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Department of Engineering and Safety – Faculty of Science and Technology

RAM Analysis of Oil and Gas Production Facilities Operating in the Arctic Offshore

Expert Judgements and Operating Conditions

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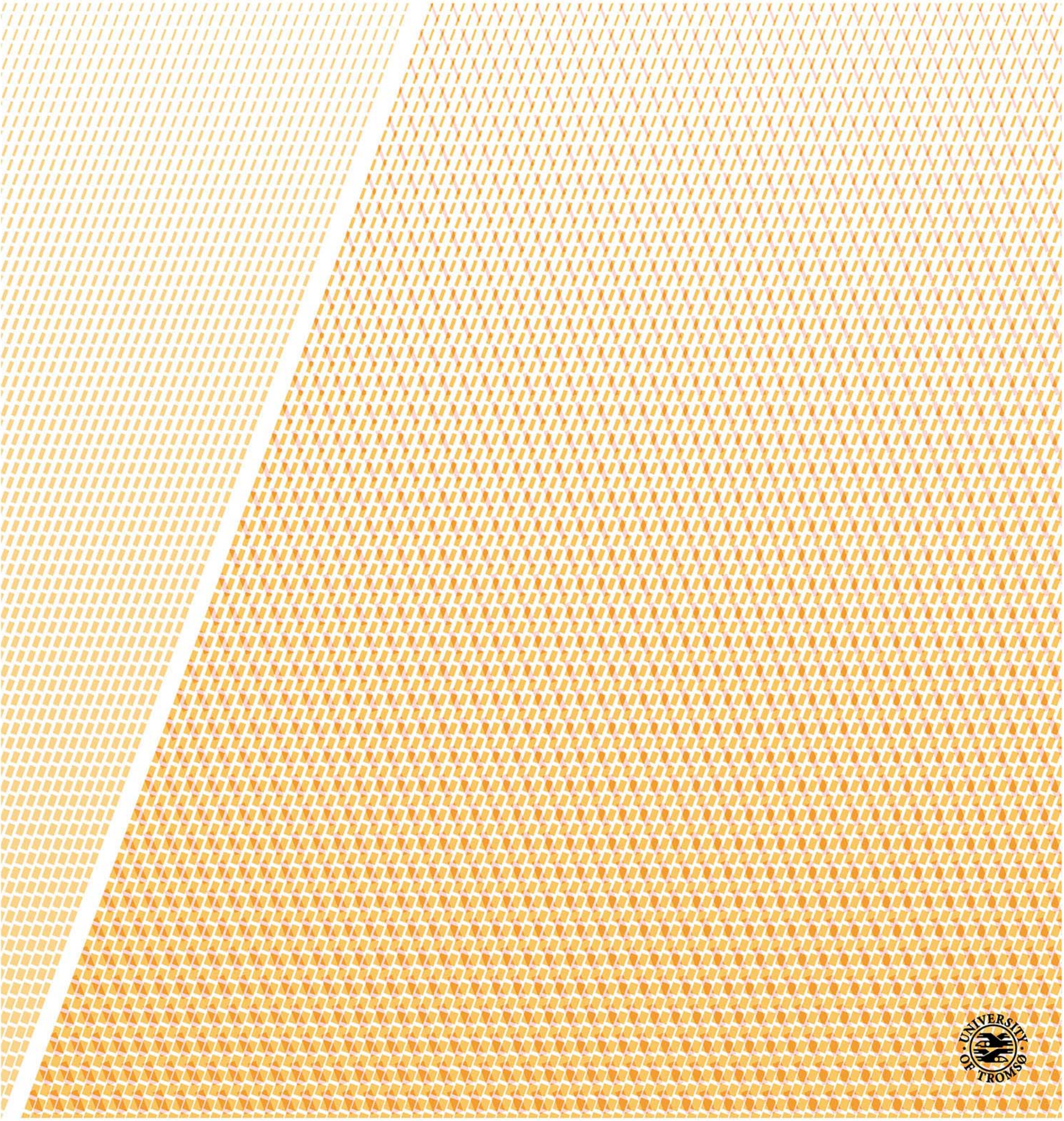
Masoud Naseri

A dissertation for the degree of Philosophiae Doctor – June 2016



RAM Analysis of Oil and Gas Production Facilities Operating in the Arctic Offshore

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By

Masoud Naseri

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy (PhD)

UiT The Arctic University of Norway
Faculty of Science and Technology
Department of Engineering and Safety

To my wife, ***Tannaz****, and my parents,* ***Saeideh*** *and* ***Abdollah***

Preface and acknowledgements

This thesis is the result of a four-year PhD programme with 25% of the time allocated for teaching. The PhD was carried out from August 2012 to June 2016 in the Department of Engineering and Safety at the Faculty of Natural Science and Technology, UiT The Arctic University of Norway. This work has been conducted in close collaboration with my main supervisor, Prof. Javad Barabady. A part of the work was carried out between February and July 2015 in the Department of Energy at the Polytechnic University of Milan, in collaboration with the research group in the Laboratory of Signal and Risk Analysis and under the supervision of Prof. Enrico Zio.

This PhD project has provided me with a unique opportunity of making contributions in the field of reliability, availability, and maintainability analysis and assessment of oil and gas platforms operating offshore under harsh Arctic environmental conditions. I hope the present work will provide useful inputs to the industrial decision-making processes in Arctic offshore oil and gas projects.

Although studying for a PhD is to some extent a personal and independent project, it cannot be carried out without the help and support of others. First and foremost, I would like to thank my main supervisor, Prof. Javad Barabady, for all his support, guidance, supervision, and encouragement during the course of this project. I would also like to thank my co-advisors, Prof. Uday Kumar and Prof. Alfred Hanssen, for sharing their knowledge and ideas and for providing me with their comments on different parts of my project.

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Summary

The Arctic offshore has a sensitive environment and is associated with a range of harsh operating conditions with considerable year-round variations. Such conditions can adversely affect the reliability, availability, and maintainability (RAM) of oil and gas (O&G) production facilities in different ways, including affecting equipment reliability performance, causing the performance of the maintenance and operation crew to deteriorate, imposing logistic delays, etc. One of the main challenges in RAM analysis of Arctic offshore O&G facilities is the lack of adequate historical data due to the comparatively limited experience of the O&G industry in Arctic regions. Moreover, adopting the historical data collected in normal-climate regions (e.g., the North Sea) may lead to wrong results and a great deal of uncertainty for Arctic offshore applications due to the fact that such data do not reflect the impact of harsh operating conditions.

The aim of this research is to identify and discuss the key elements of Arctic operating conditions and their effects on RAM performance of O&G production facilities and to develop expert-based models for RAM performance analysis of such facilities operating in the Arctic environment.

At the first step, a detailed literature review has been conducted to identify different elements of the Arctic offshore environment and their potential impact on RAM performance of O&G production facilities. Thereafter, expert-based models are developed to analyse the RAM performance of O&G production facilities under such effects. The issue of lack of adequate historical data is tackled integrating the data elicited from experts with the historical data obtained from O&G operations and activities in normal-climate regions. In real practice, however, Arctic operating conditions such as weather elements vary on a daily basis. In this regard, accelerated failure time models are adapted to build an availability model capable of reflecting upon such a time-dependency of environmental conditions. Moreover, uncertainties involved in weather conditions are analysed by the integration of time-series approaches in the developed plant availability model.

The results of this study illustrate that harsh Arctic operating conditions adversely affect the RAM performance of O&G production facilities, and thus their production levels. It is also shown that the expert-based techniques are useful and powerful tools for RAM modelling of Arctic offshore facilities.

Due to the effects of harsh Arctic conditions on equipment failure and repair rates, the results of the case studies show that the expected number of failures and expected downtimes in the Arctic offshore operations are higher than those of normal-climate areas. Accounting for year-round variability of operating conditions indicates cyclic changes in plant availability performance. The ultimate uncertainties involved with such results, which are of great concern, depend, among other factors, on the precision of expert data and uncertainties associated with operating conditions and their impact on plant performance.

Key words: reliability, availability, and maintainability; oil and gas; Arctic offshore; operating conditions; expert judgement; proportional hazard model; accelerated failure time model.

List of appended papers

Paper 1 **Naseri, M.** and Barabady, J., 2016. On RAM performance of petroleum exploration and exploitation and production facilities operating in the Barents Sea. *International Journal of System Assurance Engineering and Management*. Advance Online Publication. DOI: 10.1007/s13198-016-0463-x

Paper 2 **Naseri, M.** and Barabady, J., 2015. System-reliability analysis by use of Gaussian Fuzzy Fault Tree: application in Arctic oil and gas facilities. *SPE Oil and Gas Facilities*, 4(3), pp. 1-11. DOI: 10.2118/170826-PA

Paper 3 **Naseri, M.** and Barabady, J., 2015. Developing an expert-based model for reliability analysis of Arctic oil and gas processing facilities. *Journal of Offshore Mechanics and Arctic Engineering*. Accepted for publication.

