replications of the findings in more case studies (Yin, 2003). Such case studies have not been possible to perform within the period of this research study.

3. Discussion of the results

This chapter discusses and presents the results of the research study (thesis). The areas of discussions focus on the stated research objectives.

3.1. Methodology for identifying suitable drilling waste handling systems

To propose measures and address and mitigate undesirable events, the factors that can affect the performance of the waste handling system need to be understood. Hence, the first objective of this research study is to analyse suitability of waste handling systems, by assessing the technological and operational challenges of the Arctic region. Paper I presents a methodology for the identification of suitable drilling waste handling systems for Arctic offshore drilling (Figure 2 in Paper I); and discusses the main technological and operating factors that need to be considered when preparing a drilling waste handling program, which is going to be deployed in the Arctic environment. The proposed methodology involves:

- Defining drilling waste handling goals and analysing influencing factors
- Assessing the applicability and suitability of offshore disposal techniques
- Assessing whether or not onshore disposal option is applicable and suitable
- Decision making and monitoring

The proposed methodology starts with defining the drilling waste management goals and criteria, by considering international and national standards, guidelines, regulations prevailing the process of waste handling and management. After defining the goals, subsequently, the main technological and operational influencing factors has been assessed and identified (Figure 1 and Table 3 in Paper I). The Arctic challenges (influencing factors) has been categorised as: *i*) environmental and climatic, *ii*) geographical, and *iii*) cost-related factors. Due to Arctic operational environmental and climatic factors such as large variations in temperature during a short period of time, sudden wind increase and large changes in wind direction, snow, and inadequate weather forecasting, it is expected that the uncertainty will be magnified and the risk associated with the drilling waste handling will be much higher than other operating environments, for instance, the North Sea (Det Norske Veritas, 2009). Further, cold temperatures reduce the performance of components of the drilling waste handling system, ranging from primary shale shaker and mud cleaner to screw conveyor.

With respect to the geographical influencing factors, transportation and logistics are going to present a challenge to achieving the drilling waste handling system performance objectives while we operate in the Arctic, since the area is sparsely populated and has insufficient infrastructure (Martin, 2004). Furthermore, the long-distance transporting of drilling cuttings to shore has an overall negative effect on the environment by increasing air pollution and solid waste generation (Ayele et al., 2013a). Not only does it increase energy consumption (for ships, cranes, trucks and earth-moving equipment at waste disposal sites) but the increase in marine traffic could also have an impact on subsistence hunting (Guo et al., 2005; IUCN, 1993; Heather et al., 2013). Furthermore, the cost of a drilling waste handling system operation and design in Arctic areas can be categorised into two main groups: *i*) internal cost factors – as a result of company decisions and goals. To a great extent these cost factors are managed by the company and, if necessary, can be changed. *ii*) external cost factors – not controlled by the company but will impact the overall cost and the decisions. The cost of winterisation, which reflects the winterisation enclosures and heating systems to protect waste handlind systems and prevent freezing, is the other cost-driven factor in Arctic drilling. The additional cost factor when planning and performing drilling operations in the Arctic region is environmental related taxes.

In step II, the advantages and disadvantages, and the potential impacts of the main offshore disposal methods, such as offshore discharge, offshore re-injection, friction-based thermal desorption, on the surrounding environment has been assessed (Table 2 in Paper I). For instance, according to the current practices, discharges of water-based mud into the Norwegian part of the Barents Sea are evaluated based on: *i*) the expected characteristics of chemicals to be used for the drilling activity, *ii*) the quantities of drilling waste to be discharged into the sea, and *iii*) how the discharge will take place (for example discharging the drilling waste from the rig directly to the sea/ocean).

When the evaluation to dispose offshore is finalised, the result will possibly suggest two choices: *i*) offshore disposal of the drilling waste can be the favoured option, or *ii*) offshore disposal might not be suitable, then hauling the drilling waste back to shore could be the next available option. Hence, in Step III, different types of onshore drilling waste handling systems, such as landfill, composting, bioremediation methods, etc. has been assessed, to check their suitability or applicability under the Arctic operating condition. Finally, in Step IV, after a detailed assessment and comparative analysis of available techniques, the operator should make a decision and request permission from the regulators. The regulator will assess the permit request and also study and map the specified area (the area in which the drilling and disposal activity will take place). Afterwards, the regulator will or will not allow the proposed drilling waste handling practice.

