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A study of how asset management and condition based maintenance can improve utilization of assets involved in the O&G industry on the NCS

By

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Abstract

In the highly competitive and customer oriented oil and gas industry on the Norwegian Continental Shelf, organizations experience increasingly higher demands for efficiency and optimization of performance. The market conditions have in fact become so unforgiving that only minutes of downtime of equipment could result in substantial losses of income. Thus it can be understood that the ability to manage and operate complex offshore assets in such a way that they can deliver their functional services to the customer near 100% of the time throughout their lifecycle are fast becoming a necessity for today's organizations.

This thesis seek to find actionable solutions to what steps the actors may take in order to retain and maintain a competitive advantage in the complex industrial environment they are involved. The subject of asset management, and more explicitly the implementation of an asset management strategy to organizations, have been studied and identified as one important element that may serve as a facilitator towards obtaining this goal. The thesis presents some key factors that needs to be considered by organizations that want to implement such a strategy for managing their assets in new ways that can enable improved asset utilization.

With the rapid development and increasing availability of novel and advanced technological solutions with respect to information communications technology new possibilities for managing and operating complex offshore assets are presented. This development have accelerated throughout the last decade, and resulted in a paradigm shift, culminating with the introduction of integrated operations. The introduction of virtual organizations, where traditional organizational boundaries and limitations are erased also open up for new possibilities in relation to implementing novel technological solutions that can perform advanced diagnostics and prognostics for determining the expected lifetime of equipment. This thesis presents an introduction to the terms condition monitoring and condition based maintenance, and contextualize these towards the highly relevant technology of integrated operations.

A case study of the drilling contractor company COSL Drilling Europe is presented, with the goal of identifying improvement potentials related to their approach for managing the asset COSL Innovator. A review of the current implementation of condition monitoring of equipment, and especially the application of condition based maintenance have been performed, with the aim of detecting how an extended implementation of this strategy can improve the utilization of the asset in the future.

This thesis is aimed at providing useful insight towards how asset management practices and the application of novel technological solutions related to condition based maintenance can provide improved utilization of assets involved in the oil and gas industry on the Norwegian Continental Shelf.

Acknowledgements

The thesis you are now reading conclude my Masters of Science degree in Offshore Technology with specialization in Asset Management at the University of Stavanger.

The work and progression with my studies at the University of Stavanger culminating with the writing of this thesis have been both challenging and interesting, including periods with hard work and long hours. Even though the studies have been exigent I think that the work with the thesis has been a delightful journey which have provided me with heuristic insight in the topics studied.

The writing of this thesis had not been possible without the help from several friends, and I would like to take this opportunity to present my sincerest gratitude for their aid.

First and foremost I would like to thank my professor, academic supervisor and mentor Jayantha Prasanna Liyanage. Professor Liyanage has helped me obtain a higher degree of learning in many subjects by his high standards and extensive knowledge throughout his teaching in several of the courses during the studies. His insight and ideas, sharing of articles and other sources as well as knowledge and professional guidance during the progression with the thesis have served as important facilitators to progression with the work. We have had many fruitful discussions, and his always welcoming hospitality has enabled me to sort out challenges when they were met.

Secondly I would like to thank my colleagues at COSL Drilling Europe for always providing me help when this was needed. First I would like to thank my Technical Section Leader Gustav Nedrebø for helping me to become a better engineer by his sharing of knowledge and providing me with professional challenges during my work. Secondly I would like to thank the Rig Manager of COSL Innovator Joar Tjelmeland for admitting me the opportunity of performing a case study of the company and the rig. Writing this thesis would not have been possible without it. Lastly I would like to thank my company supervisor Adrian Rognerud for sharing his valuable time for providing me with comments and guidance through many discussions related to the performing of the case study.

