Activity-Based Life-Cycle Cost Analysis
Design, Operation and Maintenance in Arctic Environment

Doctoral Thesis by

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Abstract

Currently the oil and gas exploration and production is moving north towards the Barents Sea on the northern coast of Norway, north of the Arctic Circle. This unfamiliar operational environment of the Arctic poses new challenges for the industry, as climate is harsher, the geographical location is more remote from the market and oil and gas fields are located in an environmentally sensitive area. Due to lack of data and experience with Arctic operations, the uncertainty and risks can be higher than in the familiar climate on the North Sea, as well as it is expected that there may also be increased operational and maintenance costs.

This research highlights the main challenges of the Arctic climate affecting life-cycle costs of advanced, complex and integrated offshore oil and gas production facilities. The research evaluates the current practices of the usage of the conventional life-cycle cost analysis by the oil and gas industry and identifies the needs and motivation for development of a more suitable and simplified engineering decision making support tool.

The research work demonstrates and discusses a comparison of the conventional and non-conventional cost systems, life-cycle cost (LCC) analysis and activity-based life-cycle costing (AB-LCC) analysis, respectively. This thesis studies the activity-based life-cycle costing method as an alternative cost assessment methodology, and suggests it as a more suitable methodology when designing of oil and gas production facilities to be used in the harsh, remote and sensitive environment of the Arctic.

Keywords: Activity-based costing; Life-cycle costing; Strategic engineering decision making; Maintenance costs; System performance; Arctic environment; Capacity-driven activity-based costing.

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List of appended papers

Paper I Kayrbekova, D. and Markeset, T. (2008). LCC analysis in design of oil and gas production facilities to be used in harsh, remote and sensitive environments, In: *The Proceedings of the European Safety and Reliability Conference (ESREL2008)*, ISBN 978-0-415-48513-5, September 22^{nd}-25^{th}, Valencia, Spain

Paper II Kayrbekova, D. and Markeset, T. (2010). Economic decision support for offshore oil and gas production in Arctic conditions: identifying the need, In: *The Proceedings of the European Safety and Reliability Conference (ESREL2010)*, September 5^{th}-9^{th}, Rhodes, Greece

Paper III Kayrbekova, D., Ghodrati, B. and Markeset, T. (2011). Activity-based life-cycle cost analysis as an alternative to conventional LCC in engineering design, Accepted for publication in *International Journal of Systems Assurance Engineering and Management*

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, Accepted for publication in *Journal of Quality in Maintenance Engineering*

Paper V Markeset, T. and Kayrbekova, D. (2011). Capacity-driven, activity-based life-cycle costing in strategic maintenance decision making: modeling the cost of performance, Accepted for publication in *Journal of Quality in Maintenance Engineering*

Additional papers, not included

Paper VI — Kayrbekova, D. and Markeset, T. (2009). Activity-based life-cycle costing analysis for design of Arctic petroleum facilities, In: *The Proceedings of the 20th International Conference on Port and Ocean Engineering under Arctic Conditions (POAC2009)*, June 9th-12th, Luleå, Sweden

Paper VII — Kayrbekova, D., Panesar, S.S. and Markeset, T. (2011). Activity-based life-cycle cost assessment of petroleum modification projects, Accepted for publication in: *The Proceedings of the International Conference on Advances in Production Management Systems (APMS2011)*, September 26th-28th, Stavanger, Norway

Paper VIII — Homlong, E., Kayrbekova, D., Panesar, S.S. and Markeset, T. (2011). Operation of offshore production facility in Arctic conditions: assessment of maintenance costs and uncertainty using Monte Carlo simulations, Accepted for publication in: *The Proceedings of the International Conference on Advances in Production Management Systems (APMS2011)*, September 26th-28th, Stavanger, Norway

Paper IX — Kayrbekova, D. and Markeset, T. (2011). Non-conventional cost methods in engineering decision-making in equipment selection process, Accepted for publication in: *The Proceedings of the 20th International Symposium on Mine Planning and Equipment Selection (MPES2011)*, October 12th-14th, Almaty, Kazakhstan

Paper X — Ravnestad, G., Panesar, S.S., Kayrbekova, D. and Markeset, T. (2011). Periodic preventive maintenance strategies: Improving strategies using condition monitoring, Accepted for publication in: *The Proceedings of the International Conference on Advances in Production Management Systems (APMS2011)*, September 26^{th}-28^{th}, Stavanger, Norway

Part I – Thesis summary

1. Introduction and background

The development of offshore oil and gas is technologically complex and capital-intensive. In Norway many offshore production facilities have been developed in the North Sea in the south of Norway and in the Norwegian Sea. Currently, the Norwegian oil and gas industry is moving north towards the Barents Sea on the northern coast of Norway, north of the Arctic Circle. The harsh, sensitive and remote environment of the Sub-Arctic can pose new challenges for the design, installation and operational phases of the oil and gas facilities, and they have to be designed as reliably and in as environmentally friendly a way as possible (Gudmestad et al., 2007). Due to the lack of data and experience in Arctic operations, the uncertainty and risk may be higher. However, much of the data and experience from the 40 years of operations in the North Sea can be used in the design and construction, operation and maintenance of production facilities in the Barents Sea, but the special Arctic conditions and the location need to be taken into consideration in order to reduce costs and achieve the performance goals (see e.g. Markeset, 2008a; Markeset, 2008b; Larsen and Markeset, 2007).

The oil and gas industry is capital-intensive and utilizing increasingly advanced and complex products; a large percentage of the projected cost can be allocated to maintenance and support activities associated with keeping the production facility at a desirable operational state. The cost of system maintenance and support can often be in the range of up to 75 % of the total life-cycle cost of the given system (Blanchard et al., 1995). Exploration and production facilities to be used in Arctic conditions will employ advanced equipment, machines, systems, etc. (from here on referred to as systems), where mechanical, electrical, hydraulic, etc. components are integrated with software and electronics, utilizing sensors and automation to control their operation and performance. Specialized knowledge is needed to maintain advanced and integrated systems since they often have more complex failure modes and patterns. There may also be increased investment costs as well as operational and maintenance expenditures. Hence, it is a more complex and difficult task to assess the life-cycle costs and benefits. Therefore, it will be critical to select and implement appropriate technical solutions to keep the facility in an optimum operational state and to be economically effective.

Examining, comparing and selecting reliable and cost-effective technical, managerial and organizational solutions still constitute one of the bottlenecks when designing or modifying oil and gas production facilities. It has been, and often still is, a tradition to mainly focus on the capital expenditure when assessing the financial viability of projects (ISO 15663, 2000). Operating expenditures are often ignored in the decision-making process. Various decision support tools have been widely applied, but they seem to be less used in the oil and gas industry in spite of there being international standards on the topic. The selection of technology, as well as operational and maintenance strategies, needs to be founded on a sound and rigorous basis, reducing economic and health, safety and environmental (HSE) risks. In this situation, it is critical to develop tools and methods to trace, assess and predict costs for comparing alternative solutions and equipment/systems and to assess costs throughout the total life cycle of a system.

In general one can assume that the life-cycle cost (LCC) will be higher in the Arctic (Kayrbekova and Markeset, 2008). Hence, special consideration needs to be given with respect to more accurately assessing the life-cycle costs during the design phase to reduce the risk and consequences of unwanted events and incidences, to reduce lead-time and to increase profitability. The need for more precise cost assessment methods and techniques, therefore, becomes more important.

This research study on the development of an economic decision support tool is conducted in the context of the process of designing the production facility to be used on the Goliat offshore oil and gas field located 85 km from the shore in the north of Norway, where the environment can be considered as Sub-Arctic. However, the research work can also be useful in the cost assessment of oil and gas production facilities to be used in the normal climate of the North Sea.

