Production Performance Analysis
Reliability, Maintainability and Operational Conditions

Doctoral Thesis by

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Thesis submitted in fulfillment of
the requirements for the degree of
PHILOSOPHIAE DOCTOR
(PhD)

University of
Stavanger

Faculty of Science and Technology
Department of Mechanical and Structural Engineering and Material Science
Center for Industrial Asset Management
2011

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Abstract

With the increasing demand for energy over recent decades, the Arctic region has become an interesting area for future exploration and development for the oil and gas industry. The Arctic region is known to have a harsh climate and a sensitive environment in a remote location. The severe and complex operational conditions in the Arctic can significantly affect the lifetime of a system, the repair processes and the support activities. Hence, it is important to consider the effect of the operational conditions on the performance of the production facility/systems/equipment and machines, and the related reliability and maintainability characteristics.

The aim of this thesis is to study, analyze and suggest a methodology for production performance analysis considering operational conditions. Furthermore, the study focuses on developing and modifying the available statistical approach for prediction of maintainability performance and spare part provision considering the effect of time-dependent and time-independent covariates (influence factors).

In this research study, firstly a brief survey of technological and operational challenges in the Arctic region from a maintainability and reliability performance point of view is presented. Then, available statistical approaches for reliability and maintainability performance analysis considering the effect of covariates are reviewed. Thereafter, a methodology is developed and proposed for production performance analysis considering time-dependent and time-independent covariates. The methodology is based on the concept of the proportional hazard model (PHM) and the proportional repair model (PRM), as well as their extensions. A case study from the mining industry is presented to demonstrate how the proposed methodology can be applied.

In the second part of this research study, the application of the extension of PHM is developed and discussed in order to predict the maintainability performance considering time-dependent covariates. Furthermore, the existing methods for calculating the number of spare parts on the basis of the reliability characteristics, without the consideration of time-dependent

covariates, is modified and improved to enhance their application in the presence of time-dependent covariates. The applications of these methods are demonstrated and discussed using a case study.

The result of the study shows that the operational conditions may have a significant effect on the reliability and maintainability performance of a component. This also consequently affects the number of the required spare parts for a given operational condition. The result also shows that considering time-dependent covariates as time-independent covariates may lead to wrong results in the prediction of reliability and maintainability performance as well as the required spare parts. Therefore, before any analysis, the time-dependency of covariates must be checked. Thereafter, based on the result of the analysis, the appropriate statistical approach must be selected.

Keywords: Production performance, Reliability, Maintainability, Availability, Throughput capacity, Arctic conditions, Proportional hazard model, Proportional repair model, Spare parts.

Acknowledgements

This thesis is submitted as a partial fulfillment of the requirements for the degree of Doctor of Philosophy (PhD) at the University of Stavanger (UiS), Norway. The research work was carried out at the UiS in the period from September, 2008 to November, 2011. The compulsory courses were given and attended at the UiS.

I would like to thank the Research Council of Norway and EniNorge AS, Norway, for assisting in providing financial support for accomplishing the research work. Moreover, I would like to thank the reference group members for their valuable inputs and guidance.

I wish to express my gratitude to my supervisor, Professor Tore Markeset, for introducing me to the research area, and for providing me with all the necessary facilities and continuous support during this study. I would also like to thank him for sailing me out of the turbulent times of confusion and bewilderment. I would like to thank my co-advisor, Professor Ove T. Gudmestad, at the University of Stavanger, Norway, for his valuable guidance and helpful discussions for improvements in the thesis.

I am particularly grateful to Professor Javad Barabady at the University of Tromsø (UiT), not only for his valuable suggestions and sharing his valuable professional experience through innumerous discussions but also for his support throughout my study and living in Norway.

I would like to express my appreciation to all my colleagues at the Department of Engineering and Safety at the UiT. In particular, I would like to express my thanks to Terje F. Olsen, head of the department, Dr. Are Sydnes, Dr. Jarle Andre Johansen, Dr. Kristin Sørung Scharffscher, Inger Johanne Lurås, Tor Schive and Lars Andreas Munch for their help and support. I would like to thank the personal at the university library and IT department for their willing support.

Contents

List of appended papers

Paper I   Barabadi, A. and Markeset, T. (2011). Reliability and maintainability performance under Arctic conditions, *International Journal of Systems Assurance Engineering and Management*, DOI 10.1007/s13198-011-0071-8.

Paper II   Barabadi, A., Barabady, J. and Markeset, T. (2011). A methodology for throughput capacity analysis of a production facility considering environment condition, *Reliability Engineering and System Safety,* Vol. 96, No. 12, pp. 1637-1646.

Paper III Barabadi, A., Barabady, J. and Markeset, T. (2011). Maintainability analysis considering time-dependent and time-independent covariates, *Reliability Engineering and System Safety*, Vol. 96, No. 1, pp. 210-217.