The application of the proposed methodology is demonstrated by a case study for drilling waste handling activity, for an oil field development project, in Barents Sea, northern Norway. The result from the case study illustrates that the proposed methodology have a potential to help the user to identify a suitable waste handling system for Arctic offshore operation, which assures the operational performance requirements with a low level of environmental impact.

3.2. Risk and occupational hazard assessment

The second objective of this research study is to evaluate and assess the HSE risks peculiar to the Arctic offshore drilling waste handling activities and develop a risk assessment model by considering the complex and time-dependent operating environment. In Paper II, a risk assessment model based on the dynamic Bayesian network (DBN) for Arctic offshore drilling waste handling practices is presented. DBN is chosen as the primary modelling structure because of its suitability to model complex time-dependent and uncertain variables. In addition, Bayesian belief networks are particularly useful in risk analysis as they do not require complete knowledge of the relation between causes and effects (Røed et al., 2009). The proposed DBN based risk analysis model consists of two parts: qualitative and quantitative. The main aim of the qualitative part is to investigate the interaction of the predominant Arctic risk influencing factors (RIF's) such as snowstorms, atmospheric and sea spray icing, negative air and sea temperature, etc. and their negative synergy effect on the drilling waste handling practices. Aven (2008) defines risk influencing factors (RIF's) as factors that potentially affect the barriers and barrier performance. On the other hand, the focus of the quantitative part is to estimate the posterior probabilities of the environmental risks and quantify the dynamically changing operating environment of the Arctic by employing time-series analysis.

In the qualitative analysis the specific steps that help to understand the Arctic operational challenges and construct a dynamic Bayesian structure for Arctic drilling waste handling practices has been outlined (Figure 2 of Paper II). The main steps in qualitative analysis are:

- *Evaluation of the peculiar Arctic risk influencing factors (RIF's):* here the purpose is to study and investigate the influence of the peculiar Arctic RIF's on the drilling waste handling practices.
- *Perform drilling waste handling system identification:* here the main disposal techniques and the key solids-control system needs to be investigated.
- *Evaluating the causal dependencies between the main variables:* At this stage, the interactions or causal dependencies between the main variables, i.e. the RIF's, the drilling waste handling practices and the environmental risks need to be understood and then the structure of the dynamic Bayesian network has to be decided.
- *Construct a DBN structure:* The final stage in the qualitative evaluation is to construct a DBN structure that captures the time-series nature, which comprises both discrete and continuous variables.

The quantitative part of the proposed DBN based risk model (see Figure 3 of Paper II), illustrates the specific steps that should be followed to estimate probability of the environmental-related risks. To model the time series or sequences of environmental data, in the first stage of the quantitative analysis, the dynamic operating environment of the Arctic needs to be transformed into a Markov chain. The aim of this transformation is to specify the time dependencies between the states and satisfy the first-order Markov property (Figure 9 and Equation 11 in Paper II). In the next stage, the state of each discrete node has to be defined. After specifying the states of discrete nodes, then the next step is to quantify the relationships between the connected nodes (variables). In this step, the marginal and conditional probability table needs to be assigned and defined. For each particular discrete node, all possible combinations of values of those parent nodes needs to be observed. Thereafter, the discretized conditional probability distributions of each continuous node have to be calculated. Typically, there are two approaches to handle the continuous variable: static and dynamic discretization. Both approaches try to specify the states of the continuous nodes.