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List of abbreviations

AHD –Active Heave Drawworks

BOP –Blow out preventer

CAPEX –Capital Expenditures

CBM –Condition Based Maintenance

CDE –COSL Drilling Europe

CM –Corrective Maintenance

CMMS –Computerized Maintenance Management System

CMS –Company Management System

CMS –Continuous Machinery Class

COSL –China Oilfield Services Limited

DMP –Dynamic Maintenance Planning

EPIM - Exploration & Production Information Asset Management Association

ETA –Event Tree Analysis

FTA –Fault tree analysis

GCE –Global Center of Excellence

GFMAM –Global Forum on Maintenance and Asset Management

HMI –Human-Machine Interface

HPU –High Pressure Unit

HSEQ –Health, safety, environment, quality

ICT –Information and communication technology

ILAP - Integrated Lifecycle Assets Planning

IO –Integrated Operations

LCC –Life Cycle Costs

LIR –Local instrument room

MEG –Maintenance Evaluation Group

MIMOSA -Machinery Information Management Open Standards Alliance

MTBF –Mean time between failures

MTTF –Mean time to failure

MTTR –Mean time to repair

NDT –Non-destructive testing

NODE - Norwegian Offshore & Drilling Engineering

NOV –National Oilwell Varco

O&G Industry –Oil and Gas industry

OEM –Original Equipment Manufacturer

OLF –Oljeindustriens Landsforening

OPEX –Operational Expenditures

OSA-CBM –Open System Architecture for Condition-Based Maintenance

PHM –Prognostics and health management

PM –Preventive Maintenance

PSA –Petroleum Safety Authority

RCM –Reliability Centered Maintenance

ROP –Rate of penetration

SAMP - Strategic Asset Management Plan

SDI –Smart Drilling Instrumentation

SOTS –Stavanger Offshore Tekniske Skole

STAR IPS –Star Information and Planning System

UiS –University of Stavanger

UPS –Uninterrupted power supply

WO –Work Order

WOCS –Workover Control System

XMT –X-mas tree

Part 1: Background and objectives

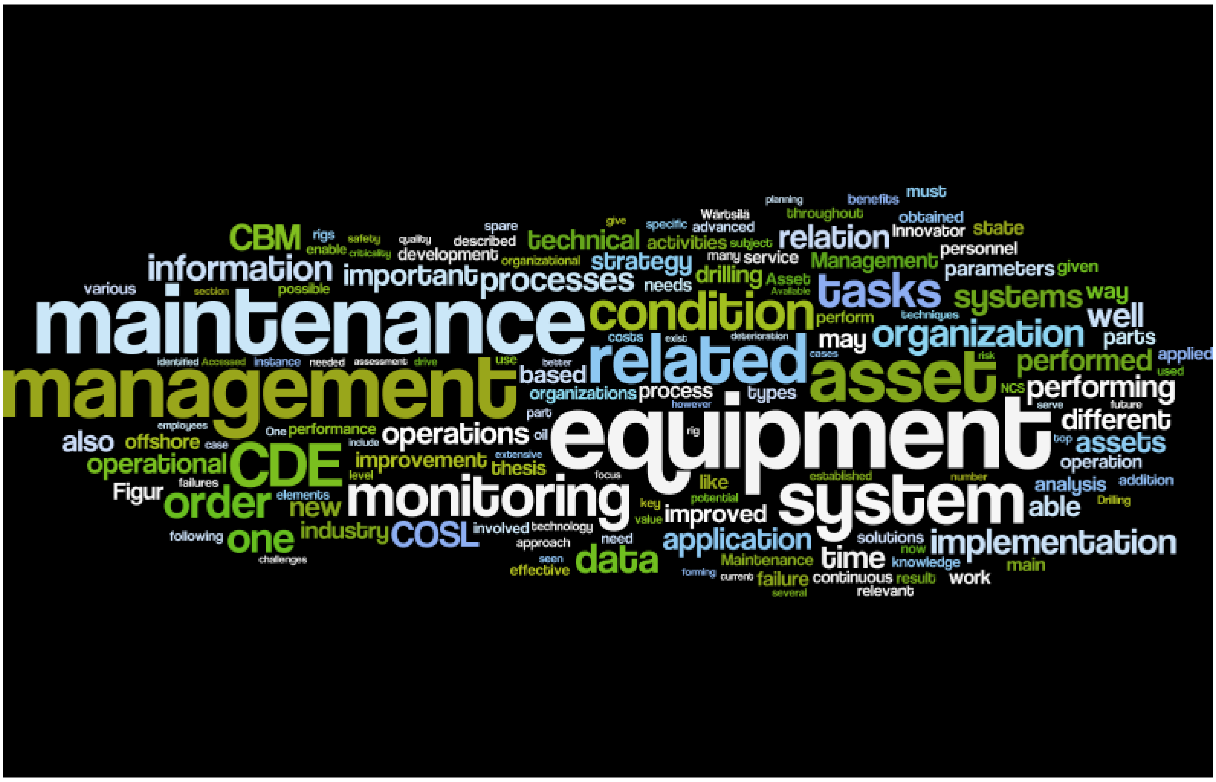


Figure 1 Word cloud generation of the most commonly used words in the thesis (Wordle, 2015)

1.1 Background

Due to the ever increasing complexity of operations being performed in the O&G industry on the NCS today, which involve a series of complex interactions between different stakeholders, new needs in relation to identifying how these operations can be performed more efficiently have developed. The need for improved efficiency in all parts of the industry have become more pressing during the last year, as one experience rising costs related to the extraction of natural reserves from the NCS, while at the same time the offering prices of these reserves have been substantially reduced. This recent development have imposed the involved actors to be more open minded towards new possibilities given by various efficiency measures.

One such possibility that present itself in this relation is the implementation of an asset management system to organizations. This involve new thinking in relation to how organizations are structured, as well as to how they organize and perform their activities. There seems to be a developing trend throughout the industry where organizations seek to go from their traditional performing of tasks, into a more process oriented way of thinking, where a holistic approach is taken in order to enable the implementation of new ideas which can give the benefits of improved value making in processes and improved asset utilization. While the actors involved in the O&G industry on the NCS seems to have recognized the need for implementing new measures to how they perform their activities, many seem to lack a holistic strategy for how they are going to make this happen.