Paper 4 **Naseri, M.** and Barabady, J., 2016. An expert-based approach to production performance analysis of oil and gas facilities considering time-independent Arctic operating conditions. *International Journal of System Assurance Engineering and Management*, 7(1), pp. 99-113. DOI: 10.1007/s13198-015-0380-4

Paper 5 **Naseri, M.**, Baraldi, P., Compare, M. and Zio, E., 2016. Availability assessment of oil and gas processing plants operating under dynamic Arctic weather conditions. *Reliability Engineering & System Safety*, 152(8), pp. 66-82. DOI: 10.1016/j.ress.2016.03.004

List of papers not included in the thesis

1. **Naseri, M.**, Barabadi, A., Barabady, J., 2014. Bioremediation treatment of hydrocarbon-contaminated Arctic soils: Influencing parameters. *International Journal of Environmental Science and Pollution Research*, 21(19), pp. 11250-65.
2. **Naseri, M.**, Barabadi, A., Barabady, J., Voskoboynikov, G., 2015. Application of biofilter plantation for oil spill cleanup in the Arctic coastal waters. In: L. Podofillini, B. Sudret, B. Stojadinovic, E. Zio, and W. Kröger (editors), *Safety and Reliability of Complex Engineered Systems - Proceedings of the European Safety and Reliability Conference (ESREL 2015).* CRC Press: Boca Raton, pp. 3541-3550.
3. **Naseri, M.**, and Barabady, J., 2015. Performance of oil skimmers in the Arctic offshore oil spills. In: T. Nowakowski, M. Młyńczak, A. Jodejko-Pietruczuk, and S. Werbińska-Wojciechowska (editors), *Safety and Reliability: Methodology and Applications - Proceedings of the European Safety and Reliability Conference (ESREL 2014)*, CRC Press: Boca Raton, pp. 607-614.
4. **Naseri, M.**, Yuan, F., Barabady, J., 2015. Performance-based aggregation of expert opinions in reliability prediction of Arctic offshore facilities. *Proceedings of IEEE International Conference on Industrial Engineering and Engineering Management (IEEM)*, 6-9 December, Singapore, pp. 1062-1066.
5. Bergan, H. H., **Naseri, M.**, 2015. Well control operation in the Arctic: A qualitative risk model. *Proceedings of International Conference on Port and Ocean Engineering under Arctic Conditions (POAC15)*, June 14-18, Trondheim.
6. Shouli Pour, F., **Naseri, M.**, Barabady, J., 2015. Drill cutting and waste injection assurance in the Barents Sea. *Proceedings of International Conference on Port and Ocean Engineering under Arctic Conditions (POAC15)*, June 14-18, Trondheim.
7. **Naseri**, M., Barabady, J., 2013. Offshore drilling activities in Barents Sea: Challenges and considerations. *Proceedings of the International Conference on Port and Ocean Engineering under Arctic Conditions (POAC13)*, June 9-13, Espoo.
8. Barabadi, A., **Naseri, M.**, Ratnayake, R.M.C., 2013. Design for the Arctic conditions: Safety and performance issues. *Proceedings of ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2013)*, June 9-14, Nantes.

Nomenclature and notations

AFT	Accelerated failure time
ALT	Accelerated life testing
AR	Auto-regressive
CDF	Cumulative distribution function
CM	Corrective maintenance
DM	Decision maker
MTTF	Mean time to failure
MTTR	Mean time to repair
NCS	Norwegian Continental Shelf
OREDA	Offshore reliability data
O&G	Oil and gas
PHM	Proportional hazard model
PM	Preventive maintenance
RAM	Reliability, availability, and maintainability
TDT	Total downtime
TTF	Time to failure
TTR	Time to repair
WDT	Waiting downtime
WIL	Weather intensity level

$F_{TDT}(t)$	Cumulative distribution function of total downtimes
$F_{TTR}(t)$	Cumulative distribution function of active repair times
$MTTR$	Mean time to repair
$N(0,1)$	Standard normal distribution
$R(t)$	Reliability function
t	Time
TDT	Total downtime
WDT	Waiting downtime
β	Weibull shape parameter
ϵ	Temporally independent standard normal random process
η	Weibull scale parameter
λ	Failure rate
μ	Repair rate

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Part 1: Summary of the thesis

1 Introduction

1.1 Background

The number of oil and gas (O&G) activities in Arctic regions has increased over recent years. According to the US Geological Survey assessments in 2008[1], Arctic resources hold about 13% of the undiscovered oil, 30% of the undiscovered natural gas, and 20% of the undiscovered natural gas liquids in the world. In total, such resources add up to about 22% of the undiscovered, technically recoverable, hydrocarbon resources in the world, 84% of which are located offshore. Figure 1 shows the special distribution of hydrocarbon resources over the Arctic (Budzik, 2009; USGS, 2008).

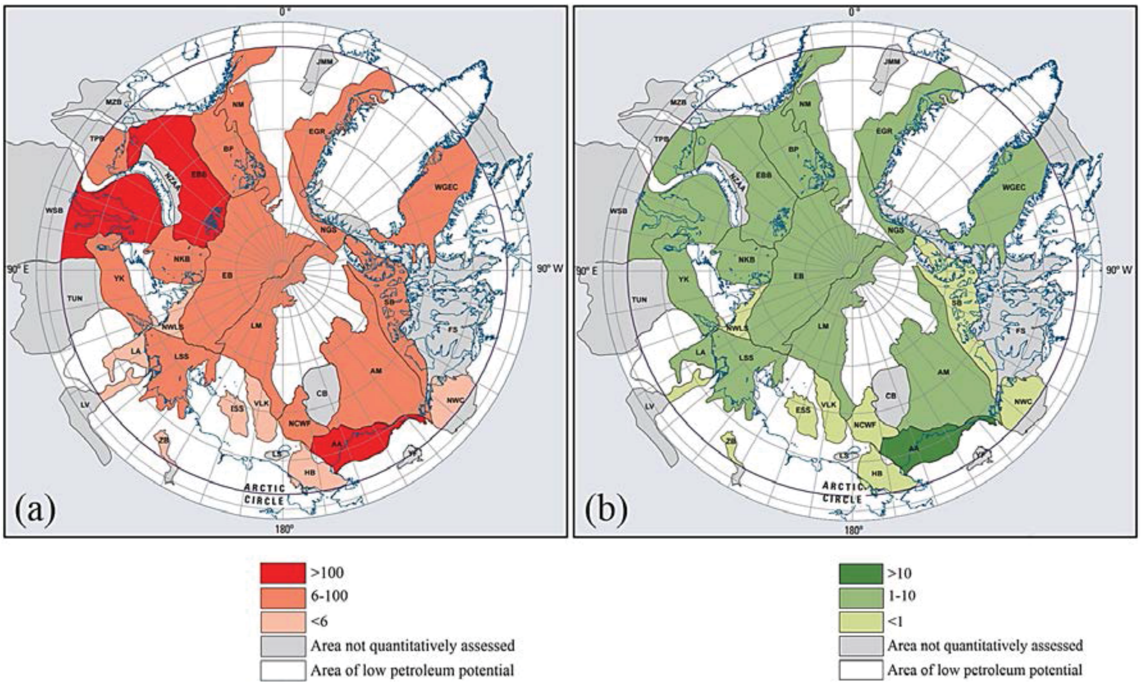

Figure 1. (a) Mean estimated undiscovered gas in trillion cubic feet, and (b) mean estimated undiscovered oil in oil fields in billion barrels (USGS, 2008)

In addition, the increasing trend of melting sea ice (Serreze and Barry, 2011), advances in offshore technology, and maturity of O&G resources in normal-climate regions, are among other driving factors for such a growing trend in O&G activities in the Arctic offshore (Hasle et al., 2009). For instance, as shown in Figure 2, oil production on the Norwegian Continental Shelf (NCS) peaked in 2000 and has since experienced a declining trend.

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[1] The estimation, which was made in 2008, may have changed over recent years.

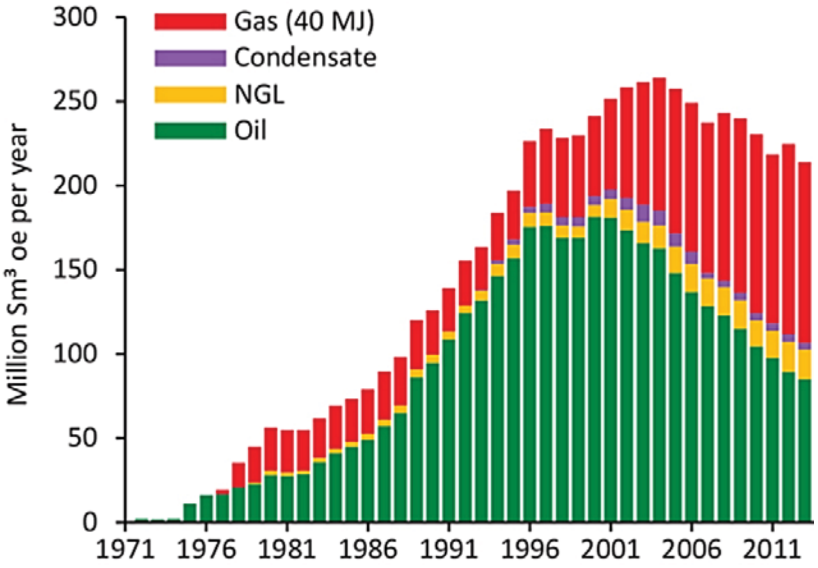

Figure 2. Production profile of different hydrocarbon resources on the NCS (NPD, 2014)

However, Arctic O&G project developments encounter limitations due to the fragility of the Arctic ecosystem. The Arctic marine ecosystem is vulnerable to hydrocarbon- and other chemical-related pollutions. Chronic effects of hydrocarbon pollutants can persist in Arctic marine environment for more than 20 years because of the low degradability of hydrocarbon compounds at low temperatures. Such a slow recovery rate of the Arctic ecosystem endangers marine biomass and the food chain and can cause chronic health effects for indigenous people (AMAP, 1998; Boehm et al., 2008; Hasle et al., 2009; Naseri et al., 2014; Paul Arthur Berkman and Vylegzhanin, 2011; Prince et al., 2002; WWF, 2007).