Afterwards, a prior reliability or failure rate distribution function needs to be asserted for the defined solids-control system. This function describes the probability of n or fewer failures of waste handling systems, during a time interval of $(0, t)$, when all risk influencing factors are equal to zero or absent (i.e. ''normal'' operating environment), during waste handling practices. After defining the prior probability function and observing the RIFs data, then the likelihood function has to be constructed. The last two steps of quantitative analysis are learning in a DBN as well as probabilistic inference/ computing the posterior distribution. The posterior distribution of the system or component failure, considering discrete RIF's (variables), based on Glickman and van Dyk (2007) approach, can be expressed as:

The application of the proposed model is illustrated by using a holistic risk assessment case study, to assess the environmental risks due to the release of untreated drilling waste, because of failure of the shale shaker, which is one of the key solids-control system (Paper II). The inference result shows that the peculiar Arctic RIFs significantly reduces the posterior shale shaker reliability and consequently increases the environmental risk (Figure 10, 11 and 12 in Paper II). Moreover, the result from the temporal link or time-series analysis demonstrates that these negative impacts of the peculiar Arctic RIF's is more significant with time. Furthermore, the maximum environmental risk, i.e. the worst marine ecosystem damage can be anticipated during the month of January to March. That means during these months, the probability of waste handling system failure will be higher due to the high probability of icing formation and low and very low temperature conditions. These system failures consequently, lead to higher environmental risks.

The outlined steps in the proposed DBN based risk model (Figure 2 and 3 in Paper II) as well as static BN based risk model are proved valuable. They can assist the risk analyst to estimate the probabilities of the environmental risks due to the release of untreated drilling waste, because of the failure of the drilling waste handling system, such as solids-control system. Further, by employing the proposed BN and DBN based risk assessment (Paper II), the risk barriers and mitigation measures can be allocated based on the level of estimated risk.

Furthermore, the other sub-objective of this study is to propose a risk-based approach to manage exposures to occupational hazards during the handling of the drilling waste in the cold and harsh operational condition. In Paper V, a risk-based approach to manage the occupational hazards in the Arctic drilling waste handling practices suggested. The proposed approach can help the user to investigate the occupational hazards, by recognizing, predicting and interpreting information about the potential hazard/risk influencing factors which are caused by the operating environment of the Arctic region (Figure 2 in Paper V). The proposed risk-based approach consists the following stages:

- *Preparation of the occupational hazards (OH's) management plan* – The plan needs to explore the overall effect of the physical operating environment of the Arctic region on the performance of the workers, the drilling waste handling tasks and how they are performed as well as the type of equipment, materials and drilling substances used.
- *Evaluation of the main exposure routes* – This evaluation needs to include the understanding and identifying of the peculiar exposure routes such as ingestion, inhalation, skin contact and absorption for the range of possible drilling waste handling technologies/solutions to be deployed in cold and harsh Arctic environment.
- *Assessment of the potential occupational hazards (OH's)* – At this stage, it is crucial to identify and recognise all possible OH's related to the handling of drilling wastes in the cold Arctic region, using techniques such as checklist analysis, what-if analysis, and hazard and operability (HAZOP) analysis.
- *Evaluation of the hazard/risk influencing factors (IF's)* – The evaluation process comprises the assessment of technical IF's (such as design, material characteristic and technical condition), organisational IF's, and human-related IF's (such as competence, workload, and working environment).
- *Evaluation of the planned barriers* – in this stage the identification of the planned barriers such as technical, administrative, and organisational barriers, which controls or reduces the occupational hazards needs to be performed.
- *Approval of the OH's management plan* – After evaluating the planned barriers as well as the influencing factors, then, the occupational hazards management plan will be approved, when the results suggests that all required acceptance criteria are met. The decision utilises the evaluation, identification as well as analysis results in order to eliminate and manage the occupational hazards related with handling of drilling wastes in cold Arctic region.

Furthermore, the step-by-step risk reduction measures have been proposed, which can help to prevent, reduce and control the occupational hazards associated with the handling of drilling wastes in the cold Arctic environment (Figure 3 in Paper V). The proposed measures includes implementing the hazard/risk prevention or control measures at the source level (e.g. elimination of the hazard, substitution, and redesign), along the path (e.g. during processing and transporting of the drilling waste), and at the worker.