As a result of this the author of this thesis have chosen to look into the subject of asset management, as implementing this way of thinking in organizations can serve as an important enabler towards improved asset utilization by introducing integrated measures throughout the organizations. Such measures can take many forms, but the improved sharing of data and information between different departments and across disciplines in the organizations can enable substantially improved decision-making processes. In addition to this improved collaboration with key stakeholders can serve as an important facilitator towards achieving operational excellence.

With the substantial technological development throughout the last decades new opportunities in relation to continuous monitoring of the technical state of equipment, as well as the ability of storing and transferring large amounts of data independent of physical locations, presents themselves to equipment owners. The availability of novel technical solutions, as well as significantly reduced costs related to proven technological solutions, have fueled the rapid growing application of the condition based maintenance (CBM) concept throughout the world's industries. Its popularity and wide application now spreads from the aviation industry to the subsea sector. This development may be seen as a result of increased demands in relation to availability, maintainability, safety and reliability. In addition to this there is now an increased demand for reduced operation and maintenance costs of assets.

Current maintenance practices often relate to proactive measures in the form of preventive maintenance (PM) or reactive measures like corrective maintenance (CM), where both approaches are wasteful and result in unnecessary loss of production time. Even though equipment failures often appear to occur without any notice in advance for the human being, the fact is that most equipment types go through a measurable degradation process before they fail. The application of condition monitoring for detecting such deterioration processes can serve as an important aid for avoiding unnecessary maintenance tasks, and render equipment owners the possibility to intervene with emerging challenges in a timely manner. Novel technological solutions that are capable of performing advanced diagnostics and prognostics of equipment are now being introduced to the markets. Even though the implementation of such technology not can be seen as a panacea to all maintenance solutions, it may revolutionize the way that operation and maintenance of assets are being performed today. This development must be seen in relation to the recently introduced integrated operations strategy, where assets are being managed and operated from remote locations. Several of the actors involved with the O&G activities on the NCS have already implemented this concept for operating complex offshore assets, while others are considering doing the same.

It seems clear that in order to retain a top position in the industry and to obtain competitive advantages in the marked the actors need to keep a strong focus on these developing trends, and investigate which processes they need to initiate in order to implement them into their own organizations.