Moreover, developing Arctic O&G resources as commercially profitable ventures is challenging. The Arctic offshore is associated with harsh environmental conditions, such as low temperatures, snowstorms, icing events, and sea ice with considerable temporal and spatial variations (Aleksandrov et al., 2005; Barabadi and Markeset, 2011; Barabadi et al., 2013; Crowley, 1988; Gudmestad, 1999; Gudmestad and Karunakaran, 2012; ISO, 2010; Larsen and Markeset, 2007; Løset et al., 1999; Løset et al., 1997; Markeset et al., 2015; NORSOK, 2007; Przybylak, 2016). The development of technologies withstanding such harsh environmental conditions, as well as less-developed infrastructure, uncertain time-windows of operations, and remoteness from the world's manufacturing centres, are among the contributors to the elevated costs of Arctic O&G projects (Budzik, 2009; Krieger et al., 2003; Markeset et al., 2015). For instance, Alaska North Slope project development incurred a capital cost ranging from 1.5 to 2.0 times more than similar O&G projects carried out in Texas (Budzik, 2009).

Therefore, due to elevated costs and risks, it is important to formulate robust strategies and operating positions based on an accurate understanding of Arctic industry cost and risk drivers and trends. To this aim, O&G production facilities should have an acceptable level of performance to be economically viable (Markeset et al., 2015). Such a level can be determined in accordance with company goals as well as national and international standards and regulations. For an O&G facility, ISO 20815 defines production performance as the "capacity of a system to meet demand for deliveries or performance" (ISO, 2008). For example, a drilling platform should be able to continue drilling operations at a desired rate, 24 hours a day without interruptions; an offshore production facility should be able to produce O&G at a planned daily/monthly/yearly rate; planned maintenance activities should be implemented and accomplished within assigned time intervals; the risks associated with a specific activity or operation should be kept below a determined threshold, etc.

To operate in the demanding environment of the Arctic offshore, while achieving pre-established acceptable levels of performance, O&G companies and stakeholders need to establish and implement a set of production assurance programmes. The aim of such programmes is to ensure that the designed activities/operations/facilities have the capacity to meet the demands for delivery or performance at an optimum level in terms of the overall economy (ISO, 2008).

To ensure that such production assurance programmes are effectively in place, different performance measures can be used for a systematic evaluation and assessment of the production performance of a system. The results of such evaluations and assessments contribute to the alignment of design and operational decisions with corporate business aims and objectives (ISO, 2008). Item and system availability, production availability, and deliverability of an O&G production facility are examples of performance measures that can be used to analyse and assess the platform performance. The relationship between such measures that are used in production assurance programmes is illustrated in Figure 3.

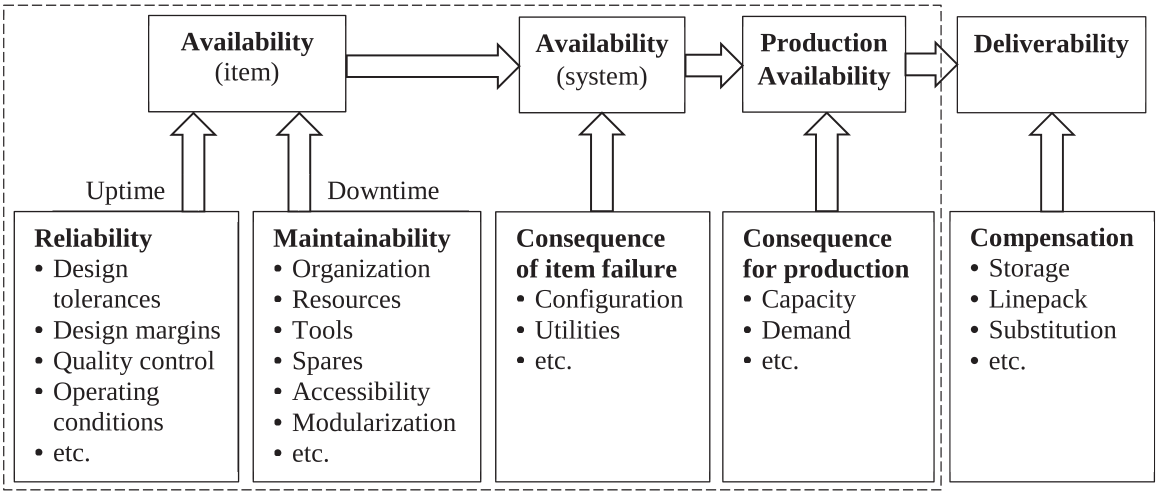

Figure 3. Illustration of the relationship between some production assurance terms (ISO, 2008)

Choice of design solutions and operations for an acceptable level of performance cannot be made without accounting for the requirements of the demanding and challenging Arctic environment (Gao et al., 2010; Gao and Markeset, 2007; ISO, 2010; Kumar et al., 2012; Markeset et al., 2015). In particular, the RAM of an O&G production facility operating in the Arctic offshore will be adversely affected by harsh Arctic environmental conditions in various ways. For instance, cold weather and harsh climatic conditions cause the performance of operation and maintenance crew to deteriorate (Bercha et al., 2003; Havenith et al., 1995; Larsen and Markeset, 2007; Noroozi et al., 2014), leading to a potential increase in human error rate and operation downtimes. Coupled with the remoteness of Arctic offshore platforms and the lack of developed infrastructure, harsh Arctic climatic conditions can impose logistic delays in transferring personnel and delivering the daily needs and spar parts of O&G platforms by means of helicopter and offshore supply vessels (Freitag and McFadden, 1997; Halvorsen-Weare et al., 2012; Larsen and Markeset, 2007; Pavlenko et al., 2014). As a consequence, this contributes to extended operation downtimes. The reliability of O&G platforms can be reduced due to the adverse impact of harsh climatic conditions on the performance of operation crew and equipment units (Barabadi, 2014; Barabadi et al., 2013; Bercha, 2004; Bercha et al., 2004; Dutta, 1988; Gao et al., 2010; Kayrbekova et al., 2011; Keane et al., 2013; Kumar et al., 2009; Markeset et al., 2015; Singh, 2013; Younan et al., 2007; Yun and Marsden, 2010). Moreover, coping with harsh Arctic climatic conditions and the adaption of new designs may lead to a more complex design through the integration of hardware, software, sensors, controls, information technology, etc. This, consequently, can create systems with more complex failure modes that are more difficult to diagnose and repair (Markeset et al., 2015).

Hence, it is crucial to analyse and assess the production performance of Arctic offshore O&G platforms in both the design and operation phases, while taking account of the impact of Arctic operating conditions. In this regard, such analyses and assessments can provide the stakeholders with essential information for design modification, cost-benefit ratio assessment, production rate assessment and prediction, optimisation of maintenance strategies, to name but a few, with potential lower levels of uncertainties (Barabady et al., 2010a; Barabady et al., 2010b; Calixto, 2013; ISO, 2008).

1.2 Problem definition

Analysis of the RAM of an O&G production facility requires historical data on the failure and repair of plant components. Such data may be collected in the field, extracted from maintenance reports, or extracted from databases and handbooks such as the process equipment reliability database (CCPS, 2016), Offshore Reliability Data handbook (OREDA) (OREDA Participants, 2009), the handbook for reliability prediction of mechanical equipment (Center, 2011), electrical equipment (Department of Defense, 1991; IEC, 2004), and safety instrumented systems (Håbrekke et al., 2013).

One of the main challenge in RAM analysis of Arctic offshore O&G production facilities is the lack of adequate historical data that effectively reflects upon the adverse impact of harsh Arctic operating conditions (Barabadi et al., 2015). That is mainly due to the limited experience of the O&G industry in Arctic regions. Besides, there is a lack of a suitable reliability handbook or database for Arctic offshore O&G production facilities.

Moreover, adopting the historical data collected in regions with normal operating conditions (e.g., the North Sea, Gulf of Mexico, etc.) may lead to a great deal of uncertainty or wrong results for Arctic offshore applications since,

- The Arctic offshore has harsh climatic and operating conditions that can negatively impact the performance of equipment units by accelerating failure rates (e.g., effects of low temperatures on material properties, lubricants, processing fluids, etc. (Caenn et al., 2011; Dutta, 1988; Singh, 2013; Stachowiak and Batchelor, 2006)).