The starting point of this thesis was to study the current practices of life-cycle cost assessment in the Norwegian oil and gas industry and the influence of the good quality costs assessment of the selected alternatives on the total life-cycle cost. Thereafter, the study explores the need for better economic decision support methodology in the design and operation phases of oil and gas offshore production facilities to be used in different operational environments. This thesis studies the activity-based life-cycle costing method as an alternative cost assessment methodology, and a more suitable engineering decision support when designing for oil and gas production facilities to be used in the harsh, remote and sensitive environment of the Arctic climate.

The next sections address the state of the art, research questions, research scope and objectives as well as the limitations of the study.

1.1 State of the art

The LCC analysis is an engineering and economic optimization technique, in which the main goal is to identify and choose the alternative that generates the highest revenue over the lifetime, or in other words, generates the lower life-cycle cost (Fabrycky and Blanchard, 1991). However, performing credible cost analysis for a facility to be used in a harsh, remote and sensitive environment, poses a challenge due to the lack of knowledge, experience, research and published data and information. In the Norwegian oil and gas industry a standard for life-cycle cost analysis was developed in the 1990s (NORSOK O-CR-001 and -002, 1996), but was later replaced by ISO standard 15663 (ISO15663, 2000). Extensive literature exists on life-cycle cost analysis techniques (for a review see e.g. Fabrycky and Blanchard, 1991; Barringer and Weber, 1996; Barringer, 2003; Markeset and Kumar, 2000; Markeset, 2003; Emblemsvåg, 2003; Blanchard, 2004; Markeset and Kumar, 2005 a, b, etc.).

1.1.1 LCC

Life-cycle costing analysis provides us with a possibility to test the incurred cost and determine the solution for how this cost can be reduced through better planning. It also allows us to compare different scenarios and what cost-effect the compared scenarios may have.

The National Research Council of USA (1991) defines life-cycle costing as a method used thus: "D*etermining how to assess, compare, select, and then control costs so that facility will provide adequate service throughout its life is the subject of life-cycle cost analysis*". It further underlines that "*the idea that life-cycle costs can be controlled and minimized has wide appeal*". Life-cycle cost analysis is one of a number of tools that can be used to assess the cost-effectiveness of various investment options, which is extensively described in literature. See also Fabrycky and Blanchard (1991), Barringer and Weber (1996), NORSOK O-CR-001 (1996), Kawauchi and Rausand (1999) and Barringer (2003).

The LCC analysis is an engineering and economic optimization technique, in which the main goal is to identify and choose the alternative that generates the highest revenue over lifetime, or in other words, generates the lower life-cycle cost. Fabrycky and Blanchard (1991) define Life-Cycle Cost (LCC) analysis as "*a systematic analytical process for evaluating various alternative courses of actions with the objective of choosing the best way to employ scarce resources*". In the oil and gas industry the focus is on forecasting the total ownership costs of systems due to unreliability, failures and errors, accidents, etc. According to NORSOK standard (NORSOK O-CR-001, 1996), it is recommended that an LCC model be developed based on the input data of the cost elements in the LCC analysis. Several of the LCC analysis structures that exist use the LCC analysis methods of evaluation and comparison of alternative design to avoid system failures and errors, minimize system downtime and achieve higher revenue (see e.g., Greene and Shaw, 1990; Fabrycky and Blanchard, 1991; Garin, 1991; Blanchard, 1998).

A complete LCC analysis may be very complex and require huge amounts of data especially if the analysis is to be performed for a whole production facility. Also, in this case, much of the data may be imprecise and uncertain. However, in the design and development phase of a production facility, LCC analysis may also be used for comparing alternative technical solutions, alternative equipment/ machines/systems, as well as different design configurations and alternative operational and maintenance concepts with respect to the lowest LCC and the highest life-cycle profit (Markeset and Kumar, 2000; Markeset and Kumar, 2005a; Markeset and Kumar, 2005b).

These conventional cost assessment methods guide the analyst to accomplish the LCC analysis, but it is still a challenge to compare the most preferred scenarios in a financial perspective. Many of the LCC analysis methods focus on the cost accrued for the owner of a product or system over the whole life cycle. However, in a review of published case studies related to life-cycle costing, Korpi and Ala-Risku (2008) state that: "*Despite existing life cycle costing (LCC) method descriptions and practical suggestions for conducting LCC analyses, no systematic analysis of actual implementations of LCC methods exists*". Furthermore, they found that "*many of the case study applications: covered fewer parts of the whole life cycle, estimated the costs on a lower level of detail, used cost estimates methods based on expert opinion rather than statistical methods, and were content with deterministic estimates of the life cycle costs instead of using sensitivity analysis*".

The use of life-cycle cost analysis would inform the decision maker about future expenditure, how to manage the existing budget and how to make decisions which lead to the lowest life-cycle cost. LCC analysis can be used as a tool to find the compromise between cost, time and performance of the facility that will meet the operational requirements in Arctic conditions. However, the traditional life-cycle cost assessment method usually ignores the processes and activity view, and may not be able to take into account the difficulty in performing the various activities in the harsh and remote environment of the Arctic climate. By using a non-conventional cost assessment method such as activity-based life-cycle costing, we think it will be easier to establish cause-and-effect relationships between the activities and the costs, as well as to take into account the influence of the physical factors of the Arctic climate on production facility performance and total life-cycle costs. It may be easier to show what activities take place and to keep track of what efforts are needed to achieve the desired performance. It may also be easier to avoid non-value-adding activities with respect to quality, time and efficiency.

1.1.2 AB-LCC

Activity-based life-cycle costing (AB-LCC) in combination with Monte Carlo simulation (Emblemsvåg, 2003) was first developed and directed towards activity-based cost and environmental management (ABCEM) (Emblemsvåg and Bras, 2001). Emblemsvåg (2003) highlights that while traditional life-cycle costing is cash flow oriented, the AB-LCC is both costs and cash flow oriented. In general, instead of focusing on tracing resources directly, in AB-LCC the focus is on tracing the cost of activities performed in processes. This is important since many processes take place in the future (e.g. planned maintenance to prevent failures, unplanned maintenance due to sudden failures, modifications due to changes in capacity needs, etc.). The technique handles overhead costs and allocates them more accurately than traditional life-cycle costing, and is also more capable of analyzing several equipment alternatives simultaneously. It is essential to identify the activities and cost drivers since they will allow us to identify critical success factors that are important in the design and management processes.

Developing the AB-LCC model can also be helpful to illuminate uncertainty in data and statistical sensitivity in the model. The data used will in many cases have to be adjusted for Arctic influence factors (e.g. temperature, wind, etc.), and this will introduce more uncertainty. However, by using the AB-LCC we should be able to increase the long-term profitability by identifying improvement opportunities and by making appropriate and proactive adjustments during the design phase.

The AB-LCC method enables the decision maker to observe the activity-based cost information and allocate indirect and support costs, first to activities and processes, and then to services and production. The AB-LCC can give a more certain picture of the oil and gas production facilities' operations and provide more accurate cost information. AB-LCC helps the decision maker to think from an economic perspective, and to act like an engineer to discover the solution with the lowest life-cycle cost and to indicate all possible related expenditures (Barringer and Weber, 1996). AB-LCC also helps to determine how many resources need to be spent on each activity which has to be performed on the production facility (Kaplan and Cooper, 1998). An alternative approach using activity-based life-cycle-costing may provide advantages when compared to traditional LCC methods.

Emblemsvåg (2003) stated that activity-based LCC provides the following advantages, namely:

- It handles both cost and cash flows.
- It is process oriented.
- It relies on the establishment of cause-and-effect relationships.
- It handles overhead costs.
- It estimates the costs of all the cost objects of a business unit simultaneously.