1.2 Problem definition

Based on the above the author have chosen to study the subject of asset management, with the aim of identifying whether this new way of thinking can serve as a facilitator for improved value making for the actors involved in the O&G industry on the NCS. It is a goal to also identify how this can be achieved. In other words, being able to identify which processes can be initiated to obtain improved value making processes for the actors involved with the O&G industry on the NCS.

A study of existing and novel technological solutions for condition monitoring of equipment have been performed, with the aim of identifying whether an extended use of such technology can be applied for the implementation of CBM strategies. Whether such strategies can improve the utilization of assets involved in the O&G activities on the NCS is sought answered.

In order to be able to find relevant answers to these questions a study of the drilling contractor company COSL Drilling Europe (CDE) have been performed. The aim of this study was to identify how one of the actors involved in the O&G activities on the NCS have chosen to approach the subject of asset management, as well as to identify how they utilize condition monitoring and CBM for operating their asset COSL Innovator. By comparing this state of the art with the presented possibilities related to improved asset management and extended use of CBM the answers of how improvements can be made in the organization have been sought answered.

1.3 Scope of work and objectives

This thesis aims to present an insight on the history and development of the aspect of asset management into what it have become today. It seeks to present some key benefits that can be obtained by implementing the elements of an asset management strategy in organizations, and further the benefits that can be obtained by performing good asset management practices.

A conceptual model for the implementation of such asset management to organizations will be introduced and discussed, with the aim of presenting some actionable steps that can form the way to obtain optimal utilization of assets throughout a life-cycle perspective.

A study of emerging trends related to current asset management practices in the O&G industry on the NCS will be performed, with the objective of identifying some key factors that hinder the effective performing of operations, and further which initiatives the industry have taken to overcome these challenges.

The concept of applying various condition monitoring techniques in order to establish a CBM strategy for equipment will be explained to form a basis for the further studies in the thesis. The advantages and disadvantages with such a strategy will be clarified in order to enlighten some important issues that needs to be taken into consideration before a process of implementing such a strategy should be initiated. A contextualization of CBM in relation to integrated operations (IO) will be provided, in order to identify new possibilities related to remote control and operation of equipment. Some developing trends in relation to novel technical solutions for implementing advanced diagnostics and prognostics of equipment, which provide the opportunity of substantially improved operation and maintenance of equipment, will be introduced. The objective of this is to provide an overall perspective on how such novel technological solutions can be applied for increase value making processes in organizations.

A major part of the scope with this thesis is the performing of a thorough case study of the drilling contractor company CDE, and furthermore a detailed study of one of their assets; the semi-submersible drilling rig (SSDR) COSL Innovator. The objectives related to the performing of these studies are many. Firstly the organizational study of CDE is performed with the objective of describing how this organization have chosen to structure itself in order to manage its assets in the best possible way. A key part of this study is describing the maintenance management strategy, and how they have developed their maintenance program for the equipment of which their assets comprise. The study of the asset COSL Innovator is performed with the objective of identifying which condition monitoring techniques they have applied in the asset, as well as identifying equipment types where they have implemented a CBM strategy in order to enable improved asset utilization. A detailed description of how the implementation of a CBM strategy have helped them to obtain improved safety and operability in combination with reduced operational and maintenance costs is provided, with the objective of revealing the substantial benefits that can be achieved by implementing such a strategy.

Another objective enabled by the detailed study of CDE and COSL Innovator is the identification of areas where improvement measures can be taken in order to achieve improved utilization of their assets. A discussion of improvement potentials in relation to the three aspects of improved asset management practices, current and future application of condition monitoring techniques and the identification of equipment types where CBM strategies can be implemented is provided. The objective of this discussion is to present current issues that the organization is experiencing, and to provide constructive and actionable solutions for overcoming these identified challenges, so that the organization can achieve improved value making throughout their organization.

The last scope of this thesis is to perform and evaluation of the work that has been done. The objectives in this respect are to identify the main findings, the areas where learning was obtained and further a discussion of the challenges that were met during the progression with the work. Subsequently a short conclusion will be provided, with the objective of summing up the work in an informative manner. Finally some recommendations for further studies related to the topic of this thesis will be presented, in order to provide others that find the subject of the thesis interesting with some topics that can be further looked into.