- Some specific elements of Arctic offshore operating conditions are not experienced in normal-climate regions, and thus their contribution to the failure and repair rate of equipment units is not accounted for in available handbooks, databases, or maintenance reports such as OREDA. Examples of such elements include snow accumulation on failed components, contribution of harsh weather conditions to human error rate, ice accretion, snowstorms and polar low pressures, platform-sea-ice interactions.
- The harsh weather and meteorological conditions of the Arctic offshore can limit the availability of the window-of-weather for support activities such as spare parts deliveries, crew transfer, installation activities, etc. Such logistic delays are not usually experienced in normal-climate regions, and thus plant downtime distributions can differ from normal-climate regions to the Arctic offshore.
- Arctic environmental conditions are subjected to considerable year-round variations (Gudmestad, 1999; ISO, 2010; Løset et al., 1999) that are not reflected upon in available databases specific to normal-climate areas.

To account for the impact of operating conditions on equipment reliability, several studies have adopted the concept of proportional hazard models (PHMs) (Ansell and Philipps, 1997; Dale, 1985; Jardine et al., 1987; Kumar and Klefsjö, 1994; Kumar et al., 1992; Martorell et al., 1999). PHMs consider a baseline failure rate, describing the evolution of the degradation process under base conditions (e.g., normal operating conditions). They further employ a multiplicative function to the base failure rate, which accounts for the impact of different operating conditions (e.g., environmental conditions, loads, and stresses). Center (2011) has modelled the effects of operating conditions and component characteristics on component reliability by introducing multiplicative factors to the base failure rate. PHMs have been employed for reliability analysis (Barabadi et al., 2011b; Barabadi et al., 2014; Furuly et al., 2013; Gao et al., 2010; Gao and Markeset, 2007) and for reliability-based spare parts predictions (Artiba et al., 2005; Barabadi, 2012; Barabadi et al., 2014) of equipment units operating under harsh conditions. In addition, accelerated life testing (ALT) models have also been employed for component reliability analysis, where the impact of environmental conditions is quantified by introducing exponential multiplicative factors to component life times (Barabadi, 2014). Using similar approaches, PHMs have also been used to quantify the impact of different environmental factors on component maintainability (Barabadi et al., 2011a; Barabadi et al., 2011b; Gao et al., 2010; Kayrbekova et al., 2011; Simon et al., 2014).

However, such models rely on an extensive range of historical data and information on prevailing environmental conditions throughout the component life history. The lack of such detailed data and information is one of the major drawbacks of the aforementioned methods in practice. This is of special significance, for applications in new locations with severer environmental conditions (e.g., northern parts of the Barents Sea). Moreover, although such studies model component reliability and maintainability, they do not account for the accumulated damage imposed by varying operating conditions on component life.

In this regard, new approaches and models are required to tackle the lack of detailed historical data throughout the life of the components. Expert judgements can be used to cope with such a shortcoming by eliciting expert opinions on failure and repair rates. It may also be beneficial to not thoroughly disregard the data collected in normal-climate regions. In other words, expert judgements can be acquired on the impact of harsh operating conditions on reliability and maintainability characteristics of plant components, which will be further combined with the historical data collected in normal-climate areas.

1.3 Research questions

The main research problem is defined as how to analyse and assess the RAM of O&G production facilities operating in the Arctic offshore under the impact of harsh environmental conditions. The main research problem is narrowed down by formulating the following research questions:

1. What are the key elements of the Arctic offshore operating conditions and their potential impact on the RAM performance of O&G production facilities?
2. How can expert judgements be used for reliability analysis of O&G production facilities operating in the Arctic offshore?
3. How can the impact of time-dependent and time-independent Arctic offshore operating conditions be considered for RAM analysis of O&G production facilities?

1.4 Research aim and objectives

The aim of this research is to identify and discuss the key elements of Arctic operating conditions and their effects on RAM performance of O&G production facilities and to develop expert-based models for RAM performance analysis of such facilities operating in the Arctic environment. More specifically, following objectives are determined:

1. To review, identify, and discuss the elements of Arctic offshore operating conditions and their impact on the RAM performance of O&G production facilities.
2. To discuss the application of expert judgements and to develop expert-based models and methodologies for reliability analysis of Arctic offshore O&G production facilities.
3. To develop an expert-based model for RAM analysis of Arctic offshore O&G production facilities, considering the impact of time-independent and time-dependent elements of harsh operating conditions.

1.5 Research scope and limitations

The proposed models and methodologies in this research can be employed for facilities and activities designed for Arctic regions or in new locations with harsh operating conditions, without loss of generality. The scope of the study is, however, limited to the O&G production facilities operating in the Barents Sea. The internal and external boundaries for identifying the systems of interest in case studies are developed arbitrarily and can change depending on the available data, resources, budget, and the aim of the analyses.

The impact of operating conditions on the reliability and maintainability of the components is obtained by eliciting expert opinions, and thus their accuracy of quantified effects depends on the number of experts, the level of their expertise, as well as elicitation and aggregation approaches. In this research, experts were selected based on a criterion discussed in the appended papers. Time, budget, and accessibility to a wide range of experts and field engineers limited the choices for expert pool selection. Moreover, although expert data could have been collected through a formal Delphi method, such data were collected during only one round of elicitation due to lack of resources and time. However, the major contribution of this research study relies on the development of expert-based models and methodologies, which can be used for real-life applications.

A part of the developed RAM models relies on historical data collected in a normal-climate region or a base area. Selection of the base area is arbitrary, as long as the study experts have knowledge on its prevailing operating conditions. In this study, the North Sea is considered as a normal-climate region, and the Barents Sea is considered as an Arctic area, for the sake of the familiarity of study experts with these regions.

In this study, the overall impact of Arctic operating conditions is modelled, assuming that the failure modes and mechanisms are the same in both Arctic and normal-climate areas. For investigating the effects of dynamic operating conditions, this project solely considers the effects of air temperature and wind chill effects on the reliability and maintainability of plant equipment units, respectively. This assumption was discussed with the involved research group and a number of experts in the O&G industry.

Although current industrial practices include platform winterisation, this study focuses on platform RAM analysis before the implementation of winterisation measures as a set of preliminary analyses. However, the proposed models and methodologies can be used for a winterised platform if the detailed layout of processes, equipment units, and implemented winterisation measures is known.

2 Research methodology

2.1 Introduction

Engineering subjects, including RAM engineering, can be categorised as a branch of design science, whose goal is to design and create artefacts and to find solutions to given problems. Design science also aims to modify the existing solutions that can be used in real-life applications and problems or employed to provide better results (Dresch et al., 2015). From the viewpoint of design science, research work is carried out to propose a solution for a given scientific problem (Dresch et al., 2015).

In this regard, the present research study aims to provide solutions and modify existing ones to the problem of the RAM modelling of O&G production facilities operating in the Arctic offshore. Figure 4 shows different steps for conducting the present research study, which are suggested by Dresch et al. (2015) to produce scientific knowledge.

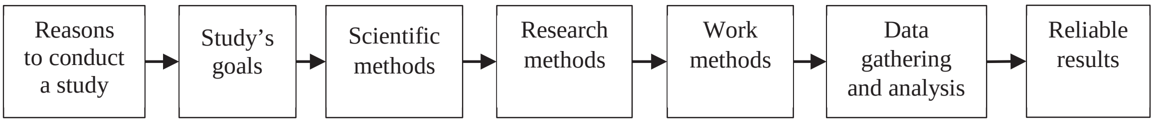

Figure 4. Methodology for conducting the present research work, adopted from (Dresch et al., 2015)

The reason for this research study is discussed in Sections 1.1 and 1.2. In the next step, some research questions were defined in accordance with the main project problem, as given in Section 1.3. To find solutions to research questions, the main goal of the research was defined and was further broken down into several objectives, which are presented in Section 1.4. Note that the work method consists of a sequence of logical steps that a researcher follows to reach the established research aim and objectives. In this report, work methods have not been discussed in a separate section. However, in each step, activities and applied techniques, coupled with due justifications, are described. The work method ensures the replicability of the study and its results and thus helps the validity of research results to be recognized by the scientific community (Dresch et al., 2015).

2.2 Scientific method

Scientific method refers to "a body of techniques for investigating phenomena, acquiring new knowledge, or correcting and integrating previous knowledge" (Seel, 2012) and can be divided into three inferences: induction, deduction, and abduction (Dresch et al., 2015; Flach and Kakas, 2000; Saunders et al., 2012). The inductive scientific method is founded on premises and is developed based on processing an idea from previously investigated or observed data. In inductive inference, statements are made based on a large amount of observed data to generate knowledge and find the rules covering such observations (Flach and Kakas, 2000;

Saunders et al., 2012). Deductive inference may be defined as the process of inferring conclusions from known premises based on formal logic rules. In the deductive scientific method, while the premises are true, what is inferred from the premises is necessarily true, and thus there is no need to validate the results by experiments (Dresch et al., 2015; Seel, 2012). Abductive reasoning is applied to find the best explanations for observed facts (Flach and Kakas, 2000; Seel, 2012).