1.2 Research questions

The literature survey shows that the existing LCC standard focuses on comparing alternatives, and the result is that only some of the cost information is included in the assessment. However, if the task is to select the best possible maintenance strategy, more information is needed on each individual maintenance activity to be performed on the installed system. The traditional LCC analysis initially set up, for example, for selecting between alternative technical solutions, will not be usable in the operational phase if one would like to optimize the maintenance strategies for the current operational conditions, since much of the detailed information concerning the maintenance activities which need to be performed will be missing in the analysis. The traditional LCC is more focused on the capital expenditures, whilst operating expenditures are often ignored. Furthermore, as the production facilities become more advanced, complex and integrated, a specific blend of maintenance activities may be required to maintain the installations effectively. The appropriate maintenance strategy should be the one which is most cost-effective and which results in the best possible plant operational performance. Furthermore, the strategic engineering decision-making in maintenance concept selection for systems to be used in the Arctic will be more challenging due to the unfamiliar operational environment of the Arctic regions. To support strategic engineering decision-making, the development of suitable decision support tools and decision structures becomes essential.

The literature review, assessment of existing life-cycle costing analysis standards for the petroleum and natural gas industries, as well as our own discussions with various experts on economic assessment with respect to the design and operations of offshore production facilities on the Norwegian continental shelf (NCS) revealed interesting research questions. On the basis of the stated interests from the company and experts participating in the case study and limitations with respect to available time, financing and resources, as well as our own priorities, we selected to focus the research on the following questions, addressing gaps between practice and theory:

- What are the main challenges of the Arctic operational environment which might have an influence on the life-cycle cost of an advanced, complex and integrated offshore oil and gas production facility?
- What are the needs, motivation and mechanisms of costs assessment methods for the comparable alternative technical solutions?
- What suitable costs assessment methods exist for possible usage by the oil and gas industry for better life-cycle cost evaluation and prediction?
- Why it is important to use a credible costs assessment method in strategic engineering decision-making for an offshore oil and gas production facility to be used in the Arctic climate, and how can the use of good quality economic decision-making tools in the system design affect long-term costs?
- How can alternative costs assessment methods take into account uncertainty which arises from lack of data and information about the oil and gas exploration and production in Arctic conditions?

1.3 Research scope and objectives

The scope of this thesis is to develop and discuss a conceptual methodology to assess, evaluate and predict maintenance cost more credibly and accurately for an advanced, complex and integrated production facility to be used in the harsh, remote and sensitive environment of the Arctic. The main objective of this thesis is to study the influence of good quality costs assessment of the selected technical solution alternatives on the total life-cycle cost of an offshore oil and gas production facility to be used in the harsh, remote and sensitive environment of the Arctic.

Sub-objectives include:

- Define and discuss factors of the Arctic climate which might influence the LCC of an oil and gas offshore production facility
- Map state of the art in an engineering company in the oil and gas industry in Norway, and assess the need for development of improved LCC models
- Describe and discuss the principles and methods, models and methodologies of the available cost assessment methods and analysis for comparable alternative technical solutions in possible use by the oil and gas industry
- Discuss the importance of good quality life-cycle cost analysis performed during the design of an oil and gas production facility to be used in the Arctic
- Suggest and/or develop a conceptual model or methodology for a better prediction of life-cycle cost for production facilities to be used in the Arctic climate

1.4 Research limitations

The research study only focuses on the maintenance cost of comparable technical solution alternatives. Operational and capital costs such as logistics, taxation, emissions, asset management, etc. are not within the scope of this thesis. Based on literature surveys and the available data and time frame, it was decided to focus the research work on the maintenance cost of the technical solutions selected for the analysis.

2. Scientific approach

The purpose of the work presented in this thesis is, in general, to develop and discuss the principles, models and methodologies for analyzing, assessing and evaluating the cost of the different technical solution alternatives when we design for oil & gas production facilities to be used in the harsh, remote and sensitive environment of the Arctic. Further, the work focuses on identifying the need, motivation and the cost assessment mechanisms of comparable technical solutions in order to select the most cost-effective alternative. The work focused on conceptual model development for improvements of maintenance cost assessment methodology during the design phase through the AB-LCC methodology development for possible oil & gas industry use. All papers included in Part II have been, or will be, published in international journals or acknowledged at international conferences.

All of the work presented in this thesis has been carried out in accordance with the objective of fulfilling the following criteria of scientific work such as solidness, originality and relevance. These three scientific research quality criteria are defined by the Research Council of Norway (RCN) (RCN, 2000).

Research solidness refers to the foundation of the research claims and results; all the choices, judgments, evidence and represented data to support claims and results need to be given clearly, honestly and rationally. The research work needs to be in compliance with all assumptions, limitations, rules or constraints introduced. The research work shall be founded or anchored in the literature of the disciplines it may concern. All principles, methods and models represented in the research work need to be subjected to order and system, to make certain that critique can be raised and that this is understandable. The research solidness can be achieved by use of a recognized scientific approach, good data quality, and good referencing practice, critical attitude to methods, materials and results (RCN, 2000).

Research originality means, that the research work shall contain something "new", meaning that this professional novelty addresses new perspectives and ideas to known problems and challenges. In addition, it should illustrate and/or elaborate the implication of applying new principles and ideas or propose new solutions to indicated problems and challenges. Furthermore, the research work can contribute to new theory and/or method development which could lead to new discoveries and/or a new recognition of fundamental significance (RCN, 2000).

Research relevance and *usefulness* refers to the fact that research work shall contribute to a development within the disciplines it may concern and to which it is relevant. The research work needs to be useful for the purpose of solving known problems and challenges within a discipline, or contributing to further research by the development of new hypotheses or/and by opening new areas within any disciplines it may concern (RCN, 2000).

These principles are based on the principles for scientific quality of the Research Council of Norway, which also points out that, in addition to its scientific quality, research is relevant if it appears useful in an industrial and social context. The research is partly funded by the Research Council of Norway and EniNorge, which is part of the large international oil and gas operator company, Agip. This ensures the relevance and value of the work in an industrial and societal perspective. The research work gives the conceptual methodology for maintenance cost assessment for the industry when designing an oil and gas production facility to be used in the less familiar harsh climate of the Arctic.

The evaluation, comparison and discussion of the examples of conventional and non-conventional cost assessment methods presented in the research are an integrated part of the work. This comparison process has been limited to the use of maintenance data alone for the examples illustrating the principles, methods and models developed and/or discussed. We believe that the conceptual methodology of the maintenance cost assessment presented in this thesis can be further developed and applied, as well as be useful for the oil and gas industry in particular and other industry in general.

3. Summary of appended papers

The thesis comprises five papers covering the main concepts, frameworks, tools and methods, analytical findings and results of the research. The summary of the appended papers is presented in the following section.

Paper I discusses issues of life-cycle cost analysis as a conventional cost evaluation method applied to operations, maintenance and support considerations of offshore oil and gas production facilities to be used in the Arctic climate. The paper presents a conventional life-cycle cost analysis process for comparing alternative technical solutions, alternative equipment or systems, as well as different design configurations and alternative operational and maintenance concepts with respect to the lowest life-cycle cost. Furthermore, the paper identifies the main challenges affecting the life-cycle costs of an advanced, complex and integrated offshore oil and gas production plant to be used in the harsh, remote and sensitive environment of the Arctic.

The paper highlights that an offshore oil and gas production facility to be used in the Arctic can expect a higher life-cycle cost due to:

1) Materials and equipment. The materials, equipment, lubricants and fluids must be suitable for the low temperatures of the Arctic climate; these engineering design choices can be very costly, and it is expected that the design choices need to be as environmentally friendly as possible.
2) Work processes. The physical factors of the Arctic climate, such as low temperature, snow, wind, ice and darkness can reduce the maintainability, supportability and availability factors of the system/equipment, and as a result reduce the production performance and profitability of the facility.