3.3. Risk-based cost-effectiveness analysis

The third objective of the study is to recommend the most cost- effective commercially available drilling waste handling system that ensures sustainability and fulfil HSE (health, safety, and environment) standards as well as meet the specific drilling project demand. In Paper III, a new risk-based cost-effectiveness analysis methodology is proposed (Figure 1 in Paper III), which considers the complex and fast-changing nature of the Arctic. The proposed methodology in Paper III seeks to identify the drilling waste handling practice that is expected to provide the highest level of benefit for a given level of cost, and which has a minimal impact on HSE. The proposed methodology uses risk assessment as a key component for the cost-effectiveness analysis, and it involves the following steps:

- *Risk analysis:* the aim of this step is to identify and quantify the impact of the peculiar Arctic risk influencing factors on the drilling waste handling practices. In order to quantify negative adverse effects of the peculiar Arctic RIFs, firstly, the probabilities and consequences of undesirable events have to be estimated. In Paper III, the classical definition of risk, i.e., risk as expected negative outcome (events), is used, to estimate the expected negative outcome of scenario.
- *Cost-effectiveness analysis (CEA)*: this step comprises, *i*) determining which cost variables affect the cost-effectiveness of the chosen drilling waste handling solution, *ii)* determining inherent risk factors for the chosen drilling waste handling practices and the company tolerance for them and *iii*) determining the functional interdependence between the cost and risk variables and the degree to which each of these variables can be controlled.
- *Estimation of risk ratio and cost-effectiveness ratio:* Risk ratio (RR) is used to express the measure of relative effect the operating environment of the Arctic region has compared to that of a reference operating region, for example the North Sea. For instance, a risk ratio of 2.5 for a specific drilling waste handling practice implies that the operating environment of the Arctic region increases the risk of events by $100 \times (RR - 1)\ \% = 150\ \%$. On the other hand, the cost-effectiveness ratio (CER) is a ratio in which the denominator is the unit of effectiveness and the numerator is the present value of the cost of a particular waste handling practice. Units of effectiveness are simply a measure of any quantifiable outcome central to the drilling waste management objectives. In drilling waste management, the total volume of drilling waste treated (disposed of) would be the most important outcome and would be an obvious unit of effectiveness.
- *Sensitivity analysis:* the purpose of sensitivity analysis is to identify the key cost variables and their potential impact in terms of changes in the annualised total cost and present value cost. Partial and extreme cases are the two common sensitivity analyses.

The application of the proposed risk-based CEA methodology is illustrated via the evaluation of the drilling waste management practices for an oil field development project, in Barents Sea, Northern Norway (Paper III). The case study emphasised on measuring the relative adverse effect of the Arctic operating environment compared to North Sea. The result illustrates that the cost of re-injection in a dedicated well is higher than that of the two other practices, in both regions (Table 8 in Paper III). Comparing the cost of offshore discharging practice with skip-and-ship, for both the North Sea and the Arctic region, the cost appears to be comparable when the volume of waste is low (Table 8 in Paper III). However, as the volume of the waste increases, the cost of skip-and-ship practice increases significantly. Further, the effect of the operating environment of the Arctic region, on the cost element, becomes more significant as the volume of the waste increases (Table 9 and Figure 5 & 6 in Paper III). The risk ratio (RR) result illustrates that the operating environment of the Arctic region increases the risk of events significantly, during the waste handling practices when compared to the North Sea (Table 11 in Paper III). The CER estimation demonstrates that offshore discharge practice is the cheapest practice for Arctic offshore drilling waste handling operations, in comparison to the other two practices, based on the considered assumptions (Table 10 in Paper III). Furthermore, the sensitivity analysis illustrated that the total cost per unit ton of drilling waste disposed is dependent on the key assumption, which in our case is drilling time per well (Table 12 in Paper III).

The result from the case study provides quantitative data to back up qualitative arguments. It shows that comparing different waste handling alternatives based on the cost elements alone can be misleading. That means selecting the cheapest available alternative, without considering the risk of events, can be significant, especially in the Arctic offshore operation. Hence, evaluation of the risk of events should always be integrated with CEA for better drilling waste management decisions. The proposed methdology is valued to be helpful to the analyst to find the most suitable alternative waste handling practice that is cost-effective with the minimum HSE footprint by considering the Arctic operating environment.