1.4 Delimitations

The scope of this thesis is not to present any scientific research results per se, but it will present a holistic perspective in relation to the optimal management of assets enabled by the implementation of CBM strategies for equipment where this is found to be a feasible solution. As a result of this only some selected different techniques in relation to asset management and condition monitoring will be discussed in detail. Due to organizational policies and confidentiality reasons little quantitative data will be presented. This include the removing of some specific numbers from graphical illustrations when needed. The thesis focus on overall qualitative analysis in relation to asset management and condition monitoring, and its application in the O&G industry on the NCS.

A number of advanced condition monitoring techniques are applied by third party personnel in order to enable the performing of complex drilling operations. As drilling performance related condition monitoring techniques are not related to the technical operations of the rig they have only been given a brief explanation in the thesis.

As the scope of this thesis focus on the CBM strategy other maintenance strategies have not been given an equally detailed description in the thesis, even though they may prove to be more suitable in some cases.

The case study have been limited to the company CDE and their asset COSL Innovator. CDE have several other assets in their portfolio, and other areas for improvement may be identified by performing case studies of these. Even though other organizations involved in the O&G industry on the NCS may experience other challenges, it is anticipated that the study of CDE will bring forth issues that can also be representative for other organizations.

1.5 Methodology

The work with this thesis is based on a review of relevant academic literature on the subjects discussed, namely published books, articles, surveys, international standards and various publications. In addition to this company specific documents obtained from CDE have been obtained and studied in relation to part 3 of the thesis. Relevant lecture notes and presentations given by the lecturers at the University of Stavanger (UiS) throughout the education leading up to this master’s degree thesis serve as an academic basis for many of the considerations presented herein. Discussions with the thesis supervisor have been used for evaluation of the work during its progression, and to enlighten possibilities for studies related to the included topics. Lastly a series of conversations and interviews with leading technical personnel from CDE have been used as an aid in order to be able to present the discussion and considerations in section 5.

1.6 Structure of the thesis

The thesis have been divided into four main parts. This way of organizing the work seems suitable, as the two main parts of the scope are related to presenting the state of the art of subjects and a case study of CDE. The four main parts have been divided into 9 sections comprising of several chapters, which again are divided into subsections where this has been seen fit. The subsections are excluded from the table of content in order to make the thesis more user-friendly.

Part one consist of the sections related to the outlining of the background and a plan and objective for the work with the thesis.

Part two comprise of sections 2 and 3, describing state of the art practices related to asset management and condition monitoring and CBM, respectively.

Part three comprising of sections 4 and 5, is dedicated to the case study of CDE, and the following discussion of improvement potentials, respectively.

Part 4 first present a discussion of the thesis in section 6. In this section some thoughts related to whether the objectives of the scope of work was met during the work, findings, learning areas and finally a discussion of challenges encountered during the work is presented. This section is followed by a short conclusion in section 7 which is meant to sum up the work of thesis in a comprehensive way. Subsequently some recommendations for further studies are presented in section 8. Finally the bibliography is presented in section 9.

Part 2: State of the art

Figure 2 The offshore asset COSL Pioneer performing drilling operations on the NCS (COSL Drilling Europe, 2013)

2. Asset management

Introduction

This part of the thesis presents an introduction to the development of the term asset management and how this has evolved throughout the ages into what the term is defined as today. It contextualizes why the term asset management has regained its popularity and position in todays' competitive O&G industry by highlighting some of the key benefits it can provide to organizations. Based on relevant theory obtained from various sources a summary of the "state of the art" theory regarding the development of an asset management system for the optimal utilization of assets throughout a lifecycle perspective will be provided.

A conceptual model for asset management will be introduced, in order to highlight the subject areas that are related to asset management. Some of the subject areas included in this model are given a detailed description.

In section 2.6 a presentation of current asset management practices in the O&G industry on the NCS is given, with the focus on identifying specific challenges the industry now face, and what actions they have initiated in order to overcome them.