3) Support services and logistics. The delivery and storage of the spare parts, as well as transportation of the personnel can take a longer time.
4) The operational philosophy, support and maintenance strategies for a production facility to be used in the Arctic climate need special consideration as, compared to existing technology, modified and costly technological solutions may be demanded.

Paper II explores the current practices in the usage of conventional life-cycle cost analysis on the Norwegian continental shelf as well as evaluating the needs for an improved economic decision support for oil and gas production facilities to be used in the Arctic climate. The discussions with industrial experts indicated that conventional life-cycle cost analysis is not much in use in the oil and gas industry. The paper identifies and discusses the reasons for the low utilization of conventional life-cycle cost analysis, such as: 1) the small market and strict health, safety and environment requirements, 2) lack of analysis experts, 3) availability of quality data and information, and 4) life-cycle cost decisions over the life cycle.

The paper discusses the issues and challenges of economic decision support in oil and gas exploration and production in the Arctic. The selection of appropriate and cost-effective technical alternatives is a complex and multi-disciplinary process. Based on the discussion findings, a simplified decision support tool is needed for the special considerations which exist in the Arctic.

Paper III maps and discusses the main differences between conventional and non-conventional cost systems, such as life-cycle cost analysis and activity-based life-cycle cost analysis, respectively. Moreover, the discussion and the demonstration of the differences between the two methodologies in a simple example find that the non-conventional AB-LCC methodology may be a more suitable and credible cost system for better cost evaluation and prediction in the engineering design of production facilities to be used in the challenging and uncertain operational environment of the Arctic regions.

The result of a simple example presented in the paper indicates that non-conventional cost systems, such as activity-based life-cycle cost analysis, are more suitable economic decision-making support tools in the design phase, as they can provide more information on the activities and resources, cost and cash flows associated with the operation and maintenance of offshore production facilities to be used in the harsh, remote and sensitive environment of the Arctic climate.

Paper IV reviews the maintenance cost evaluation founded in activity-based life-cycle cost methodology utilization, identifies uncertainty elements and factors in the example presented in the paper, and introduces uncertainty analysis using the Monte Carlo simulation method for systems to be used in the Arctic region. The result of the uncertainty analysis using the Monte Carlo simulation method shows that the maintenance cost of a system in the Arctic region can be significantly increased due to the influencing factors of the Arctic climate. As a result of the high uncertainty in data and lack of information on operation and maintenance considerations in the Arctic climate, it is important to use a proper and credible engineering decision support tool that can handle uncertainty credibly.

Paper V explores an activity-based life-cycle costing methodology as an alternative to conventional costs assessment methodology in strategic engineering decision-making. Strategic engineering decision-making in a reliable and cost-effective manner is still one of the main challenges of the engineering design as well as of the development of operation and maintenance strategies for advanced, complex and integrated oil and gas production facilities. Furthermore, issues of system performance as well as the importance of the utilization of good quality economic decision-making support methodologies are discussed. The paper discusses the cost of activities issues which need to be performed in order to maintain operational performance and keep it at a desirable level.

The paper introduces a concept and model for strategic maintenance decision-making. An example for comparing maintenance strategies for a defined system presented in the paper demonstrates the activity-based life-cycle costing methodology. Activity-based life-cycle costing methodology implementation procedures have been shown and discussed. The presented approach for selecting between alternative maintenance strategies using activity-based life-cycle cost shows that it can enable a decision maker to track the proper blend of maintenance activities, to identify cost objects and their resources' consumption more satisfactorily, to avoid unnecessary activities which can reduce cost and to assure the oil and gas production facilities' availability and performance.

4. Research contributions

This thesis contributes to a better understanding of the process of maintenance costs assessment for oil and gas offshore production facilities to be used in a harsh, remote and sensitive environment. In this thesis, some of the main physical factors of the Arctic climate and its influence on maintenance performance and cost are identified and discussed.

The study presented in this thesis can assist engineers in design and management decision-making during the early stages of the conceptual design phase. The methodology of the cost assessment examined in the research can be used in selecting alternative technical solutions to meet a desirable operational state and maintain the performance systems/equipment to be used in the harsher environment of the Arctic at a level comparable with the normal climate of the North Sea. The studied cost assessment methodology can assist in meeting the desirable performance of the system addressing maintenance considerations. In addition, this cost assessment methodology can support decision-making in strategic maintenance concept selection with respect to cost.

Furthermore, the thesis presents a comparison of two methodologies: conventional and non-conventional cost systems. The demonstration examples for comparing costs assessment systems are based on data from the oil and gas industry gathered from the operation on the Norwegian continental shelf. The non-conventional cost system studied in the work is proposed as a better alternative costs assessment methodology for the cost analysis of comparable alternative technical solutions in the design of production facilities to be used in the harsh, remote and sensitive environment of the Arctic climate. Activity-based life-cycle costing can assist not only in the costs assessment process of the comparable technical solution, but in better planning of maintenance activities following selected maintenance and support strategies. A non-conventional cost assessment methodology, such as activity-based life-cycle costing studied in this work:

1) Can provide more detailed information associated with the maintenance performance which needs to be implemented on the production facility to compensate for the lack of system/equipment capacity.
2) Enables the identification of cost objects that can consume more resources (such as materials, spare parts, lubricants, labor, etc.) in order to remove unnecessary activities; this helps to identify cost drivers.
3) Analyze consumption of the consumables and reduce related costs.

5. Suggestions for further research

A lot of work needs to be done in the further development and generalization of more complex cost models for offshore production facilities to be used in the harsh, remote and sensitive environment of the Arctic. To do so, a considerable amount of reliable, statistical data and information will be required. Based on the findings presented in this thesis, the following points for future research are suggested:

- Reliable data, based on experience, need to be collected from oil and gas production facilities' operation and maintenance in the Arctic climate, and analyzed. The collected data can be helpful in the development of the cost model and/or engineering and economic decision-making support tools which can assist in strategic decision-making to reduce possible cost overruns from the budget, mitigate risks and reduce uncertainty.
- It is necessary to develop more simplified decision support tools which can enable a decision-maker to indicate cause-and-effect relations between system failures, maintenance strategies, operational costs and associated risks, and uncertainty in data and to identify how proposed technical solution alternatives may affect overall cost and profitability.
- New methodologies for the costs assessment of systems/equipment under the influence of the different physical factors of the harsh, remote and sensitive environment of the Arctic need to be further developed.
- The conceptual cost methodology proposed in the thesis represents only maintenance considerations. Further testing of the proposed

methodology in the thesis is, however, necessary to take into analysis not only maintenance considerations, but also different operational and support scenarios and data.

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Maintenance cost evaluation of a system to be used in Arctic conditions: A case study

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Abstract

Purpose: The purpose of this paper is to discuss operation and maintenance challenges under Arctic conditions and to propose a methodology to assess systems´ reliability, maintainability and maintenance costs under the influence of the Arctic operational environment.

Design/methodology/approach: A model is suggested for quantifying maintenance costs whilst taking into account uncertainty due to lack of appropriate data and operational experience using the proportional hazard model and proportional repair model as well as Monte Carlo simulation.

Findings: The results show that the operating environment has a considerable influence on the number of failures, the maintenance and repair times and consequently on maintenance cost. Forecasting the maintenance costs based on technical characteristics (e.g. reliability and maintainability) and considering the operational environment, as well as including uncertainty analysis using Monte Carlo simulation, provide more trustworthy information in the decision-making process.