Paper IV   Kayrbekova, D., Barabadi, A. and Markeset, T. (2011). Maintenance cost evaluation of a system to be used in Arctic conditions: A case study, *Journal of Quality in Maintenance Engineering*, Vol. 17, No. 4, pp. 320-336.

Paper V   Barabadi, A. (2012). Reliability and spare part provision considering operational environment: A case study, To appear in *International Journal of Performability Engineering*, Vol. 8, No. 4, pp. 417-426.

Part I – Thesis summary

1. Introduction

With the increasing demand for energy over recent decades, the Arctic region has become an interesting area for future exploration and development for the oil and gas industry. The US Geological Survey (USGS) estimates that 24% of undiscovered oil and gas resources can be found in the Arctic Ocean and the continental shelves surrounding it (USGS, 2008). The Arctic region is known to have a harsh climate and a sensitive environment in a remote location (Gudmestad and Strass, 1994; Hasle et al., 2009; Markeset, 2008a). The severe and complex operational condition in the Arctic can significantly affect the lifetime of a system, the repair processes and the support activities (Gao and Markeset, 2007; Panesar and Markeset, 2006). For example, low temperatures can change the property of materials causing an increasing failure rate, or icing on equipment can reduce its accessibility resulting in a decrease in the maintainability performance of the equipment (Diemand and Lever, 2004; Løset, 1995).

However, there exist little literature published on experience related to the operation and design of oil and gas production facilities to be used in the Arctic region (Freitag and McFadden, 1997; Gudmestad et al., 2007; Gao and Markeset, 2007). The majority of available data in the offshore oil and gas industry, such as OREDA (offshore reliability data, 2002), are restricted to the area south of the polar circle where the operational conditions can be quite different from those found in the Arctic region. Working in less familiar Arctic operational conditions will increase the uncertainty and risks related to health, safety and environment as well as the costs of investment, operation and maintenance. Hence, the design and operation of the equipment to be used in the Arctic region is fraught with high cost and risk.

Production performance plays an important role in supporting the decision-making process for the managers and the engineers dealing with the different challenges to meet the varying demands of customers as well as production control and the optimization of operation and maintenance strategy (see e.g. Hokstad, 1988; Barabady, 2007; Gao et al., 2007; Markeset, 2008b;

Barabady et al., 2010a; Barabady et al., 2010b). Production performance is defined as the "*capacity of a system to meet demand for deliveries or performance*", and different terms such as 'production availability', 'deliverability', 'throughput capacity' or other appropriate measures can be used to express production performance (ISO 20815, 2008). The production performance can be described as the combination of the dependability concepts and functional performance (Figure 1).
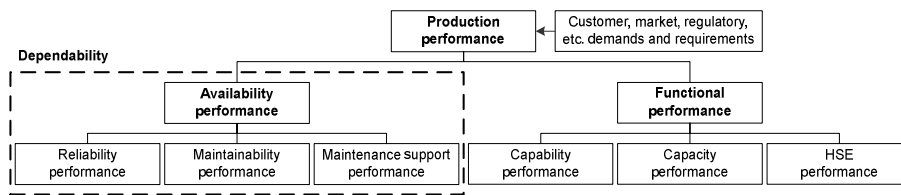
Figure 1: The production performance concept (Markeset, 2010)

Figure 2 shows a procedure that must be implemented in the design phase to optimize the design for production performance. The starting point is the selection of the reference design, and if the deterministic criteria can be achieved by the reference design, deliverability, safety and risk-related measures are predicted. The results of these measurements constitute a basis for decision making about the modification and improvement of the production plant design. One of the important steps of this procedure is to predict the throughput capacity of a production plant in order to assess its deliverability.
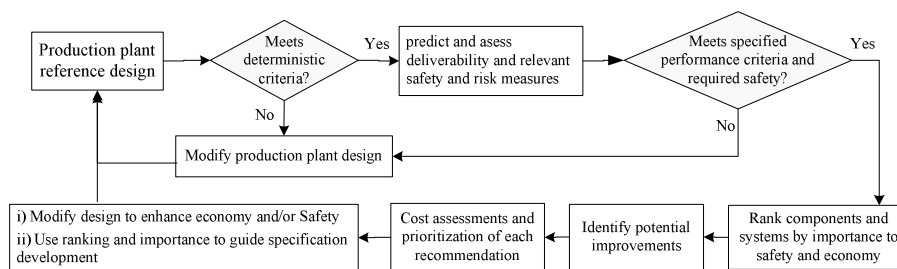
Figure 2: The procedure for designing for production performance (Barabady and Aven, 2008)

The throughput capacity of a production plant is affected in complex ways by the reliability, maintainability and capacity of the components, as

well as the relationship and interaction between the components of the production plant (Distefano and Puliafito, 2009; Rausand and Høyland, 2003). These in turn are considerably affected by operational conditions such as ambient temperature, icing, dust, wind, etc. Hence, an effective reliability and maintainability performance analysis considering all influence factors is a vital prerequisite for predicting deliverability and safety-related measures.