The selected scientific method, especially for the early stages of this research study, can be considered an inductive one. Observations of previous collected and processed reliability data indicated the negative impact of harsh operating conditions on component performance (Barabadi, 2012; Barabadi, 2014; Furuly et al., 2013). Moreover, different studies report the adverse impact of low temperatures on fluid rheological properties (Sasanuma and Matsubara, 1995; Stachowiak and Batchelor, 2006) and metal and polymer mechanical properties (Dutta, 1988; Freitag and McFadden, 1997; Rudin and Choi, 2013; Singh, 2013). Studies have been carried out on pipe corrosions in low temperature conditions (Jamaluddin et al., 1991), and the negative effects of cold weather conditions on human behaviour and reasoning capabilities have been analysed and discussed (Barabadi et al., 2011a; Freitag and McFadden, 1997; Kayrbekova et al., 2011; Markeset et al., 2015). Several discussions with experts in maintenance engineering also suggested that cold weather could cause the performance of the maintenance crew to deteriorate.

Such observations and preliminary findings in different case studies, performed by other researchers, built the conjectures of this research study: the RAM performance of O&G production facilities operating in the Arctic offshore is adversely affected by the harsh environmental conditions. Such a proposition can contribute to finding solutions to a practical problem and to supporting new models and methodologies. However, the aforementioned hypothesis was not tested by experimental results. Instead, the rest of the research was performed based on a deductive inference. In this regard, in the present research, conceptual models are built and methodologies are developed and proposed based on theoretical knowledge and in a logical manner. Such models and methodologies, which are inferred from premises, are considered true, while the premises are true (Dresch et al., 2015; Seel, 2012).

2.3 Research method

Establishing a research method helps the research work to be recognised by the scientific community and serves as evidence that the conducted work can be reliable for the field of study. The most common research methods in design science include survey, action research, case study, and modelling (Dresch et al., 2015), of which the case study and modelling have been used in this research study. A case study research is defined as “a research strategy that involves the empirical investigation of a particular contemporary phenomenon within its real-life context, using multiple sources of evidence” (Saunders et al., 2012). A case study research may be conducted when the research questions address either descriptive (i.e., questions with “what”) or explanatory questions (i.e., questions with “how” or “why”), where a particular situation requires a clearer understanding and elaboration (Dresch et al., 2015; Yin, 2006; Yin, 2009). Modelling is defined as a process that allow researchers to represent conceptual systems symbolically for building, explaining, or predicting real phenomena within such systems

(Dresch et al., 2015; Seel, 2012). In this regard, mathematical models primarily express structural aspects of conceptual systems that are described using quantitative and/or qualitative data (Seel, 2012).

In this PhD project, the first research question was investigated through a qualitative research approach, where a case study strategy is employed for an in-depth understanding and elaboration of Arctic operating conditions and their impact on plant RAM performance. For the remaining research questions, modelling has been the main strategy for conducting the research work. The case study strategy was further employed to illustrate how the developed models can be applied to real-life situations. To this aim, statistical models for reliability and maintainability analysis at a component level serve as the foundation of the developed models in this study. Such models were further integrated with expert judgements to develop expert-based failure and repair rate models. Uncertainties involved with expert opinions were modelled using probability distributions and fuzzy sets. Reliability block diagrams and fault tree models are used for system reliability analysis and identifying system minimal cut sets. Production rate analysis and predictions, as well as system availability analysis, were further performed using Monte Carlo simulation techniques applied to developed system models. Weather conditions and their dynamicity are modelled using auto-regressive (AR) time-series models.

2.4 Data gathering and analysis

Various types of data and information are collected and analysed, using techniques selected according to the goals of the study and the employed research methods. Although the choice of data collection techniques may be limited by the type of required data and further analysis techniques (Dresch et al., 2015), the employed techniques are recognised by the scientific community. Some of these data are used in the early stages of the research to establish the research objective and to design research questions, while some others are used for modelling and illustrating case studies.

Documentary and bibliographic techniques were used to collect data and information gathered and analysed by other scholars about the subjects of interest (Dresch et al., 2015; Saunders et al., 2012). By employing such data collection techniques, data and information on Arctic climatic conditions, Arctic offshore O&G technologies, cold-climate technologies, and current and previous O&G operations in the Arctic were gathered. Such data were collected from reports, standards, manuals, books, journal papers, conference proceedings, the online weather database of the Norwegian Meteorological Institute, online Norwegian O&G fields' database of the Norwegian Petroleum Directorate, the Arctic Monitoring and Assessment Programme, and US Geological Survey fact sheets, to name but a few.

In this research study, informal interviews and personal communications (Dresch et al., 2015; Saunders et al., 2012) were also conducted with other scholars, researchers, and engineers. Those data and information included discussions about the problems of interest, possible approaches, technological solutions, potential technological challenges, personal experiences in the operation and maintenance of O&G production facilities, potential impact of harsh environmental conditions, as well as underlying assumptions in available models, frameworks, and technological solutions. Such data and information are collected mostly in conferences and workshops on cold-climate technology, risk and safety, and O&G engineering, including the Arctic Technology Conference, Ocean Offshore & Arctic Engineering (OMAE), Port and Ocean Engineering under Arctic Conditions (POAC), European Safety and Reliability (ESREL), and Society of Petroleum Engineers Annual Technical Conference and Exhibition (ATCE). This information and these data helped the author to investigate topics of interest from different viewpoints, to acquire knowledge on possible gaps for the further development of new solutions or to modify available ones.

The questionnaire, which consists of the application of a series of questions to respondents, is another data-gathering technique (Dresch et al., 2015; Saunders et al., 2012), which was used in the expert judgement elicitation step.

More specifically, four main types of data are collected and analysed in this research study:

- Data on the reliability of system components,
- Data on the maintainability of system components,
- Data on Arctic operating conditions, and
- Data on the impact of Arctic environmental conditions.

Reliability data collection and analysis:

Reliability modelling of O&G plant components under normal operating conditions (i.e., in the base area) relies on analysing times to failure (TTFs) of the components. In Paper 2, TTF data are assumed to be exponentially distributed, based on which, the constant failure rate of system components was extracted from the OREDA handbook (OREDA Participants, 2009). Once the failure rate of a component, denoted by λ, is known, component reliability can be modelled as given by (Rausand and Høyland, 2004; Stapelberg, 2009):

$$R(t) = \exp(-\lambda t) \tag{1}$$

However, some O&G plant components may show time-dependent failure rates, and thus employing an exponential distribution may lead to an over-simplified model with a great deal of uncertainty. To tackle this issue, in Papers 3-5, component reliability is modelled using a Weibull distribution, which is a commonly used distribution for mechanical systems, being capable of modelling different types of failure rates including increasing, constant, and decreasing (Murthy et al., 2004; Rausand and Høyland, 2004; Stapelberg, 2009). Due to the lack of TTF data, Weibull distribution parameters are estimated using maximum likelihood estimation technique applied to 20-30 items of simulated TTF data, whose mean (i.e., mean time to failure (MTTF)) is not dissimilar to the one given in the OREDA handbook (OREDA Participants, 2009). Once the shape parameter, β, and scale parameter, η, of the Weibull failure distribution of a component are estimated, its reliability can be given by (Rausand and Høyland, 2004; Stapelberg, 2009):

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \tag{2}$$

Maintaimnability data collection and analysis:

In Papers 4 and 5, where plant availability and production rate are analysed, component maintainability under normal operating conditions is a key input for model development. For this purpose, an exponential distribution is used, whose underlying assumption is that the active repair rate of the component, denoted by μ, remains constant under a set of fixed environmental conditions. Mean time to repair (MTTR) of plant components is extracted from the OREDA handbook (OREDA Participants, 2009). Given $\mu = 1/MTTR$ for an exponential repair distribution, the cumulative distribution function (CDF) of active repair times, $F_{TTR}(t)$, for a component under normal operating conditions can be modelled as (Rausand and Høyland, 2004; Stapelberg, 2009):

$$F_{TTR}(t) = 1 - \exp(-\mu t) \tag{3}$$

However, expected repair times given in the OREDA handbook are those for active repair times and thus, do not account for any waiting downtimes before/after performing the repair tasks. To this aim, it is assumed that waiting downtimes (WDTs), are log-normally distributed (Rausand and Høyland, 2004), with m and σ being the mean and standard deviation of natural logarithms of WDTs. WDT distribution parameters are determined by processing the information obtained through personal communications with a number of field engineers. Finally, the total downtime (TDT) of a component is obtained by:

$$TDT = WDT + TTR \tag{4}$$

where TTR is active repair time distributed exponentially, WDT is waiting downtime distributed log-normally, and TDT is total downtime, whose empirical CDF, $F_{TDT}(t)$, is obtained by applying Monte Carlo simulation techniques.

Data on Arctic environmental conditions:

Various types of qualitative and quantitative data and information on the Arctic offshore environment and parameters of prevailing operating conditions are used sporadically during the course of this research. Such data are extracted from different sources including standards (e.g., Norwegian Standard NORSOK-N003 (NORSOK, 2007), ISO-19906 (ISO, 2010)) databases (e.g., the online climate database of the Norwegian Meteorological Institute), as well as reports, books, journal papers and conference proceedings.

In Paper 5, where the results of the thesis in accordance with the third objective are presented, the developed system availability model relies on long-term prediction of certain elements of Arctic weather conditions. To develop such a model, historical daily temperature and wind speed data for two specific locations in the North Sea (i.e., base area) and the Barents Sea (i.e., an Arctic location) are extracted from the online climate database of the Norwegian Metrological Institute, available at http://eklima.met.no.