Practical implications: 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 in a different operational environment, may result in uncertain or incorrect analysis results. Hence, the method that is used for maintenance cost analysis must be able to quantify the effect of the operating environment on the system reliability and maintainability as well as to quantify the uncertainty.

Originality/value: The paper 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. 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.

Keywords: Maintenance costs, Arctic conditions, Uncertainty analysis, Monte Carlo simulation, Proportional hazard model, Proportional repair model, Offshore petroleum production facilities.

Paper type: Research paper

Introduction

The Norwegian oil and gas industry is moving north towards the Barents Sea where production facilities need to be operated in the less familiar Arctic climate. Due to the lack of reliability and maintainability data (e.g. time to failure, time to repair) and other types of data, as well as lack of experience in Arctic operations, the uncertainty and risks related to for example, health safety and environmental issues are higher compared to other areas such as the North Sea (Barabadi et al., 2010). There may also be higher investment costs as well as operational and maintenance expenditure compared to other areas such as the North Sea. Specific emphasis must be placed on those uncertainty factors whose consequences are difficult to quantify, for example reputation (Flage et al., 2007). Identification of potential areas of economic risk may help to reduce cost, lead-time, and to avoid unnecessary hazards and accidents. Maintenance is one of the important areas of economic risk and uncertainty under Arctic conditions. El Hayek et al. (2005) stated that maintenance ownership costs and operational losses depended on how well decision making and predictions were performed, and whether such decisions were built on accurate information and knowledge. For the offshore oil and gas business, maintenance costs can be very high. Due to the additional challenges in the Arctic region, it is expected that the costs may be even greater. Under these circumstances, an effective maintenance program will be critical for the overall system life cycle cost, and it will be essential to establish maintenance strategies based on the best possible analysis and data.

Challenges for effective maintenance in the Arctic region can be categorized in three main groups: *i)* harsh climatic conditions; *ii)* lack of suitable and sufficient infrastructure; *iii)* long distance to the market. When designing and planning the maintenance activity and strategy for the Arctic region, it is necessary to know how these challenges will affect the planned production facility's performance and maintenance activity (Freitag, 1997; Markeset, 2008 a, b; Kayrbekova & Markeset, 2008). In practice, it is also difficult to define facility operation or maintenance strategies that could lead to reduced costs (Gao et al. 2010a).

One of the main sources of uncertainty in the offshore Arctic arises from inadequate data and information about *i)* working conditions, *ii)* the equipment's performance (reliability, maintainability and supportability), and *iii)* cost of maintenance activity and spare parts. The lack of data about the operational environment can be related to the lack of a robust weather forecasting infrastructure, weather modeling and forecasting techniques in this area. Moreover, the small amount of industry activity in this area is the main reason for the lack of data on the equipment's performance and cost of maintenance activity and spare parts. Keith & Marshall (1987) emphasize that the life cycle costing analysts should take the trouble to collect verified data and make the comparisons and deal with the uncertainties.

The starting point for analyzing the maintenance costs for the Arctic area could be the poor data from the actual operating environment and thereafter to make use of the existing data from a normal climate and to perform estimates and simulations for various operational and climate scenarios with respect to economic factors.

Various methods have been developed in order to describe the uncertainty related to the data collection, such as reliability boundary, confidence intervals and probability distribution based on the Monte Carlo simulation (Moss, 1991; Yin et al., 2001; Sonnemann et al., 2003). However, for a complex system such as an offshore facility with different sources of uncertainty, the simulation method is more applicable (Moss, 1991). As the Monte Carlo simulations provide more information about risk and uncertainty in the data and information, they may assist a decision maker to identify the most sensitive parameters and to estimate the confidence in the outputs. Hence, the aim of this paper is to quantify the uncertainty related to the cost of maintenance in Arctic conditions based on available data from other operation areas (e.g. the North Sea or the Norwegian Sea) using the Monte Carlo method as a simulation tool.

The next section briefly reviews challenges for maintenance in Arctic conditions. Thereafter the reliability and maintainability prediction under Arctic conditions is discussed followed by a proposed method for uncertainty analysis based on Monte Carlo simulation. Finally, the application of the proposed model is demonstrated by the means of a case study.

Maintenance strategy under Arctic conditions

Due to costs and technological considerations, it is difficult to design a system that does not degrade or fail. Therefore, maintenance is performed to compensate for failures and degradation in performance (Markeset, 2010). Various maintenance scenarios exist in relation to carrying out maintenance activities to improve performance or keep it at a desirable or projected level (Michelsen, 2007). For example, performing periodic preventive maintenance or inspecting/checking/monitoring the system/equipment systematically may reduce failures and losses.

The climate of the Arctic regions is harsh, with low temperatures, strong winds, ice and snow. Low polar pressure storms may cause rapid changes in wind speed and direction all year round (Gudmestad et al., 1999; Gudmestad et al., 2007; Larsen and Markeset, 2007). The Arctic design solutions for the production facilities can be costly in comparison to the more familiar operational climate of the North Sea; it is also expected that support strategies will be costly. For instance, the economic impact of the Arctic conditions on maintenance needs to be considered with special care, as these factors can cause additional corrective maintenance and repairs. In addition, probable delays in the performance of maintenance tasks need to be predicted as reliably as possible and estimated.

In the Arctic region, preventive maintenance such as lubrication can be affected and result in an increase in wear and failures of moving parts. Furthermore, maintenance tasks that are normally simple may become difficult and can take longer time. Preventive maintenance programs may be established using generic maintenance concepts or by performing detailed maintenance analysis (see e.g. NORSOK Z-008, 2001). The oil and gas companies usually use generic maintenance concepts for equipment based on experience, rules and regulations. The concepts include estimates of total required man-hours to perform maintenance tasks, total repair time, and also indicate the required competence of the maintenance personnel. These concepts usually exclude any economic evaluations, as these are normally performed separately.

The main physical factors of the Arctic climate that may have an impact on operation and maintenance strategies include (see e.g. Freitag, 1997; Larsen & Markeset, 2007):

- **Low temperature:** Low temperature may increase the number of failures of equipment/system/ materials and human errors. The use of warm and heavy cloth and gloves can reduce the quality of the performance of maintenance tasks on the outdoor equipment. Reduced sensitivity, coordination and blood flow can also increase the risk of injuries.
- **Icing and snow:** Icing and snow may affect the reliability and maintainability (R&M) characteristics of the production facilities. For example, low temperature can change a material's properties and decrease the reliability.
- **Wind:** Wind in combination with snow in sharp temperature changes can result in the accumulation of ice on the face of the equipment/system and can reduce maintainability and reliability factors.
- **Darkness:** Darkness may affect the cognitive capabilities of personnel and result in more human errors in tasks to be performed on the production facility. The work can be slower because of the physical and physiological factors. Darkness, combined with low temperatures, wind and fog, reduces

the time spans for marine operations such as interventions, trenching, pipe laying, maintenance, etc.

- **Fog:** The fog can be very heavy and remain for long periods. This may have an effect on the overall operational state of the production facility. Fog may affect the performance of outdoor tasks due to poor visibility and may cause icing on equipment and structure.
- **Less developed infrastructure:** The less developed infrastructure and the remote location from the market and suppliers may affect the overall support strategy and logistics. This may result in longer transport time for material and personnel, and long delays in delivering parts or tools.

To establish an effective maintenance strategy for an item, the reliability and maintainability (R&M) of the item must be calculated. Hence, all relevant information must be collected and analyzed with an appropriate statistical approach. Thereafter, based on the desirable availability goals and integration of technical and commercial issues, the optimal maintenance strategy must be selected (see also Norsok Z-008). Any statistical approach that is used for the analysis must be able to identify and assess the effect of the Arctic operational environment on R&M performance. The main sources of uncertainty for the optimization of the maintenance strategy are related to uncertainties associated with the reliability and maintainability.