1.1 Problem statement

Failures of components, especially critical components, can significantly affect the production performance of a system. Due to costs and technological considerations, it is almost impossible to design a system without failure (Markeset, 2010). Therefore, the concept of reliability, maintainability and product support should be introduced from the beginning of the design for production performance (Blischke and Murthy, 2000). An effective reliability, maintainability and product support analysis provides essential feedback which can reveal design shortcomings, unanticipated loading, user abuse and other problems which may increase the failure rate (Kececiglu, 1991). These analyses can help the designer to modify the design as well as establishing an effective maintenance schedule to improve the reliability and maintainability performance of system and consequently the system production performance.

With respect to the prediction of reliability and maintainability performance, selecting the appropriate statistical approach is one important step. Most of the statistical approaches which are used in reliability and maintainability analysis rely greatly on historical data. However, suitable data are often not available − especially from the Arctic region. Moreover, most of these methods consider the repair time and failure time as the only variables (Kumar and Westberg, 1996; Ghodrati and Kumar, 2005a; Gao et al., 2010; Lloyd and Line, 1999). Furthermore, historical data have often been collected under different conditions (Kumar and Westberg, 1997). Examples of the conditions that may influence the reliability and maintainability performance are the surrounding environment (e.g. temperature, humidity, dust, etc.), the skill of the operator and maintenance crew, the history of the repair activities carried out on the system, etc., which statistically are referred to as covariates (Kumar and Klefsjo, 1994).

Several methods have been developed to quantify the effect of covariates on the reliability performance of a system such as proportional hazards model (PHM), proportional covariate model (PCM), accelerated failure time model (AFT), stress-strength models, etc. (Cox and Oakes, 1984; Cox, 1972; Kumar

and Westberg, 1997; Meeker and Escobar, 2006; Gao et al., 2010; Richard and Nelson, 2002; Kim et al., 2003). These methods are mostly used to calculate the effect of time-independent covariates. However, in accordance with the operational conditions in the Arctic region, it is important to model and quantify the time-dependency of covariates, because taking into consideration time-dependent covariate such as time-independent covariates may lead to the wrong result (Kumar and Westberg, 1996; Lloyd and Line, 1999; Kleinbaum and Klein, 2005; Schemper, 1992).

The Arctic operational conditions (e.g. snow, rain, icing, etc.) can also easily influence maintainability performance (Gao et al., 2010; Larsen and Markeset, 2007). There is a common belief that the exact shape of the distribution of repair time has in general less influence on the availability performance at system level (Blanchard et al., 1995; Birolini, 2007). This belief may have led to less attention being paid to quantifying the effect of covariates on the maintainability performance. However, in an industry with a high level of investment, such as offshore oil and gas, the costs of the production losses due to a long downtime are substantial which can affect business performance. Hence, it is essential to develop models for better prediction of repair times and maintainability performance, taking the effects of covariates into consideration.

Furthermore, product support and spare parts planning can greatly affect the production performance of a production plant in the Arctic region by reducing its downtime (Markeset, 2008a; 2008b). Estimation and calculation of the required number of spare parts with respect to reliability and maintainability performance have rarely been considered and studied. Most of these studies consider the operation time as the only variable for estimating failure rate and the required numbers of spare parts (Kumar et al., 2000; Ghodrati and Kumar, 2005b; Louit et al., 2011; Vlok et al., 2002). Ghodrati (2005) showed that ignoring the covariates' effects can lead to 20% difference in the expected number of required spares for hydraulic jacks (lifting cylinder) of load-haul dump machines in the Kiruna Mine. Furthermore, due to the changes in operational conditions, a specific system may need different amounts of spare parts for different periods, which has a direct effect on spare part inventory management. For example, a sensitive electronic component on an offshore oil and gas installation in the Arctic region may experience different failure rates during winter and summer due to the effect of ambient temperature. It is obvious that the system may need more spare parts during the winter than the summer.

1.2   Research questions

Based on the above discussion, the main problem of the research study is to take into consideration the effect of operational conditions on the reliability performance, maintainability performance and spare part provision. The following research questions are posed on the basis of the research problem:

1. What are the main technological and operational challenges affecting the reliability and maintainability performance of a production plant in the Arctic region?
2. How can the production performance of a production plant be predicted considering the effect of operational conditions?
3. How to consider and integrate operational conditions in spare parts prediction to minimize the downtime of a production plant and maintenance cost?

1.3   Research purpose and objectives

The purpose of this research is to study, analyze and suggest a methodology for production performance analysis for a production plant, taking into consideration the operational conditions. The main objective of the study is to develop and modify the available statistical approach for prediction of the production performance considering the effect of time-dependent and time-independent covariates. More specifically, the sub-objectives of the research are:

- To review and discuss the technological and operational challenges for reliability and maintainability performance of a production plant under Arctic conditions.
- To discuss and present a methodology for prediction of the throughput capacity considering operational conditions.
- To study and analyze the effect of operational conditions on the provision of spare parts as well as maintenance cost.