3.4. Spare parts transportation considering dynamic operating conditions

The fourth objective of this research study is to develop a dynamic model for spare part transportation, by considering the effect of the Arctic conditions. As discussed above, the reason behind estimating spare parts transportation time is to cope up with the drilling-performance demand and waste handling system availability. Hence, In Paper IV, a dynamic spare parts transportation model for Arctic production facility is presented. The problem considered in Paper IV is a dynamic spare parts transportation problem with time-dependent and time-independent operating environments. Suppose we have a finite number of mode-of-transportation options, each with a different transport time. The idea is to use the most suitable mode of transport and shortest transportation route. However, considering the dynamic effect of the Arctic operational condition on the time to deliver and cost of delivery, a decision maker will face a time-variant decision making process. In other words, the decision maker is faced with an optimisation problem, since the operating environments can be considered as covariates.

To optimise the spare parts availability and determine what mode of transport will be used, the proposed DSTBD (dynamic spare parts transportation block diagram) model, in Paper IV, constantly assesses the operating environment in the general framework of probability models. The proposed model attempts to capture the effect of the dynamic behaviour of the Arctic operating environment on the spare parts transportation. To do this, the model combines operating environment information with actual observed data from weather forecasting: *i)* to predict the probability of choosing one transport mode from available choices, *ii)* to estimate the mean time to delivery of the spare parts, and *iii)* to predict the probability of having the requested spare parts on-site within the planned delivery time. The approach continuously updates the prior probabilities and deliverability according to the most recent time-dependent covariates to provide posterior probabilities and deliverability.

In the proposed dynamic model, the probability of a decision maker *t* selecting a transport mode *i* from *N* number of available alternatives can be expressed as a multinomial logit (MNL). Then, the MNL model proposed by Ben-Akiva and Lerman (1985) can be extended as:

$$P_{it} = \frac{e^{(\beta_i X_{it} + \delta_i X_{it})}}{\sum_{j=1}^{N} e^{(\beta_j X_{jt} + \delta_j X_{jt})}} \tag{1}$$

where:

- P_{it} is the probability of the decision maker *t* choosing transport mode *i*
- x_{it} and X_{jt} are vectors describing the attributes of modes *i* and *j*.
- β, δ are column vectors consisting of the regression parameters associated with time-independent and time-dependent covariates, respectively.

After estimating the probability, P_{it}, the next step is to estimate the spare parts deliverability. Spare parts deliverability, for a given network and specific transport mode, is defined as (Ayele et al., 2013b): ‘‘a probability that the spare parts will be delivered, under a given condition, within a scheduled delivery (transporting) time’’. Typically, for each transport mode *i*, the spare parts deliverability can be quantified using a covariate model, such as the proportional hazard model (PHM) (Gao et al., 2010; Cox, 1972). In the proposed dynamic model, the spare parts deliverability for a given transport mode can be estimated as follows, by considering *R* time-independent and *M* time-dependent covariates:

$$D_i\,(t, z, z(t)) = 1 - \exp\left[-\int_0^t \left[A_{i0}(\tau)\exp\left[\sum_{r=0}^{R}\beta_{r,i}z_{r,i} + \sum_{m=0}^{M}\delta_{m,i}z_{m,i}(\tau)\right]\right]d_\tau\right] \tag{2}$$

where:

- $A_{i0}(t)$ is the baseline delivery-rate function, when the effects of all time-dependent and time-independent covariates are summed to zero (for detail, see Equation 7 and 8 in Paper IV).
- z and $z(t)$ are time-dependent and time-independent covariates, respectively.

The concept of the proposed dynamic mode is illustrated for transporting spare parts from the south-western part of Norway to an offshore oil field, in Barents Sea, northern Norway. The presumed transport modes are air-cargo, ship-cargo, truck-cargo and helicopter. The illustrative case study demonstrates that the operating environment of the Arctic has a significant effect on spare parts transportation, especially during the winter period (Table 3, 4 and 8, as well as Figure 6 in Paper IV). The proposed DSTBD approach is valuable to the user (such as spare parts planner, maintenance operator, warehouse manager), for investigating the appropriate path for spare parts transportation, based on user preferences and needs and by considering the time-dependent and time-independent covariates.

Moreover, by considering time-independent and time-dependent covariates, estimation of spare parts deliverability will reduce the extended downtime and stock-outs due to un-deliverability of spare parts within the scheduled delivery time.