R&M performance prediction under Arctic conditions

Different models have been developed to calculate the R&M performance of the system. These methods can be divided into two main groups: parametric and non-parametric methods. The available data and the aim of the analysis define the appropriate method for a set of data. Many of the parametric methods consider the time to failure and time to repair as the only variables (see e.g. Rezvanizaniani et al., 2009; Barabady and Kumar, 2008). However, in order to quantify the effect of operational condition, these methods are not suitable, and other methods such as the proportional hazard model (PHM) and the accelerator failure model must be used. In these methods, influence factors are considered as explanatory variable or covariates.

The main data source for the design of production facilities to be used in the Arctic is the OREDA database (2009). The OREDA project was started in the early 80s in a collaborative framework between the Norwegian Petroleum Directorate and the eight biggest companies on the Norwegian continental shelf (NCS). The experience, information and data from the NCS can be used for Arctic engineering design solutions for much of the equipment performance and failure data. However, these data cannot be used directly without adjustments for the Arctic climate conditions. When designing offshore installations to be used in the Arctic, the difference in operating conditions needs to be taken into consideration. Gao et al. (2007) discussed the application of the PHM, and Barabadi et al. (2010) developed a framework based on the accelerated failure time model to predict the R&M of the equipment in the Barents Sea based on the collected data from the North Sea and the Norwegian Sea under the OREDA project. However, the concepts of uncertainty have received less attention in these studies. Consequently, in such conditions when the component is subject to uncertainty, such obtained reliability cannot be assessed with certainty.

Figure 1 shows the process which must be carried out to obtain the R&M of equipment in the Arctic region (target area) based on the collected data in other areas such as the North Sea (reference area). As this figure shows, in the first stage in the reference area, the R&M and covariates' effect is formulated using appropriate statistical methods such as the accelerated failure time model or the PHM. In the next stage, based on the magnitude of covariates in the target area and the obtained reliability model in the reference area, the result will be extrapolated. In this process, three types of input data are needed; these include historical failure and repair data in the reference area, covariates in the target area, and covariates in the reference area.

During the process of collecting data, a lot of uncertainty can be associated with these data. Therefore, any single-value estimation of the R&M is not enough to represent the R&M performance, and another supplement to the point estimate, such as confidence interval, is necessary. It is also important to identify all potential sources of uncertainty in order to make a good prediction.

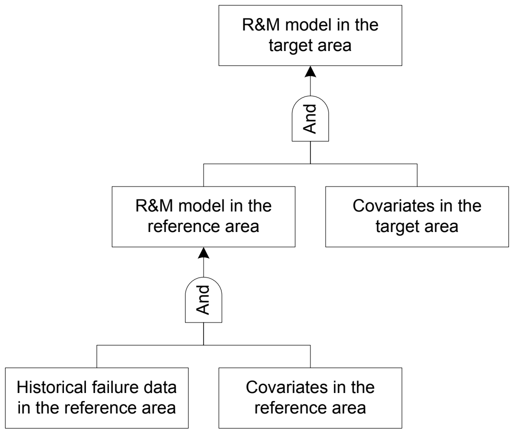

Figure 1. R&M assessment in the target area based on collected data in the reference area
(Barabadi et al., 2011a)

R&M uncertainty analysis under Arctic conditions using Monte Carlo simulation

Several approaches have been used to describe the uncertainty. The available methods for uncertainty analysis can be divided into two main groups: analytical (e.g. Bayesian uncertainty analysis, fuzzy logic, interval analysis, Laplace and Mellin transformations) and simulation methods such as Monte Carlo simulation (Barabadi et al., 2011a). The Monte Carlo simulation method is useful when modelling phenomena with significant uncertainties in the input. The statistical nature of the method relies on random sampling to compute results by the series of discrete random events generated by probability distributions (CSEP, 1995). In order to estimate maintenance cost and optimize the maintenance strategy in the Arctic region based on the available data and experience such as OREDA (OREDA, 2009), the potential sources of uncertainties include:

- Equipment characteristics such as reliability, maintainability and capacity, etc.
- Human reliability and performance
- Cost of repair activity and logistic support activity
- Spare part and logistic support strategy and delay

Figure 2 illustrates a general schematic for a Monte Carlo simulation that can be used to quantify such uncertainty. In this method, the first stage is building a model of the system based on the relationship between different equipment and components. In this stage, different models can be used such as reliability block diagram, reliability phase diagram, etc. The second step of a Monte Carlo simulation is identifying the item's characteristic such as mean time to repair (MTTR), mean time to failures (MTTF), the cost of repair activity which may include the price of spare parts, etc. The next step is identification of the probability distribution for each of these characteristics for the simulation model. This method is followed by a random trial process to provide the probability distribution of the number of failures (mission time/mean time to failure (MTTF)) and total down time during the mission (number of failures × MTTR). During each pass, a random value from the distribution function for each parameter is selected and entered into the calculation. The appropriate number of passes for an analysis is a function of the number of input parameters, the complexity of the model and the desired precision of the output. The final result of a Monte Carlo simulation is a probability distribution of the maintenance cost.

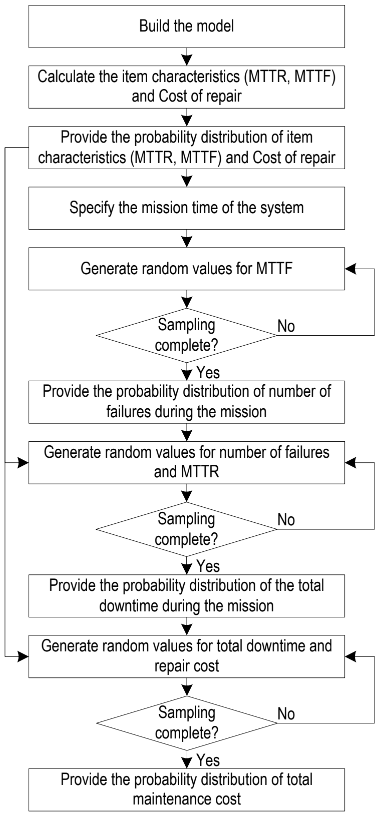

Figure 2. Schematic representation of methodology used to evaluate the uncertainty in maintenance cost

Case study

A centrifugal pump is a heavy rotating equipment and is used for a variety of applications, including the pumping of crude oil on offshore petroleum production facilities. Such a centrifugal crude pump has many serious failure modes that could be costly if not dealt with. In this case study we decided to evaluate the costs of following planned periodic preventive maintenance activities; 1) change of impeller wear ring; 2) replace pipe stack seals. Furthermore, we decided to demonstrate the Activity-Based Life Cycle Costing (AB-LCC) methodology (Emblemsvåg, 2003; Kayrbekova & Markeset, 2010) for calculation of maintenance cost for these two failure modes of the selected system in order to keep it simple and not overload a simple example with data. Overhead cost is excluded as well for the same purposes. The analyzed life cycle of the system is 15 years. The personnel need is one mechanical engineer. A system is installed outdoors and used in a normal environment. The spare part needs are provided in the bill of materials. A Bill of Activities (BOA) for predefined failure modes is given in Table 1. Moreover, Table 1 contains failure and repair data related to the selected system, such as MTTR and MTTF, as these factors might change under the influence of the main physical factors of the Arctic climate and might influence the life cycle cost of the system in the short and long term. The uncertainty in this data will be analyzed separately and will follow. The Bill of Material (BOM) is given in Table 2. The calculation results of the maintenance cost of the selected system using AB-LCC are given in Table 3.