To predict the long-term daily air temperatures and wind speeds, the employed model should be able to capture the stochasticity of such data in the long term. For this purpose, a seasonal auto-regressive (AR) time-series model is adopted as a common model for forecasting long-term daily air temperatures and wind speeds. AR time-series models describe daily temperatures and wind speeds using deterministic and stochastic terms, generating the mean and residual processes, respectively. The deterministic term includes the seasonality term (i.e., linear and cyclic trends) as well as the AR process, whereas the stochastic term consists of a zero-mean and temporally independent standard normal random process denoted by $\epsilon \sim N(0,1)$ and a seasonally time-dependent standard deviation function denoted by $\sigma(t)$. The approach adopted in this research study is described in detail by Alexandridis and Zapranis (2013), Benth and Benth (2010), Benth et al. (2007), Caporin and Preś (2012), and Benth and Benth (2012). A step-by-step approach, specific to the long-term modelling and prediction of daily air temperatures and wind speeds, is presented in Paper 5. Once model parameters are estimated by fitting historical daily air temperatures and wind speeds to AR time-series models, a Monte Carlo simulation technique is used to predict long-term weather data while accounting for the associated uncertainties. An example of long-term air temperature data is illustrated in Figure 5.

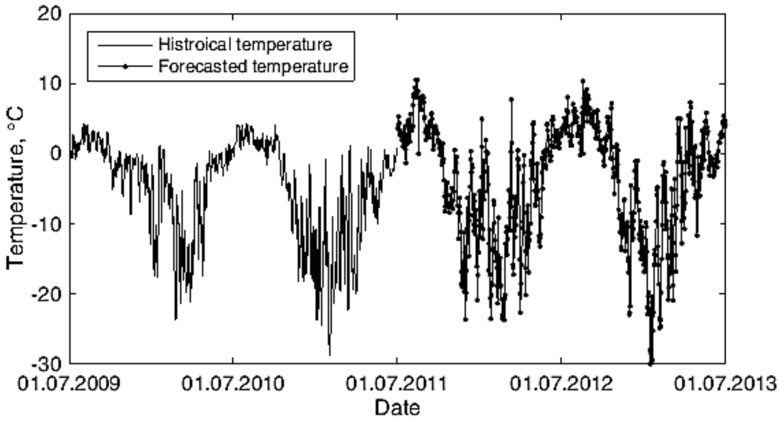

Figure 5. Snapshot of Hopen Island temperature from 01.07.2009 to 30.06.2011 and forecasted temperature data from 01.07.2011 to 30.06.2013

Data on the impact of Arctic environmental conditions:

In this research study, expert opinions were used to quantify the impact of Arctic operating conditions on the performance of equipment units and maintenance crew. Expert opinions were further integrated with reliability and maintainability models in analogy with PHMs and accelerated failure time (AFT) models. To elicit expert opinions, a questionnaire, which consists of a series of questions to respondents (Saunders et al., 2012), was used as the mode of communication with experts (Meyer and Booker, 1991). Among various forms of response modes, such as single probability values, set of probability values, probability distribution, quantiles of a distribution, parameters of a distribution, etc. (Bedford and Cooke, 2001; Cooke, 1991; Kuselman et al., 2014; Meyer and Booker, 1991), experts were asked to present the 5th, 50th, and 95th percentiles of their opinions. Expert data could have been collected through a formal Delphi method to help experts achieve better forecasts than that which they might obtain at the first round of elicitation (Cooke, 1991; Meijering et al., 2013; Meyer and Booker, 1991; Rowe and Wright, 2001). However, due to lack of resources and time, only one round of elicitation was performed.

For the illustrated case studies, seven experts with a working experience ranging from 3 to 40 years were chosen from Norwegian academic and O&G sectors. All experts have acceptable levels of knowledge on operating conditions of both the North Sea (i.e., normal-climate region), and the Barents Sea (i.e., an Arctic offshore location). In addition, selected experts have expertise in various fields including maintenance and reliability engineering, cold climate engineering, mechanical engineering, and process engineering. Such diversity in experts' background helps the analyst to consider the problem from different standpoints and thus avoid the excessive influence of an individual (Mannan, 2012; Meyer and Booker, 1991; Rowe and Wright, 2001).

The overall opinion of the decision maker (DM) is further formed by aggregating expert opinions. This research study adopts the weighted linear averaging, which is a commonly used aggregation technique (Clemen and Winkler, 1999; Genest and McConwa, 1990; Genest and Zidek, 1986) with different methods for computing experts' weighting factors, discussed widely in the literature (see e.g., (Bedford and Cooke, 2001; Clemen and Winkler, 1999; Cooke et al., 1988; Cooke, 1991; Cooke and Goossens 2000; Cooke and Goossens, 2008; Genest and McConwa, 1990; Genest and Zidek, 1986)). Bayesian aggregation of expert opinions is another technique to form the DM's opinion using Bayes' theorem (Clemen and Winkler, 2007; Morris, 1977; Mosleh and Apostolakis, 1986; Podofillini and Dang, 2013; Rosqvist, 2000; Rufo et al., 2012; Winkler, 1981). In this research study, the model developed by Winkler (1981) is adopted for Bayesian aggregation of expert opinions; its underlying assumption is that experts' distributions are normal.

Monte Carlo simulation technique is employed to account for the uncertainties associated with expert opinions (Zio, 2013). Alternatively, fuzzy set theory, coupled with the extension principle, is used in Paper 2, where expert data are elicited in the form of fuzzy numbers (Chen and Pham, 2000; Dubois and Prade, 1980; Hanss, 2005; Zadeh, 1965).

2.5 Reliability and validity of research results

A piece of research is reliable and replicable when the study can be implemented by other researchers and the same results can be obtained (Yin, 2009). In order to improve the reliability of the research, different steps for the implementation of the present research work, including the data collection and analysis, are established based on standards recommended and clearly described in Chapter 2.

Mentzer and Flint (1997) define the validity of the research as a hierarchy of procedures to ensure that what we conclude from a research study can be stated with some confidence, i.e., the conclusion is valid. Hevner et al. (2004) suggest a number of evaluation forms to assess the reliability and validity of the research, including analytical, observational, experimental, testing, and descriptive forms.

In this research study, the application of the developed models for improving the performance of the systems (i.e., analytical form of evaluation) (Dresch et al., 2015; Hevner et al., 2004) is clearly discussed and highlighted, especially through the conducting of illustrative case studies. Observational evaluation is usually performed with the help of field studies (Dresch et al., 2015; Hevner et al., 2004). In this research study, no field studies were performed. However, developed models and methodologies and their expected results were presented to academia and to the industry at different seminars, project meetings, and conferences and are published in peer-reviewed journals. Descriptive evaluation aims to demonstrate the utility of the developed models and methodologies (Dresch et al., 2015; Hevner et al., 2004). For this purpose, methods for data collection and analysis, as well as taking a step-by-step procedure to analyse the production performance of Arctic offshore O&G facilities, are clearly established by implementing illustrative case studies. Logical arguments are made and the application of the models and methodologies are described in different scenarios. However, due to lack of resources and time, the developed models are not tested with experimental results.

3 Summary of papers

This thesis has five appended papers, which are published or accepted for publication in peer-reviewed international journals. This chapter presents the summary of the appended papers.

Paper 1

This paper mainly contributes to Research Question 1. The aim of this paper is to identify the environmental conditions of the Arctic offshore specific to the Barents Sea, both the Norwegian and Russian parts. Paper 1 also investigates various effects of such conditions on the RAM of offshore O&G production facilities. It broadly reviews and discusses the elements of the Barents Sea environmental conditions, including weather and meteorological conditions, sea state, seasonal darkness, reduced visibility, and infrastructure level. Each of these elements can affect the RAM of O&G facilities in different ways. Such an overview and discussion plays a key role in building knowledge about O&G operations in the Arctic offshore, including the Barents Sea, and their associated risks.

Paper 2

This paper mainly contributes to Research Question 2. The aim of this paper is to develop a methodology, whereby an expert-based fuzzy fault tree model is employed to analyse the impact of Arctic climatic conditions on component and system reliability. For this purpose, expert opinions are used to modify the mean of exponentially distributed failure times, collected in normal-climate regions, in order to reflect upon the impact of operating conditions. Expert judgements are fuzzified using Gaussian fuzzy sets and further plugged into a fuzzy fault tree model to account for the uncertainties involved in expert opinions.

Paper 3

This paper mainly contributes to Research Questions 2 and 3. The purpose of this paper is to provide an expert-based reliability model to analyse the reliability performance of Arctic offshore O&G production facilities. The proposed model is able to tackle the issue of the lack of adequate historical data in Arctic offshore O&G applications. This is achieved by modifying the data available in normal-climate regions using expert judgements. The model is developed in analogy with PHMs, where the impact of harsh operating conditions is accounted for by introducing multiplicative factors to the Weibull failure rate of system components operating under normal climatic conditions. Such multiplicative factors are modelled using data elicited from experts. To this aim, experts are asked to provide their subjective distributions on the degree of reduction in MTTF of system components due to the adverse effects of Arctic conditions. Expert data are combined using Cooke's performance-based aggregation method, where a weighted arithmetic averaging rule is used to combine expert judgements. In this method, each expert receives a weighting factor computed based on his or her performance on a set of calibration variables. A Monte Carlo simulation technique is further used to develop the DM's CDF and, finally, to analyse plant reliability under the uncertainties associated with expert data. The proposed model is illustrated by a case study. The importance of each component and minimal cut set of the O&G production facility operating in an Arctic location is identified under the uncertainties associated with expert opinions. Such importance measures are finally used to rank the critical components of the plant, reliability wise, and to further test some plant reliability improvement scenarios.