1.4   Limitations of the research

During this study the effect of Arctic operational conditions on production performance of a production plant is studied and existing method for maintainability performance and spare parts provision is modified. However due to the lack of real data from the Arctic region, the data used in the case studies come from a mine and a power distribution system. In the case study it

is assumed that all covariates are included in the model, that there is no influences of covariate omission, as well as there is no interaction between the covariates.

A procedure is developed to predict the reliability and maintainability performance of production facilities which are going to be used in Arctic region, based on the available historical data. The proposed approach can be quantified the differences between the operational condition in the Arctic region and the area that data have been collected. However it is assumed that the failure mode, failure mechanism and repair process in the both area is the same.

Furthermore, even though the focus in the study is Arctic conditions, for offshore petroleum production facilities, for mining production systems, the models may be applied for other industry. However, in that case, the assumptions need to be checked.

2. Research methodology

This chapter provides a brief description of the research approach, methodology, and the techniques for data collection and data analysis which are used in this study in order to achieve the research objectives. Research can be defined in many ways. Most generally research is defined as a process through which questions are asked and answered systematically (Dane, 1990). There are two types of research, 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. Applied research conducts a study to address a specific concern or to offer solutions to a problem. Applied research usually means a quick, small-scale study that provides practical results that people can use in the short term (Neuman, 2003). A piece of research may have multiple purposes, but one is usually dominant. Based on what the research is trying to accomplish, the purpose may be classified into three groups: exploring a new topic (exploratory research), describing a phenomenon (descriptive research), or explaining why something occurs (explanatory research) (Neuman, 2003).

This research study is a piece of applied research that is not only going to study and develop a methodology for predicting throughput capacity, but also develop a statistical approach for reliability, maintainability performance and spare part provision analysis, taking into consideration the operational conditions, using fundamental and other related experimental knowledge. Therefore, in order to fulfill the propose of this research study, an exploratory research is intended to generate new knowledge and a model regarding the effect of operational conditions on reliability and maintainability performance as well as on the provision of spare parts. The obtained results and knowledge can be used in both the design and operational phases of a production plant.

2.1 Research approach

The research approach involves building and testing a theory from three directions, namely deductive, inductive and abduction. The deductive approach begins with an abstract, logical relationship among concepts, and then moves toward empirical evidence. In an inductive approach, the research starts with detailed world-scale observations and moves toward more abstract generalizations and ideas. Abduction can be seen as a combination of deduction and induction. In the abduction 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. In short, abduction creates, deduction explains, and induction verifies (Neuman, 2003).

In this study, the research started as a deductive approach with a literature study to gain a deeper understanding of how operational conditions can affect the reliability and maintainability performance of a production facility. The result of the literature study shows that the existing methods must be modified to be more applicable for the prediction of reliability and maintainability performance in the Arctic region. Thereafter, some models were adapted and improved in order to analyze the historical data. The improved models were then applied in an inductive approach by studying the empirically obtained data. Thereafter, the validity of the model was studied, and conclusions were drawn based on the experience gained from empirical case studies. As the research study started with a deductive approach followed up by an inductive approach it can be characterized as having an abductive research approach.

2.2 Research strategy

Due to the purpose of the study and the research questions, the selection of a research strategy mostly depends on which kind of information the researcher is looking for (Yin, 2003). Yin (2003) describes five different research strategies to apply when collecting and analyzing 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. The rest of the strategies (experiments, surveys and case studies) usually refer to the present situation.

Experimental research uses the logic and principles found in natural science research which can be conducted in laboratories or in real life. They usually involve a relatively small number of cases and address a well-focused question. In survey research, the researcher asks many people numerous questions in a short time period, and then summarizes the answers to questions in percentages, tables, or graphs. Survey techniques are often used in descriptive or explanatory research. In case study research, the researcher examines, in depth, many features of a few cases over a period of time. The data are usually more detailed, varied and extensive. Case studies use the logic of analytic instead of enumerative induction (Yin, 2003; Neuman, 2003).

With reference to the different forms of research strategy presented above and considering the goal, approach and the questions of the present research, this study can be classified into the case study research strategy group. We have used scientific logic and principles (e.g. reliability and maintainability analysis methods) and have applied them in the real life of a system/machine to find out some further features. We have also examined the findings of current research study in a few cases and confirmed those findings.

2.3 Data collection and analysis

Yin (2003) presents six main sources of collecting data, namely: documentation, archival records, interviews, direct observations, participant-observations, and physical artifacts.