3.5. Summary of appended papers

This research study includes five papers appended in full. The approaches followed, the results and the conclusions of the appended papers are summarised in this section. However, each paper makes its own contribution toward the research question and reports the finding of the case study. The relationship between the papers and the research questions is illustrated in Table 3-1. Three + (+++) represents the highest correlation between the research question and the appended paper, while blank is the lowest.

Table 3-1. The relations between the papers and the research questions

Paper	Research question 1	Research question 2	Research question 3	Research question 4
Paper I	+++	+	+	+
Paper II	++	+++	+	
Paper III	++	++	+++	
Paper IV	++	+	+	+++
Paper V	++	+++	+	

Paper I: As the demands to reduce the environmental impact of oil and gas operations increase in the Arctic region, the need to identify suitable waste handling systems becomes more essential. Further, prior to carrying out drilling activities, it is vital to identify the main challenges and other factors that may influence the performance of the chosen drilling waste handling technology. It is also important to analyse how these factors affect the system characteristics to be deployed in the Arctic environment where one has less experience and data. Hence, in Paper I, a methodology for identifying a suitable drilling waste handling system, by considering the distinctive operating conditions of the Arctic region is proposed.

The paper highlights the major technological and operational challenges related to drilling waste handling activities under the Arctic operational conditions. Further, the paper also focusses on evaluating the drilling waste streams, treatment technologies and the potential environmental impacts of the waste, etc. Moreover, the paper covers the current drilling waste handling practices in the Arctic, such as waste minimisation, recycle/ reuse, and offshore disposal as well as onshore disposal methods. Further, the paper shows the step-by-step procedure, via illustrative case study, for making a decision and choosing the appropriate drilling waste handling techniques for Arctic offshore drilling, which can be more sustainable and economically viable.

Paper II: The increased complexity of Arctic offshore drilling waste handling facilities coupled with stringent regulatory requirement such as zero ‘hazardous’ discharge is calling for rigorous risk assessment and management practices. Hence, Paper II seeks to determine the probabilities of the potential hazards, risks, and consequences of the undesirable events by considering the peculiar Arctic risk influencing factors such as snowstorms, atmospheric and sea spray icing, negative air and sea temperature, etc.

The paper proposed a risk assessment model based on the dynamic Bayesian network. The proposed risk model combines prior operating environment information with actual observed data from weather forecasting to predict the future potential hazards and/or risks. The model continuously updates the potential risks based on the current risk influencing factors information. Further, the paper focuses on integrating the principles of risk assessment approaches with time series or sequences analysis of the observed environmental data. The mathematical formulations, such as estimating the posterior probabilities of the drilling waste handling system failure and the environmental risks are given. Thereafter, a case study for an oil field, located in Barents Sea is presented. The result from the temporal link (time-series analysis) proves that the negative impacts of the peculiar Arctic RIF is more significant with time.

Paper III: The main purpose of Paper III is to propose a methodology for risk-based cost-effectiveness analysis of drilling waste handling practices, by considering Arctic operational condition. The proposed methodology uses risk assessment as a key component for the cost-effectiveness analysis. The paper focuses on determining the impact of the operating environment such as the ice conditions, negative sea and air temperature, etc. on cost and risk profile. The paper emphasises on measuring the relative effect of the Arctic operating environment to that of reference operating region, such as the North Sea, while posed the following questions: firstly, how can effectiveness techniques be implemented, to identify the most cost-effective commercially available drilling waste handling system for Arctic oil and gas industries? Secondly, how can the Arctic drilling waste management solutions be planned in order to ensure sustainability and meet or exceed HSE (health, safety, and environment) standards? Afterwards, the application of the proposed methodology is demonstrated by a case study of the drilling waste handling practices of an oil field in the Barents Sea, northern Norway.

Paper IV: Timely delivery of the required spare parts plays an important role in meeting the drilling-performance demand and reducing the downtime of waste handling facilities. Hence, the model that is used for prediction of the spare parts transportation time, which quantifies the effect of the dynamic operating environment of the Arctic on transportation time, is regarded as essential. However, the missing point in all of the spare parts logistic literature is to capture and model the time variant operating environment of the Arctic. Therefore, Paper IV introduced a dynamic model for spare parts transportation called Dynamic Spare Parts Transportation Block Diagram (DSTBD).