Table 1. Activity based life-cycle cost analysis – Bill of Activities (BOA)

Activity level 1	Activity level 2	Competence	Labor cost (NOK/hr)	Resources consumed	MTTR (Hr)	MTTF (Years)
Maintain centrifugal crude pump	Change impeller wear ring	Mechanic	650	Impeller wear ring	76	7.5
	Replace pipe stack seal	Mechanic	650	Pipe stack seal	9.2	2

Table 2. Activity based life-cycle cost analysis – Bill of Material (BOM)

Bill of Material (BOM)	Units required	Cost per unit (NOK)	Total (NOK)
Impeller wear ring	4	40 000	160 000
Pipe stack seal	6	10 000	60 000

Table 3. Activity based life-cycle cost analysis – Maintenance cost calculation results

Activity level 1	Activity level 2	Compe-tence	Labor NOK/hr	Resources consumed	MTTR (Hr)	MTTF (Year)	Material NOK/time	Total NOK/15yr
Maintain centrifugal crude pump in normal climate	Change impeller wear ring	Mechanic	650	Impeller wear ring	76	7.5	160 000	418 800
	Replace pipe stack seal	Mechanic	650	Pipe stack seal	9.2	2	60 000	461 860

5.1. Pump R&M characteristics under Arctic conditions

The proportional hazard model (PHM) and its extensions (e.g. proportional repair model (PRM)) can be used for reliability and maintainability analysis (Gao et al., 2010b; Barabadi et al., 2011b). In these methods, the hazard rate/repair rate of a component is the product of a baseline hazard/repair rate and a functional term $\psi(z\beta)$ that describes how the hazard/repair rate changes as a function of operational environmental influence factors (e.g. temperature, wind, etc.). z is a row vector consisting of the covariates and β is a column vector consisting of the regression parameters. The baseline hazard/ repair rate represents the hazards/repair rate that an item will experience when all operational environment influence factors (covariates) are equal to zero. In PRM, the repair rate ($\mu(t,z)$) is described as follows (Gao et al., 2010b):

$$\mu(t,z) = \mu_0(t)\exp(z\beta) = \mu_0(t)\exp\left(\sum_{j=1}^{q}\beta_j z_j\right) \tag{1}$$

where $\mu_0(t)$ is the baseline hazard rate, $z_j, j=1, 2, ..., q$, are the covariates associated with the system and $\beta_j, j=1, 2, ..., q$, are the unknown parameters of the model, defining the effects of each of the q covariates. As mentioned above, the baseline repair rate is the repair rate under the standard conditions, $z=0$, and requires $\psi(z\beta)$=1, when there is no influence of covariates on the repair time. The maintainability function is given by (Gao et al., 2010b):

$$M(t,z) = 1 - \exp\left[-\int_0^t \mu(t',z)dt'\right] = 1 - (1 - M_0(t))^{\exp\left(\sum_{j=1}^{q}\beta_j z_j\right)} \tag{2}$$

where $M_0(t)$, is the baseline maintainability function expressed by:

$$M_0(t) = 1 - \exp\left[-\int_0^t \mu_0(t')dt'\right] \tag{3}$$

The baseline maintainability is assumed to be identical and equal to the actual maintainability when the covariates have no influence on the repair pattern. The covariates can increase or decrease the maintainability. For example, in the case of bad operating conditions (e.g. wind. icing, snow) the actual maintainability may be smaller than the baseline maintainability (Gao et al., 2010b).

The hazard rate, based on the PHM, can be obtained by (Cox, 1979):

$$h(t,z) = h_0(t)\exp(\beta z) = h_0(t)\exp\left(\sum_{j=1}^{q} \beta_j z_j\right) \tag{4}$$

where $h_0(t)$ is the baseline hazard rate, z_j, $j=1, 2, ..., q$, are the covariates associated with the system and β_j, $j=1, 2, ..., q$, are the unknown parameters of the model, defining the effects of each of the q covariates. PHM in the form of the reliability can be written as:

$$R(t,z) = [R_0(t)]^{\exp\left(\sum_{j=1}^{q} \beta_j z_j\right)} \tag{5}$$

where $R_0(t)$ is baseline reliability function expressed by:

$$R_0(t) = \exp\left[-\int_0^t h_0(x)dx\right] \tag{6}$$

Gao et al. (2010b) developed a case study in order to demonstrate how the PHM and PRM can be used in a practical case in order to assess the production performance in Arctic conditions. They calculated the repair rate and hazard rate of a gas production process offshore installation consisting of one separator, two turbo-compressors, one triathlon glycol and one gas export which are supposed to be working in the Goliat offshore oil & gas field. They used the failure rate and repair rate in OREDA (OREDA, 2009) as the base repair and hazard rate. The effect of the operational environment is modeled based on the collected historical data and influence factors that were collected in the Goliat offshore O&G field using the PRM and PHM (Tables 5 and 6). In order to calculate the effect of Arctic conditions on the pump characteristic, we used the data as the reference area that Gao et al. (2010b) used with the assumption that the operational environment is the same as in their case study.

Before any analysis using the PHM and PRM, the influence factor must be formulated. To ensure uniformity, the influence factor was formulated based on considering two alternatives: good/ desired (0) and bad/ undesired (1) conditions. The influence factors are presented in Table 4. The factors that may have significant effects on the maintainability and reliability of the equipment are included. For example, consider a repair activity on a failed item carried out during bad weather conditions such as heavy rain or snow. In order to formulate this condition, the CLCON(z_2), which represents the climatic condition, will be set equal to 1.

Table 4. Formulation of influence factors used in the case study for reliability and maintainability in reference area

		Values	
Characteristic	**Influence factors**	**1**	**0**
Reliability	PRCON (z_1): protection condition	Improper protection	Proper protection
	EQQU (z_2): equipment quality	Bad quality	Good quality
	CLCON (z_3): climatic condition	Bad weather	Good weather
	OPSK(z_4): operator skill	Unskilled operator	Expert operator
Maintainability	MADE(z_1): maintenance design	Bad design	Good design
	CLCON(z_2): climatic condition	Bad weather	Good weather
	MCSK(z_3): maintenance crew skill	Unprofessional crew	Expert crew

Tables 5 and 6 show the collected historical data. A cell in the censored column with zero value indicates that the compressor was stopped due to some reason other than the compressor itself, and a cell with value unity indicates compressor failure. For example, failure number 1 of the turbo-compressor occurred after 22345 hours. The operator skill, climatic condition and equipment quality were good during the operating time. Hence, the OPSK, CLCON and EQQU which represent operator skill, climatic condition and equipment quality will be set equal to 1. However, since the protection condition of this turbo-compressor was not good, the PRCON factor, which represents the protection condition, will be set equal to zero.

Table 5. Time between failures (TBF) data of the turbo-compressor in the reference area

TBF (h)	Censored	OPSK	PRCON	CLCON	EQQU
31840	1	0	0	0	0
22345	0	1	0	1	1
26730	1	0	1	1	1
26935	1	0	1	1	0
30750	1	1	0	0	1
25140	0	0	1	1	1

TBF (h)	Censored	OPSK	PRCON	CLCON	EQQU
25930	1	0	0	1	1
31830	1	0	1	0	0
33240	0	0	0	0	0
32230	1	1	0	0	0
32740	1	1	0	0	0
30140	1	1	1	0	0
27250	1	0	1	1	0
25230	0	1	1	1	0
26240	1	0	0	0	1

Table 6. Time to repairs (TTR) data of the turbo-compressor in the reference area

TTR (h)	Censored	MADE	MCSK	CLCON
98	1	0	0	0
152	0	0	1	0
220	1	0	0	1
145	1	0	1	0
183	1	1	0	0
302	0	1	1	1
220	1	1	0	0
112	1	0	1	0
95	1	0	0	0
213	1	1	1	1
285	1	1	0	1
201	1	0	1	0
251	1	0	0	1
165	0	0	0	1
98	1	0	0	0

To estimate the value of regression vector, with this assumption that the baseline repair rate and hazard rate follow an exponential distribution, the ALTA software is used (ReliaSoft, 2007). The influence factors that have a significant effect on the repair rate and hazard rate are identified and presented in Table 7. In this table, the confidence intervals of these parameters at 90% are shown as well.