Based on the objectives of the study, historical data from different industries (i.e. offshore oil and gas (Papers I and IV), mining (Paper II), crushing plant (Paper III) and power distribution system (Paper V)) have been used in order to study the effect of operational conditions on the performance of equipment (Table 1). Documentation, archival records (existing statistical data), direct observation and interview methods are used in this research study. Some tables have been designed to sort and arrange the data in a chronological order for using statistical analysis.

The analysis of reliability and maintainability data is usually based on the assumption that time between failure (TBF), time to failure (TTF) and time to repair (TTR) data are independent and identically distributed (*iid*) in the time domain (Murthy et al., 2004). However, after testing the *iid* assumption, the relevant reliability and maintainability analysis method can be chosen. For the study of the influence of covariates on the reliability and

maintainability performance of a system, the proportional hazard model (PHM), proportional repair model (PRM) and their extinctions were implemented. The time-dependency of covariates is an important criterion for selecting the appropriate statistical approach.

Table 1: Data used in this study

Paper No.	Industry	Type of data	Period	Covariates	Source of evidence
Paper I and V	Oil and gas	TTF, TTR	-	Protection condition, equipment quality, climatic condition, operator skill, maintenance design, maintenance crew skill	Documentation, archival records
Paper II	Mining	TBF	3 years	Rock type	Documentation, direct observation and interview
Paper III	Crushing plant	TTR	2 years	Temperature, shift, location, wind, icing and rain	Documentation, archival records, direct observation and interview
Paper IV	Power distribution	TTF	2 years	Month of failure	Documentation, archival records, direct observation and interview

In order to check the time dependency of covariates, various graphical and numerical methods have been developed. Graphical methods are based on the partitioning of TBF, TTF or TTR data sets with respect to arbitrary time intervals or based on different levels of desired covariate. If the covariate is time-independent, log minus log survival plot (LML) or log cumulative repair plot versus time for different selected groups yield parallel curves (Kumar and Klefsjo, 1994; Schemper, 1992; Kalbfleisch and Prentice, 2002). Figures 3 and 4 show the LML and cumulative repair plot versus time in order to check the time-dependency of temperature (z_1) as a covariate on the repair rate of a crushing plant (see Paper III). The TTR is divided into two different strata: *i) Stratum 1: $z_1 \geq +2°C$* and *ii) Stratum 2: $z_1 < +2°C$*. The result shows that the graphs of Strata 1 and 2 are not parallel. Hence, the temperature (z_1) needs to be considered as a time-dependent covariate.
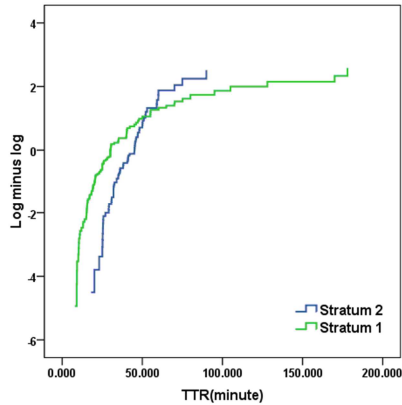
Figure 3: LML for z_1 (temperature) in two strata
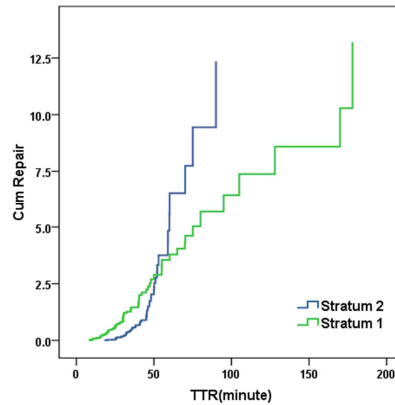
Figure 4: Cumulative repair rate in two strata for z_1

2.4 Reliability and validity of the research

According to the Yin (2003) reliability means dependability or consistency. 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 throughput capacity as well as maintainability and reliability performance analysis. In order to assure the reliability of the study, the data collection 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). This research study has a high internal validity since the findings of the study are relevant and logically connected to the existing theory. However, in order to generalize the results and findings to theoretical propositions, the proposed methodology and statistical approach 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 time frame of this research study.

3. Discussion of the results

This chapter discusses and presents the results of the research study. The areas of discussion are centered based on the stated research objectives.

3.1 Technological and operational challenges in Arctic region

The first objective of this research study is to describe and discuss the technological and operational challenges in the Arctic region and their effect on the production performance of a production plant. Paper I presents and discusses the main technological challenges with respect to the reliability and maintainability performance. The effect of the operational conditions on reliability and maintainability performance may have two different aspects, namely *i)* the effect on the production facility, and *ii)* the effect on human performance (e.g. operator and maintenance crew). Furthermore, the effect of operational conditions on the production facility may have related to the change of material properties or the physical shape of the equipment. For example, very low temperature may change the properties of seals and filters and therefore increase the failure rate and decrease the system reliability, or icing on equipment may change the shape and accessibility of outdoor equipment.