The first part of the paper describes and introduces the dynamic model, by categorising the operating environment of the Arctic region into two: time-dependent and time-independent covariates. Then, the effect of these covariates on the spare parts transportation have been modeled and characterised into two main sets: *i)* their cumulative effect on the route selection and consequently on the selection of transport mode, and *ii)* their effect on the total spare parts deliverability. In order to model the effect of the covariates on the transport mode utilization, P_{it} (probability of the decision maker t choosing transport mode i from N available alternatives) has been defined and expressed as multinomial logit (MNL) model. Afterwards, the extended proportional hazard model (PHM) has been applied to model the effect of the covariates on the spare parts deliverability. Thereafter, case study is employed to highlight some of the fundamental usage of the developed dynamic model and its application.

Paper V: The oil and gas exploration activities generate drilling-waste fluids (muds) and drilling-waste solids (cuttings). These wastes are contaminated with various chemicals, which are added throughout the drilling process and in some cases with the hydrocarbons from the formation. During the drilling waste collection, processing, transport and disposal activities the workers involved faces occupational health and safety hazards. In addition to the ‘expected’ occupational hazards, the harsh and cold operational environments have significant effect on the occupational performance of the workers, and these magnify the hazards associated with the waste handling practices. Thus, the quests for an effective occupational hazards assessment methodology for Arctic drilling waste handling practices are increased.

The focus of Paper V is to propose a risk-based approach for eliminating and managing occupational hazards, associated with the handling of drilling wastes in the cold and harsh operational condition. The suggested steps are aiming in identifying and understanding the peculiar Arctic occupational hazards, for the range of possible drilling waste handling technologies/solutions. In the second part of the paper, step-by-step risk reduction measures are recommended, by determining actions that are necessary to eliminate or reduce the occupational hazards identified as above acceptance criteria. Thereafter, it is concluded that by employing the proposed approach, an effective occupational hazard management plan – with suitable risk management and reduction measures can be selected and implemented.

4. Research contributions

This thesis contributes to a better understanding of the drilling waste handling activities in the hostile Arctic environment. In the research study, the state-of-the-art of current waste handling systems are mapped. The study specified the interaction of the predominant risk influencing factors, assesses the dependability of these factors on various variables, and evaluates their negative synergy effect on the drilling waste handling systems.

A methodology is recommended for the identification of suitable drilling waste handling systems for Arctic offshore drilling (Paper I). The proposed step-by-step methodology supports and facilitates the decision-making process, by identifying a suitable waste handling system for the region's offshore drilling activities, which assures the operational performance with a low level of environmental footprint. The application of the suggested methodology is demonstrated using a case study.

To consider and measure the complex and fast-changing nature of the Arctic during risk assessment, a dynamic Bayesian network based risk assessment model is presented (Paper II). The suggested model ensures a better perceptive of the potential hazards, mitigation measures, and inbuilt risks in the waste management practices. The proposed models are demonstrated via case study.

To support the drilling waste management strategic decision, a methodology is proposed for risk-based cost-effectiveness analysis of drilling waste handling practices, for Arctic offshore drilling operations, based on the expected risk and the cost element (Paper III). The available risk and cost-effectiveness ratio estimation methods are modified, to consider and measure the effect of the operating environment on the risk and cost profile. The application of the recommended methodology is illustrated using a case study.

The concept of a dynamic spare parts transportation model/block diagram (DSTBD) is introduced, for spare parts transportation under Arctic conditions by considering the time-independent and time-dependent covariates (Paper IV). The proposed DSTBD model investigates the influence of the covariates on possible transportation modes and routes. A case study is used to demonstrate the application of the proposed dynamic model.

In order to investigate the work place injuries associated with the handling of drilling wastes in the cold and harsh operational condition, a risk-based approach is proposed (Paper V). The proposed approach can support the user to investigate the occupational hazards, by recognizing, predicting and interpreting information about the potential hazard/risk influencing factors, which are caused by the operating environment of the Arctic region.