Table 7. The influence factors that have a significant effect on the repair rate and hazard in the reference area

Characteristic	z_1				z_2			
	Lower	Mean	Upper	Var.	Lower	Mean	Upper	Var.
Maintainability	-1.3049	-0.2683	0.7683	0.397	-1.7612	-0.7246	0.3121	0.397
Reliability	-0.7748	0.0924	0.9596	0.2778	-0.7242	0.1589	1.042	0.2881

The result of analysis shows that two covariates, maintenance design (z_1) and climatic condition (z_2), on maintainability performance and two covariates, protection condition (z_1) and equipment quality (z_2), on reliability performance are significant at the 10% level. Based on this data, the hazard rate, $h_r(t,z)$, and repair rate, $\mu_r(t,z)$, in the reference area can be written as:

$$\mu_r(t,z) = \mu_{r0}(t)\exp(-0.2683z_1 - 0.7246z_2) \tag{7}$$

$$h(t,z)_r = h_{r0}(t)\exp(0.0924z_1 + 0.1589z_2) \tag{8}$$

Table 8 shows the target area condition and the value for influence factors. Taking into consideration these data and Equations No. 7 and No. 8, the repair rate, $\mu_t(t,z)$, and hazard rate, $h_t(t,z)$, of the pump in the target area can be written as:

$$\mu_t(t,z) = \mu_{t0}(t)\exp(-0.7246z_2) \tag{9}$$

$$h_t(t,z) = h_{t0}(t)\exp(0.0924z_1) \tag{10}$$

Table 8. Influence covariates in the target area and their value

Characteristic	Influence factors	Condition	Value
Reliability	PRCON: protection condition	Improper protection	1
	EQQU: equipment quality	Good quality	0
Maintainability	MADE: maintenance design	Good design	0
	CLCON: climatic condition	Bad weather	1

Uncertainty analysis of periodic maintenance

In this study, the MTTR and MTTF of different parts of a centrifuge pump in Table 1 can be considered as the baseline hazard rate $h_{t0}(t)$ and baseline repair rate $\mu_{t0}(t)$ in the target area. Therefore, considering Equations 9 and 10 and exponential distribution for maintainability and reliability, the MTTR and MTTF of items under Arctic conditions can be calculated as $MTTR = 1/\mu_t(t,z)$ and $MTTF = 1/h_t(t,z)$.

Moreover, to obtain the probability distribution of these characteristics, the variance of the regression parameters can be used. Barabadi et al. (2011a) used the Monte Carlo simulation to obtain the probability distribution of item characteristics; they assume that regression parameters follow a normal distribution, then, based on the mean and variance of regression parameters (see Table 7), a series of regression parameters is generated, and for each set of data the MTTR and MTTF are calculated. Then the best fit distribution for obtaining MTTR and MTTF can be obtained which represents the uncertainty on these parameters. Table 9 shows the results of such analysis for the current case study.

Table 9. The probability distribution of mean time to repair (MTTR) and mean time to failures (MTTF) for different items in target area

Activity level 1	**Activity level 2**	**Resources consumed**	**MTTF**		**MTTR**	
			Distribution	Parameters	Distribution	Parameters
Maintain centrifugal crude pump	Change impeller wear ring (4 off)	Impeller wear ring (4 off)	Lognormal	Mean=11; Std=0.319	Lognormal	Mean=5.06; Std= 0.65
	Replace pipe stack seal	Pipe stack seal	Lognormal	Mean=9.67; Std=0.316	Lognormal	Mean=2.76; Std= 0.628

Table 10 shows the mean of the MTTF and MTTR according to the obtained distribution in Table 9.

Table 10. The mean of the MTTF and MTTR according to the obtained distribution

Activity level 1	**Activity level 2**	**Resources consumed**	**Mean of MTTF**	**Mean of MTTR**
Maintain centrifugal crude pump	Change impeller wear ring (4off)	Impeller wear ring (4off)	63355	195.4
	Replace pipe stack seal	Pipe stack seal	16718	19.19

According to Figure 2, the next stage is calculating the probability distribution of the number of failures and total down time during the mission based on the MTTR and MTTF and their probability distribution during the mission. Here we consider that this pump is going to be used for 15 years. The result of the analysis is shown in Table 11.

Table 11. The probability distribution of the number of failures and total down time during the mission

Item	Number of failures		Total down time		Total up time	
	Distribution	Parameters	Distribution	Parameters	Distribution	Parameters
Impeller	Exponential-2P	Lambda=0.78; Gamma=1	Exponential-2P	Lambda=0.00302; Gamma=43.78	Normal	Mean=131025; Std=298
Seal	Weibull-2P	Beta=1.73; Eta=147.64	Weibull-3P	Beta = 2.14; Eta = 7.37; Gamma = 0.75	Normal	Mean=131256; Std=85

Table 12 shows the mean of the number of failures and total down time according to the distribution obtained in Table 11.

Table 12. The mean of the number of failures and total down time according to the obtained distribution

Activity level 1	Activity level 2	Resources consumed	Mean of Number of failures	Mean of Total downtime
Maintain centrifugal crude pump	Change impeller wear ring (4off)	Impeller wear ring (4off)	2.28	374
	Replace pipe stack seal	Pipe stack seal	7.28	131

Taking into consideration the total down time, number of failures and cost of maintenance activity in Table 1 and the spare part cost in Table 2, the total cost of correct maintenance and its probability distribution can be calculated. Table 13 shows the probability distribution of the total cost of pump components.

Table 13. The probability distribution of the total cost of pump components

Item	Cost (NOK)		Var.	
	Distribution	Parameters	Beta	Eta
Impeller	Weibull-2P	Beta=0.458;Eta=454435	1.93E-05	1.01 E+08
Seal	Weibull-2P	Beta=3.065;Eta=634030	0.0005	4.79 E+06

The analysis in this case study shows that the uncertainty associated with the cost of the repair can be expressed by a Weibull distribution with the parameters shown in Table 12. According to the obtained probability distribution (two parameters Weibull distribution) for the total cost of pump components, the mean cost of the repair can by calculated by:

$$\bar{T} = \eta \, \Gamma(\frac{1}{\beta} + 1) \tag{11}$$

where $\Gamma(n)$ is the gamma function. Table 14 shows the mean cost for each component. The analysis shows that the cost of changing the impeller wear ring is almost 2.6 times more costly under Arctic conditions compared to normal conditions. The cost of replacing the pipe stack seal is 1.23 times more costly.

Table 14. The mean of the cost of pump components

Activity level 1	Activity level 2	Cost (NOK)
Maintain centrifugal crude pump	Change impeller wear ring (4 off)	1 084 000
	Replace pipe stack seal	566 710

Conclusions

The result of the analysis shows that the Arctic conditions have a great influence on reliability and maintainability performance and on life cycle costs. Hence, these effects must be considered and quantified properly using appropriate statistical approaches. The suggested approach for predicting maintenance costs using activity-based life-cycle costing in combination with the PHM and PRM analysis for taking into account the influence of Arctic conditions will be of valuable for industrial companies developing maintenance strategies for the Arctic region. Furthermore, the Monte Carlo simulation seems to be an appropriate method for analyzing the uncertainty considering the complexity of the oil and gas facilities and the many different sources of uncertainty that can be associated with maintenance cost assessments under Arctic conditions. The methodology may also be adapted to other areas where there is lack of data, information and operational experience.

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