With respect to the effect of operational condition on human performance, it must be noticed that humans are only able to work within a very narrow temperature range. In harsh conditions such as those in the Arctic region, the reliability and performance of the operator will be reduced significantly (Makinen et al., 2006). Wind, icing, snow and darkness combined with low temperatures will decrease the human-machine interface due to a reduction in sensitivity dexterity, coordination and strength (Freitag and McFadden, 1997; Linné and Juntti, 2011; Kumar et al., 2009). On the other side, the remote location, the harsh climate condition and lack of suitable commercial infrastructure can cause depression in humans. Operator performance under these conditions can lead to increasing stress overload on

components or systems due to abuse or misuse. Studies show that 80% of accidents in the offshore industry are caused by personnel (Bea, 1998). It is expected that this percentage may be greater in the Arctic region.

According to the study results, the Arctic challenges can be categorized in three main groups: *i)* harsh climatic conditions and sensitive environments; *ii)* lack of suitable and sufficient infrastructure; *iii)* long distance to the market. Considering such challenges, it seems that the technology and solutions for the oil and gas industry which have proved themselves in other world areas may have to be reassessed and modified for reliable use in the Arctic condition. This imposes additional challenges for the design, construction and operation of offshore installations. According to the literature review and the results of Paper I, in order to design and operate a production facility with a high level of reliability and maintainability performance considering operational conditions, a multi-disciplinary approach needs to be established, involving:

- Collection and usage of relevant information including operational conditions
- Selection of an appropriate statistical approach for reliability and maintainability performance analysis
- The finding of an appropriate approach for continuous improvement in reliability and maintainability performance in the operation and development phase
- Integration of technical and commercial issues

With respect to the first step, historical data play an important role in the design and operation phases. However, there are few quantitative data and little experience available regarding operation equipment in an Arctic climate (Larsen and Markeset, 2007; Gao, 2009). The lack of quantitative data can be related to: *i)* the operating environment (e.g. temperature, wind speed, etc.) due to the lack of the robust weather forecasting infrastructure, weather modeling and forecasting techniques, and *ii)* the lack of failure and repair data and information (e.g. failure and repair time, failure mechanism, failure mode, etc.) due to there being fewer industrial activities in the Arctic region (Barabadi et al., 2011). The lack of data is a big challenge for designers and engineers. Paper IV proposes a procedure that can be implemented to use the available historical data which have been collected in different areas, such as the Norwegian Sea or the North Sea (found in the OREDA), in the design phase for reliability and maintainability performance prediction under the

Arctic condition. In this procedure, at the first stage the influence covariates and their effect magnitudes on reliability and maintainability performance in the reference area are formulated using appropriate statistical methods. Then, based on the magnitude of covariates in the Arctic condition, these results will be extrapolated to predict the reliability and maintainability performance of components in the Arctic area (see Figure 1 in Paper V). However, the selection of the appropriate statistical approach for such a procedure is another challenge that is discussed in more detail in Papers II to V.

3.2 Throughput capacity analysis considering operational conditions

The second objective of this research study is to develop a methodology for throughput capacity analysis of a production plant considering the effect of covariates. In Paper II, an approach for the prediction of production performance is presented (see Figure 1 of Paper II). The methodology is based on four main tasks, namely: *i)* defining boundaries, assumptions and data collection, *ii)* identifying and formulating covariates, *iii)* selecting the analysis approach and estimating component characteristics (e.g. reliability and maintainability performance), and *iv)* system modeling and throughput capacity analysis.

The starting point of the methodology is to define boundaries at different levels such as at the component, subsystem and system level. A system boundary defines the internal components of a system in order to prevent overlaps with adjoining systems. The component boundary clearly defines all the interfaces of a specific component with other components in the system with which it interfaces via hardware or software. Exact definitions of component and system boundaries are necessary in order to clarify the application of equipment characteristics. The boundary selection has a direct effect on data collection. Furthermore, boundary definition has to be compatible with the data which are being generated.

Identification and formulation of the covariates is one of the most important stages in this methodology which is carried out in step II. Any factors that may have an influence on the repair and failure process (e.g. temperature, wind, snow, darkness, maintenance history, operational stress, etc.) must be considered as covariates in the reliability and maintainability performance analysis. In order to formulate the covariates, interaction, omission and time-dependency of covariates must be checked. Based on the

effect of covariates on production performance, they can be divided into two main groups: *i)* categorical covariates, and *ii)* continuous covariates. Categorical covariates are qualitative variables. These can be binary or have multiple categories. For example in Paper III, where the effect of icing is investigated on the maintainability performance of a screen mesh, a binary code is selected and zero is considered for the absence of icing and one for the presence of ice on a structure. Continuous covariates have a defined scale and can be quantified, which can change linear or nonlinear.