Paper 4

This paper mainly contributes to Research Questions 2 and 3. The aim of this paper is to develop a methodology for production rate availability prediction and analysis of O&G production facilities operating in the Arctic offshore. For this purpose, in analogy with PHMs, the impact of harsh Arctic conditions on equipment performance (and thus equipment reliability) and maintenance crew (and thus equipment maintainability) are modelled by introducing multiplicative factors to the failure and active repair rates, respectively. Although such factors can be estimated using historical data and parameters of environmental conditions throughout equipment life, a formal expert judgement process is used to cope with the lack of such data in Arctic offshore O&G applications. To this aim, the failure and active repair rate multiplicative factors are modelled by employing the data elicited from experts on the degree of reduction in equipment MTTF and the increase in MTTR under harsh Arctic conditions. While a Weibull distribution is used to represent equipment failure behaviour, the maintainability is modelled by combining exponentially-distributed active repair times and lognormally-distributed waiting downtimes. Such models are further employed in a Monte-Carlo-simulation-based model to analyse the availability of different production levels of an O&G production facility under the assumption of minimal repair for each failure. Uncertainties associated with expert opinions on the impact of harsh Arctic environmental conditions, and their propagation through an expert-based production rate availability model, are also accounted for.

Paper 5

This paper mainly contributes to Research Questions 2 and 3. The aim of this paper is to analyse and assess the availability of O&G production facilities operating offshore under time-varying and stressing Arctic environmental conditions. Such an availability model is developed based on a virtual age model, which describes the impact of time-dependent operating conditions on both component life history and maintenance durations. This is done by introducing weather-dependent multiplicative factors, which can be estimated by expert judgements or from ALT results, given the scarce data available from Arctic offshore operations. The application of the model by direct Monte Carlo simulation is illustrated on an oil processing train operating in the northern Barents Sea. The impact of time-varying conditions on system availability is investigated under two assumptions of perfect and minimal repairs. A scheduled preventive maintenance (PM) task is considered to cope with the potential reductions in system availability under harsh operating conditions. Furthermore, AR time-series models, which are fitted to historical weather data, are used to predict long-term weather conditions and capture their associated uncertainties. The results of this study show that plant availability follows a cyclic form in accordance with weather variations throughout the year. The sensitivity of the plant availability model is also investigated with respect to the changes in the multiplicative factors of failure and repair times.

4 Results and discussion

In this chapter the results of the thesis are presented and discussed in accordance with thesis objectives.

4.1 Arctic operating conditions and RAM of O&G facilities

The first objective of this research study was to review, identify, and discuss the elements of Arctic operating conditions and their impact on the RAM of O&G production facilities operating in the Arctic offshore. This aim is achieved by conducting a detailed literature review related to the design and operation of Arctic offshore O&G facilities and by holding discussions with different experts. The results of the research are published in Paper 1. Although some of the factors listed in this paper are more specific to the Barents Sea, such as polar low pressures, the discussion on the impact of operating conditions on plant RAM performance can be adopted for other Arctic regions without loss of generality. These conditions are subjected to temporal and special variations over the Arctic regions, including the Barents Sea. In this regard, identifying the elements of operating conditions plays a great role in the further evaluation of the RAM performance of O&G facilities in the Arctic offshore.

The results of the research indicates that, among other factors, RAM depends on operating conditions in such a way that harsh Arctic offshore conditions adversely affect the RAM performance of O&G facilities. Figure 6 illustrates a list of atmospheric and oceanographic conditions, as well as some of the Arctic offshore geographical characteristics that influence the RAM performance of offshore facilities.

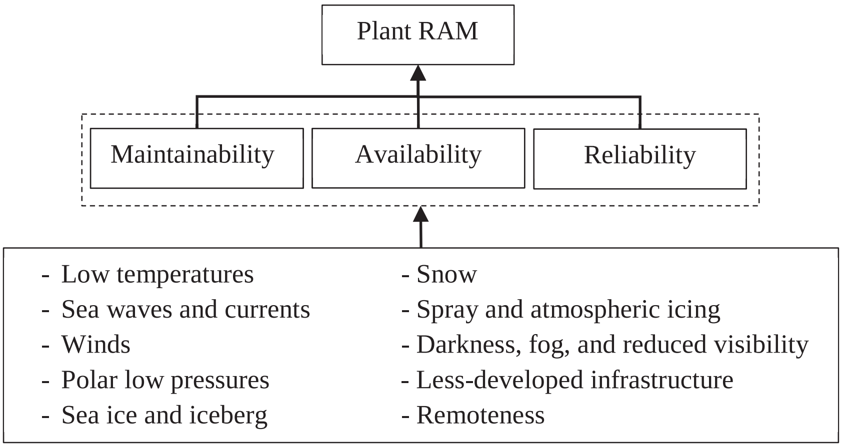

Figure 6. The Barents Sea operating conditions influencing RAM performance of O&G facilities

As discussed in Paper 1, the effects of Arctic operating conditions can be grouped into the impact on equipment units, human performance, logistics, and supply chain; these may eventually result in reduced plant availability by increasing the failure rate of equipment units and/or extending plant downtimes. While the increase in equipment failure rate can be discussed from the viewpoint of reliability performance, extended plant downtimes can be discussed in relation to maintainability and maintenance support performance.

A detailed discussion on such factors, their temporal and spatial distributions over the Barents Sea, and their potential impact on the RAM performance of O&G facilities is presented in Paper 1. For example, one can consider the negative effects of low temperatures on the rheological properties of lubricants and oils that can lead to a reduction in equipment reliability. Low temperatures coupled with winds can cause the performance of the maintenance crew to deteriorate and result in extended active repair times. The lack of a suitable weather-window for the supply of maintenance tools and spare parts and for the provision of a specialised maintenance team from remote supply centres can delay maintenance tasks. This consequently increases plant downtimes and reduces plant availability. Moreover, loading and offloading operations are limited in a degraded visual environment and under harsh weather and sea conditions that can eventually lead to extended plant downtimes.

The discussions presented in Paper 1 highlight the importance of accounting for the impact of severe operating conditions on the RAM of Arctic offshore O&G facilities. The extent of such impact can vary due to, among other factors, temporal and special variations in Arctic operating conditions. In this research study, some methodologies and models are developed to quantify the impact of Arctic operating conditions on plant RAM performance, which is discussed in the rest of the present chapter.

4.2 Expert-based reliability analysis of O&G facilities in Arctic offshore

The second objective of this research study was to discuss the application of expert judgements and to develop expert-based models and methodologies for the reliability analysis of Arctic offshore facilities.

In this research, an expert-based fuzzy fault tree model is developed for the reliability analysis of O&G facilities operating in the Arctic offshore (Paper 2). The model can be employed in both the design and operation phases of O&G facilities in the Arctic offshore, where life data is scarce. More specifically, the proposed model is used within a framework which has two phases. The aim of Phase I is to develop a fault tree model to analyse the failure probability and, thus, the reliability of a system operating under normal conditions. It includes the following four steps:

1) System identification and description,
2) Component-level analysis,
3) Fault tree construction, and
4) Estimation of system failure probability.

The aim of Phase II is to develop a fuzzy fault tree model to analyse the reliability of the plants operating under harsh Arctic conditions. This is achieved by incorporating expert judgements into the fault tree model developed in Phase I. Phase II consists of six steps as follows:

1) Expert selection,
2) Expert opinion elicitation,
3) Fuzzification of expert opinions,
4) Aggregation of fuzzified expert opinions,
5) Development of fuzzy failure probability functions for system components,
6) Performance of fuzzy fault tree analysis to estimate system failure probability

In Phase II, expert opinions are used to estimate the degree of reduction in MTTF of system components exposed to harsh Arctic operating conditions. Fuzzy set theory is used to analyse the uncertainties associated with expert opinions. For this purpose, Gaussian fuzzy numbers are used to represent the degrees of reductions in the MTTF of system components. Weighted averaging methods are used for the aggregation of fuzzified expert opinions, which are further integrated into the MTTF of system components operating under normal conditions. The application of the presented fuzzy-based methodology is illustrated by analysing the reliability of a three-phase O&G separator system. The estimations made using the proposed methodology may need to be further modified whenever new historical or laboratory life data are available.

In Paper 2, it is assumed that the TTF of system components is exponentially distributed. However, equipment units of O&G facilities can have time-dependent failure rates with increasing or decreasing trends. To model such a time-dependency of failure rates, an expert-based Weibull reliability model is developed in analogy with PHMs, whose underlying assumption is that the Arctic operating conditions increase the failure rate of components by a constant factor equal to or greater than one. That is, the ratio of the failure rate of components under two different sets of operating conditions remains constant with time.