The research study presented in this thesis have a potential to assist waste handling managers, legislators, etc. in assessing the fulfilment of local statutory legislation and requirements as well as international standards, while developing and checking the drilling waste management plan that will result in more efficient (cost-effective) Arctic operations and improved environmental protection. In addition, it can allow the spare parts managers to effectively allocate their resources, based on the covariates.

5. Suggestions for further research

Based on the research presented in this thesis, the following points for future research are suggested:

- Since lack of historical reliability (failure rate) and time to delivery data in the Arctic and sub-Arctic environment was a challenge in this study, future studies should be carried out to improve the data collection and data sharing systems. This can provide a better understanding of the effect operational condition of the Arctic region on the waste handling systems.
- Bias and uncertainty distributions analysis should be considered as an important requirement during weighting of the expert judgement results. This will improve the validity of the data obtained by expert judgement.
- Assessment of how Artic environmental conditions are likely to alter the properties of the drilling fluids and solids, and the exposure routes.

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Part II – Appended Papers

Paper I

Ayele, Y. Z., Barabadi, A., Barabady, J. (2015). A methodology for identification of a suitable drilling waste handling system in the Arctic region.

International Journal of Environment and Waste Management. Accepted.

Author contributions: Yonas Zewdu Ayele have carried out the literature review, collected the data, and prepared the first draft of the manuscript. Thereafter, Abbas Barabadi provided a feedback and suggested ideas for improvement. Javad Barabady contributed by suggestions and comments on the manuscript.

Paper II

Ayele, Y. Z., Barabady, J., Droguett, E. L. (2015). Dynamic Bayesian network based risk assessment for Arctic offshore drilling waste handling practices.

Submitted to Journal of Offshore Mechanics and Arctic Engineering

Author contributions: Yonas Zewdu Ayele developed the basic idea and, analysed the application of Bayesian Network for Arctic drilling waste handling practices, by discussing with Enrique Lopez Droguett. Then, Yonas prepared the first draft of the manuscript. Thereafter, Enrique provided comments and suggested ideas for improvement. Javad Barabady contributed by suggestions and comments on the manuscript.

Paper III

Ayele, Y. Z., Barabadi, A., Droguett, E. L. (2015). Risk-based cost-effectiveness analysis of waste handling practices in the Arctic drilling operation.

Journal of Offshore Mechanics and Arctic Engineering. In Press. DOI:10.1115/1.4032707.

Author contributions: Yonas Zewdu Ayele developed the initial idea regarding risk-based cost-effectiveness analysis by discussing with Abbas Barabadi. Then, Yonas prepared the first draft of the manuscript. Thereafter, Enrique Lopez Droguett and Abbas provided comments and suggested ideas for improvement. Yonas and Abbas revised the manuscript. Afterwards, Enrique contributed by revising, and commenting on the manuscript.

Paper IV

Ayele, Y. Z., Barabadi, A., Barabady, J. (2015). Dynamic spare parts transportation model for Arctic production facility.

International Journal of System Assurance Engineering and Management. Vol. 7, Issue 1, pp. 84 – 98.

Author contributions: Yonas Zewdu Ayele developed the dynamic model, collected data, carried out the case study analysis. Then, Yonas prepared the first draft of the manuscript. Abbas Barabadi provided comments and suggested ideas for improvement of the proposed mathematical formulations. Thereafter, Yonas and Abbas revised the manuscript. Afterwards, Javad Barabady contributed by revising and commenting on the manuscript.

Paper V

Ayele, Y. Z., Barabadi, A., Barabady, J. (2014). A risk-based approach to manage the Occupational Hazards in the Arctic drilling waste handling practices.

CRC Press 2014. ISBN 9781138026810.s. pp. 1329 – 1334. DOI: 10.1201/b17399-183.

Author contributions: Yonas Zewdu Ayele proposed a step-by-step risk-based methodology for assessing and managing the occupational hazards and, prepared first draft of the manuscript. Abbas Barabadi provided comments and suggested ideas for improvement of the proposed methodology. Thereafter, Yonas revised the manuscript. Afterwards, Javad Barabady contributed by revising and commenting on the manuscript.