In step III, the appropriate statistical approach is identified for data analysis and the estimation of component characteristics (i.e. reliability, maintainability, etc.) considering the effect of covariates. In order to identify a statistical approach for such analyses, two questions have been developed, which act as the decision criteria. Based on the answer to these questions, a suitable approach can be selected. For example, in the presence of time-dependent covariates, the proportional hazard model (PHM) and proportional repair model (PRM) can be used for reliability and maintainability analysis, respectively. Furthermore, if time-dependent covariates have the ability to be stratified, the stratified Cox regression (stratification approach) method can be used; otherwise, the extended PHM must be used. Different methods which can be used to check the time-dependency of covariates are discussed in Papers II to V.

System modeling and throughput capacity analysis is the final step of the proposed methodology (step IV). The overall throughput capacity of the production facility will depend not only on the throughput capacity of its components, but also on the way these components are interconnected in order to form the overall system. Therefore, the relationship between components must be modeled. Such a model must be able to show and to consider how component failures, maintenance activities, or other influence factors can affect the relationship between components and the production of the system. Then, based on the behavior of the system and the relationship between its components under different conditions, the appropriate model must be used. Some of the models which can be used for modeling the relationship between components are reliability block diagram, the dynamic reliability block diagram and the reliability phase diagram (RPD) which are discussed in Paper II and Paper I.

In the proposed methodology for throughput capacity analysis, when the effect of covariates provide a dynamic behavior which can be considered as distinct operating conditions, the reliability phase diagram can be used for throughput capacity analysis. For example, different phases can be defined for

a system whose components exhibit different failure distributions depending on the changes in temperature. If the time-dependent covariate can be stratified, then reliability phase diagram is a suitable model for throughput capacity analysis at the system level and each stratum can be considered as a phase.

The application of the proposed methodology is demonstrated by a case study from the mining industry (Paper II). As mentioned above, in the proposed methodology it is very important to predict the maintainability performance of the components in proper way. Due to the lack of an appropriate statistical approach for maintainability performance analysis considering covariates' effects, the concept of Cox regressions approach have been extended to the maintainability area in order to predict the maintainability performance considering time-dependent and time-independent covariates (Paper III).

3.3 Spare parts provision and maintenance cost evaluation considering operational conditions

The third objective of this research study is to modify the existing reliability-based spare part provision in order to consider the effect of covariates. In the reliability-based spare parts provision, the first step is to identify the reliability performance and failure rate of the item. When the failure rate of the item is at hand, the required number of spare parts and the probability of spare part availability can be estimated.

The application of PHM and its extensions in reliability-based spare part provision are discussed in Paper V. In the proposed approach, the reliability performance of the item considering covariates' effects can be calculated by extension of the PHM as:

$$R(t, z) = R_0(t)^{\exp\left[\sum_{i=1}^{p_1} \beta_i z_i + \sum_{j=1}^{p_2} \delta_j z_j(t)\right]} \tag{1}$$

where $R_0(t)$ is the baseline reliability performance function, β_i and δ_j are column vectors consisting of the regression parameters, z_i is a time-independent covariate and $z_j(t)$, is a time-dependent covariate, p_1 is the number of time-independent covariates, p_2 is the number of time-dependent covariates. When the reliability performance of an item is calculated, the number of the required spare parts can be calculated using an available method such as Poisson process or Renewal theory. In Paper V, the

application of a stratification approach and Renewal theory for spare parts provision of non-repairable items is demonstrated by a case study. The results show that considering time-dependent covariates as time-independent covariates may lead to the wrong results in the number of required spare parts. Therefore, before any analysis, the time-dependency of covariates must be checked. Then, based on the result of the analysis, the appropriate statistical approach must be selected.

In order to evaluate the maintenance cost, the method that is used for maintenance cost analysis must be able to quantify the effect of operational conditions on the system reliability and maintainability performance as well as to quantify the uncertainty. Paper IV presents a statistical approach that will be useful in predicting maintenance cost considering the lack of appropriate reliability data from equipment operated in Arctic conditions using the proportional hazard model and proportional repair model as well as Monte Carlo simulation. The approach presented is valuable for the industrial practitioners in the Arctic region, and may also be adapted to other areas where there is lack of data and operational experience.

3.4   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 summarized in this chapter. 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 2.

Table 2: The relations between the papers and the research questions

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

Paper I: The operational conditions can greatly affect the production performance of a system. This effect can be more critical in the harsh, remote and sensitive Arctic condition. Hence, in Paper I, we present and discuss different consequences and effects of the Arctic operational conditions on reliability and maintainability performance as two main concepts in production performance. Furthermore, some available statistical approaches and models (e.g. proportional hazard model, accelerated failure time model, reliability phase diagram) that can be used to quantify the effect of operational conditions on production performance are reviewed.

This paper highlights that for an effective design and management in the Arctic, it is necessary to recognize how, when, how long, how often and how much the operational conditions affect the production process. The result of the study shows that it is necessary to consider operational conditions as an explanatory variable through the reliability and maintainability performance analysis. Hence, it is necessary to develop and modify current models that are used in the design, operation and support phase in other areas such as the North Sea to be suitable for the Arctic conditions. This subject is the main contribution in Papers II to V.