The model, which is presented in Paper 3, uses expert opinions to quantify the impact of environmental conditions on the reliability of O&G production facilities operating in the Arctic offshore. For this purpose, Cooke's performance-based approach is adopted to elicit and combine expert opinions in order to determine the DM's CDF of the reductions in the MTTF of system components. A composite Monte Carlo sampling approach is adopted in order to finally determine the DM's empirical CDF, which can be used to represent uncertainties involved in expert opinions. To this aim, a set of weight factors for experts is computed (see Table 3 of Paper 3), based on the performance of experts on a number of calibration variables.

The proposed model and its application are illustrated by analysing the reliability performance of an O&G processing train designed for operation in the Barents Sea. Once the reliability model of the system components in the base area is developed, expert opinions are used to reflect upon the impact of harsh Arctic conditions on their reliability performance. A system fault tree is developed, using which and by employing Boolean algebra rules, system minimal cut sets are identified. The reliability block diagram concept is further employed to develop the system reliability function. In summary, the case study presented in Paper 3 illustrates how the expert-based reliability can be employed in practice for Arctic offshore application. Although in this study a weighted arithmetic averaging method is used for expert data aggregation, other methods such as Bayesian aggregation techniques may also be used. Moreover, the results of system reliability prediction, among other factors, depend on the number of experts and their expertise levels.

The model proposed in Paper 3 is further used in Paper 4 for analysing the reliability of repairable systems, their availability, and production rate.

4.3 Expert-based RAM analysis of O&G facilities in Arctic offshore

The third objective of this research study was to develop an expert-based model for the RAM analysis of Arctic offshore O&G facilities, while taking account of the impact of the time-independent and time-dependent elements of harsh operating conditions. This objective is achieved by integrating the data collected in normal-climate regions with expert opinions on the performance of equipment units and maintenance crew, using proposed models for plant RAM analysis.

The impact of time-independent Arctic conditions on the reliability and maintainability performance of equipment is modelled in analogy with PHMs by introducing constant multiplying factors to the failure and repair rates. Such factors are estimated through a formal expert judgement process, where weighted arithmetic averaging method and Bayesian technique are used for aggregating expert opinions.

Once expert-based maintainability and reliability models of system components are developed, the system RAM is predicted by employing a direct Monte Carlo simulation technique. To this aim, a step-by-step procedure (Figure 1, Paper 4) is developed and illustrated by analysing the availability and production rate of the electricity generation unit of an offshore O&G production facility. In the first step, the degrees of changes in MTTF and MTTR of each component are sampled from the corresponding DM’s CDFs (see Figures 5 and 6 of Paper 4), using an inverse transform sampling method. Sampled values from the DM’s distributions are further used for developing component reliability and maintainability models. Such models are further used in a direct Monte Carlo simulation scheme for estimating the system RAM. Such a procedure is repeated a sufficiently large number of times, each time for a new set of sampled values from the DM’s CDFs to account for the uncertainties associated with expert opinions. For instance, Figure 9 of Paper 4 shows the CDFs of mean availability of different production levels in both the base area and Arctic offshore.

As illustrated by the case study in Paper 4, although the impact of harsh Arctic operating conditions on system availability may be considered negligible, especially in highly reliable systems (e.g., a four-train redundant power generation unit), the harsh operating conditions have a considerable effect on the throughput of the system. Moreover, according to the results of Paper 4, the estimation of plant reliability, availability, and production rate is greatly affected by the method of aggregating expert opinions. The extent of such uncertainties is affected by the number of experts and their expertise levels.

To model plant availability under time-dependent Arctic environmental conditions, a virtual age model is developed in analogy with AFT models and presented in Paper 5. The virtual age model describes the impact of the time-varying and stressing operating conditions (i.e., dynamic Arctic weather conditions) on the TTF and TTR of plant components, using weather-dependent multiplicative factors.

For the sake of mathematical modelling, environmental conditions are categorised into a number of intensity levels based on some thresholds. This implies that weather conditions can be expressed by a stepwise stochastic process due to the randomness of weather conditions. The concept of weather intensity levels (WILs) and their dynamicity over the system's uptimes and downtimes is depicted in Figure 1 of Paper 5. In this regard, WILs are considered stress levels, and thus the proposed failure and repair distribution models are developed using the ideology behind step-stress accelerated life tests. That is, harsher weather conditions lead to severer stress levels, resulting in reduced TTFs or increased TTRs.

For failure probability modelling, this study assumes that component TTFs are Weibull distributed. Moreover, in analogy with accelerated life tests, it is assumed that, under different WILs, the failure mechanism of the component remains unchanged. The virtual age, also known as the equivalent age, is then employed for the estimation of the accumulated damage of system components under different WILs. To this aim, a computational approach is developed and presented in Paper 5. The evolution of the reliability of a component under dynamic operating conditions in each time interval depends on the equivalent age updated at the beginning of the interval and the WIL of the present time interval (see Figure 3 of Paper 5). The active repair rate of system components, given that the repair tasks are being performed under dynamic weather conditions, is modelled using a similar approach to that developed for failure rate modelling. Figure 4 of Paper 5 depicts the active repair rate model and the concept of equivalent repair time, given that component TTRs are exponentially distributed.

To estimate plant availability, in the first step, weather conditions are predicted for the operation time horizon. Thereafter, weather-dependent multiplicative factors for TTFs and TTRs are determined by comparing long-term predicted weather conditions against some predefined thresholds. Such factors are further integrated into the developed failure and repair rate models. Failure and repair models are further employed in a direct Monte Carlo simulation for generating random failure and repair events over the operation time horizon.

In real practice, corrective maintenance (CM) tasks do not remove all previous degradation from failed components. A more conservative assumption is that of minimal repair. Under this assumption, even though a CM task brings the failed component into its functioning state, the component preserves all accumulated degradations that have been experienced during its previous life cycles. A minimal repair assumption can be applied by modelling the virtual age of the component equivalent to its uptimes during its previous life cycles, while considering the historical evolution of WILs.

The proposed models are illustrated in Paper 5 by analysing the availability of an O&G production facility operating in the northern Barents Sea under dynamic weather conditions. Among different weather elements, this case study investigates the impact of air temperatures on component reliability and the impact of wind chill effects on maintenance-crew performance. Long-term weather conditions for the plant location are predicted by fitting historical weather data to AR time-series models.

The results of the case study show that, under a minimal repair assumption, the plant mean availability for 15 years of operation declines from 95.29% to about 88.41% due to the adverse impact of harsh Arctic weather conditions. This trend is also evident in the total number of system failures, which increases from 152 in the North Sea to 289 in the northern Barents Sea.

A sensitivity analysis of plant availability with respect to multiplicative weather-dependent factors is performed to investigate the impact of potential winterisation measures on plant performance. Based on the results of such a sensitivity analysis (Figure 14 of Paper 5), the improvement of the reliability performance of equipment units has more influence on plant availability performance compared to their maintainability. It should also be noted that, although implementation of winterisation measures can improve component reliability, they may add to equipment downtimes, due to for instance removing insulations before and putting them back after each CM task. Such combined effects of winterisation measures are not discussed in this study.

Moreover, to improve the availability, O&G facilities are subjected to different forms of PM activities. In this case study, the effects of PM on plant availability are analysed considering calendar-based overhauls. Plant components are considered new after each PM. Although PMs can improve plant availability due to improving the reliability of system components, they can add to plant downtimes. In this regard, there should be an optimum interval for performing overhauls. In this research study, such an optimum interval is determined by maximising plant mean availability (see Figures 15 and 16 of Paper 5).

As discussed in Section 2.4, the long-term prediction of weather conditions is associated with some uncertainties due to weather stochasticity. In this regard, as shown in Figure 17 of Paper 5, plant availability is estimated by employing a Monte Carlo simulation for analysing weather-condition uncertainties and their propagation through a plant availability model.

5 Research contributions, and suggestions for future work

5.1 Research contributions

The main contributions of this study can be summarised as follows:

- Different parameters of Arctic offshore environment are identified and their effects on the RAM performance of O&G production facilities are reviewed and discussed.
- Expert-based models and methodologies are developed to apply the concept of expert judgement for reliability analysis and assessment of Arctic offshore facilities. In this regard the novelty of the research lies within the integration of expert opinions on the impact of operating conditions with the reliability data available in normal-climate areas.
- Expert-based models that integrate expert opinions about the impact of operating conditions on the RAM performance of O&G facilities are developed. The proposed models are further used to develop a simulation-based methodology for analysis and assessment of plant RAM performance in an illustrative case study.
- A cumulative damage model is developed to analyse and assess the RAM performance of Arctic offshore O&G facilities under the effects of time-dependent weather conditions. Dynamic impact of Arctic operating conditions on plant RAM are investigated while examining CM and PM tasks.

5.2 Suggestions for future work

Based on the research work presented in this report, the following subjects are suggested for future research:

- Development of an availability- and/or cost-based model for prioritising the components of O&G facilities for the implementation of winterisation measures
- Development of spare parts' provision models and their potential contribution to plant availability under the impact of harsh Arctic environmental conditions
- Improvement of the data collection strategies in Arctic offshore O&G production facilities in accordance with developed RAM models

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Part 2: Appended papers