Paper II: This paper proposes and discusses a methodology for throughput capacity analysis considering operational conditions (as covariates). Throughput capacity analysis must be carried out at component level and at system level. At the component level, a suitable statistical approach must be used to estimate component performance (e.g. reliability, maintainability, and capacity) based on the effect of covariates on the repair and failure process. Thereafter, a suitable model must be selected to build a model that represents the component relationship and their interaction. The proportional hazard model (PHM), the proportional repair model (PRM) and their extensions (such as the stratification approach) are introduced as appropriate statistical approaches for reliability and maintainability performance analysis at the component level. Furthermore, this paper revised some appropriate models that can be used for modeling the relationship between components. The application of the proposed methodology is demonstrated in a case study.

Paper III: Paper III focuses on maintainability performance analysis considering covariates' effect. The covariates may have a significant influence on the maintainability performance and maintenance activities of a production plant. Therefore, it is important to identify the influence covariates and to understand how they affect the maintainability performance. However, most of the available statistical approaches in the maintainability field do not consider the influence of covariates, especially time-dependent covariates, on

the maintainability performance. Hence, the maintainability performance prediction may be imprecise and inaccurate, resulting in poor availability of performance predictions. The main objective of Paper III is to study, model and assess the effect of covariates and more especially time-dependent covariates on maintainability performance.

The applications of the extension of the PHM model and stratification approach, which are used in the reliability area, are extended to the maintainability area. These methods can be used to predicate the maintainability performance considering time-dependent covariates. In the second part of this paper, a case study is used to demonstrate how to apply the stratification approach for maintainability performance analysis. Comparing the results of the case study shows that the covariates and time-dependency of covariates may have great effect on maintainability performance.

Paper IV: There are few data and little experience available regarding the operation of offshore oil and gas production systems in the Arctic region. Using the available data collected from similar systems but from different operational conditions may result in uncertain or incorrect analysis results. In Paper IV a model is suggested to assess systems´ reliability, maintainability and maintenance costs under the influence of the Arctic operational conditions based on the available data using the proportional hazard model and proportional repair mode. Furthermore, a methodology is proposed to evaluate the uncertainty which is associated with maintenance cost due to lack of appropriate data and operational experience.

Paper V: Product support and its related issues such as spare parts play an important role in maintaining a system at a desirable throughput capacity and availability level. Although the importance of covariates' effects on spare parts is recognized, only a few papers describe quantitative models. A reliability-based model has this ability to quantify the effect of covariates on the spare part. In this method, based on the reliability performance of components, the usage rate and the number of the required spare parts in a specific period can be predicted. Hence, if the effect of covariates is quantified on the reliability performance of an item, it can be reflected in the number of the required spare parts. Paper V discusses the application of the PHM and its extension in spare part provision to consider the effect of time-dependent and time-independent covariates. The results show that it is very important to check the time-dependency of covariates as it may have a considerable influence on the required number of spare parts.

4. Research contributions

This thesis contributes to a better understanding of the production performance analysis in harsh, remote and sensitive Arctic conditions. In this research study, the major technological and operational challenges for a production plant, from the reliability and maintainability performance point of view, under the Arctic condition are reviewed.

A methodology is suggested for production performance analysis considering the operational conditions. This methodology facilitates the implementation of different statistical approaches and models for throughput capacity analysis considering time-dependent and time-independent covariates. The application of the suggested methodology is demonstrated using a case study.

The application of the extension of PHM and stratification approach is developed and extended for determining the maintainability performance considering time-dependent covariates. The application of this method is demonstrated using a real case study.

The effect of time-dependent and time-independent covariates on the spare parts and maintenance cost are studied. The available reliability-based spare parts' provision methods are modified to enhance their application to quantify the effect of time-dependent and time-independent covariates.

The study presented in this thesis can assist engineers and managers in predicting an accurate and precise throughput capacity and help them to quantify the effect of operational conditions on maintainability and the required number of spare parts. Furthermore, it can help them to find which factor of operational conditions has more effect on the reliability and maintainability performance in order to improve the design or operation of production plants.

5. Suggestions for further research

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

- Investigation of the influence of the covariates on the maintenance strategy.
- Uncertainty analysis must be considered as an essential stage to provide the necessary information for effective decision making. Therefore, uncertainty analysis for reliability and maintainability prediction considering covariates' effect is necessary.
- Development of a simple and applicable model for predicting the effect of specific atmospheric phenomena such as storm on the production performance of a system or required spare parts.
- Improvement of the data collection system in order to map and collect covariates which can affect the production performance.

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Part II – Papers

Paper I

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Paper II

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Paper III

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Paper IV

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Paper V

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To appear in International Journal of Performability Engineering, Vol. 8, No. 4, pp. 417-426.