The history and development of the term asset and asset management

The meaning and understanding of the terms *asset* and *asset management* have varied largely throughout the ages. In the earlier times the terms were mainly related to being able to manage accounting and the comparison of capital investments like funds, stocks and diversified portfolios and from this being able to optimize the yield, i.e. the optimization of costs and returns (Christopher, 1993). The financial services further used the terms in relation to being able to identify and manage risk exposure of assets in particular economical markets (Liyanage, 2012). The shortcomings of this traditional approach to asset management is explained by (Maskell, 1991), as he highlight that it has a reactive focus on monitoring the wrong parameters, in a wrong way. The development of the terms from this contextual meaning to todays' definitions and meaning is multifaceted, and several different drivers have led to this. (The Institute of Asset Management, 2014) identify two main drivers towards the development of modern industrial asset management in addition to financial services, namely the extensive troubles related to management in the public sector in Australia and New Zealand and the Piper Alpha accident in the North Sea. The former is related to the need for major improvements in management due to falling levels of quality and performance combined with escalating costs and poor planning throughout the public sectors of the named countries. The latter example relate to the forming of small and dynamic cross-disciplinary teams managing offshore assets with a whole-life management perspective in order to prevent big disasters and optimize results in relation to improved safety, performance and productivity.

In more general terms one can say that as the industrial age has developed, new elements such as focus on productivity, quality and focus on the customer and other relevant stakeholders have emerged. These aspects have been given an increasingly stronger focus during the last decades (Maskell, 1991). This can be exemplified by the introduction of management tools such as the balanced scorecard (Kaplan and Norton, 1996), the introduction of the Total Quality Management model (Christopher, 1993, Bank, 1992), the EFQM Excellence model (Fisher, 2012), as well as many others. The business performance revolution enabling organizations to achieve world class manufacturing must also be seen in relation to the new possibilities related to administering and processing large amounts of data generated by different processes in the organizations. This opportunity has been given by the introduction of revolutionary technology for managing data in new ways (Frankel, 2008). This data can be applied as a tool for improved decisions engineering and performance management, as described by Armstrong in his "Handbook of Performance Management" (Armstrong, 2009).

The renaissance of the term asset management

Whereas asset management in earlier times was a reactive way of managing the business merely looking at sales numbers and profits, its focus in todays' rapid changing working environment have developed in the direction of serving as an aid to organizations for the improved adaption to changes in the market situation and in foreseeing and acting proactively to emerging challenges. These are important aspects for organizations in order for them to develop their businesses and open up for new markets and customer needs. One key element that define the winning companies in todays' globalized and highly competitive environment is the ability to manage change processes in effective manners, while at the same time keeping a strong focus on innovation and being open to new ideas and technology (Liyanage, 2012). This can be exemplified by the large degree of innovation and implementation of new and advanced technology in the offshore drilling sector during the last decade. One specific example is the advanced and complex extended reach drilling operations that now enable drilling of wells with lengths up to 13km, which was an impossible feat just ten years ago (Ghiselin, 2012, McDermott et al.). The degree of innovation and implementation of new technology is naturally dependent on the business sector one is involved in, but in general terms one can advocate that there has been an aggressive growth in application of new technologies during recent years throughout all industrial sectors, and that the number of organizations that now implement novel technical solutions has proliferated.

Being able to manage risk in relation to both novel technical solutions as well as operational risk involved with implementing new assets in organizations have now become a main focus and challenge, and the ever growing interdependencies between different departments and sectors in the organizations calls for integrated management solutions where the organizational boundaries are erased. The forming of alliances with relevant stakeholders such as original equipment manufacturers (OEM), service providers, clients and authorities calls for a broader perspective than what exist today when it comes to managing assets in the best possible way. These developments have led to an increasing focus on the subject of asset management during recent years, and this has now culminated in the forming of the new Standard ISO55000: Asset Management –Overview, principles and terminology (Standard Norge, 2014). In section "0.3 Target audience" it is stated that "This International Standard is primarily intended for use by:

- Those considering how to improve the realization of value for their organization from their asset base
- Those involved in the establishment, implementation, maintenance and improvement of an asset management system
- Those involved in the planning, design, implementation and review of asset management activities; along with service providers."

The relevance and impact of this new standard can further be illustrated by the following examples: Several main actors in the European O&G industry have already adopted this standard, while other high-impact companies like for instance Statoil are performing studies related to whether they should do so as well. The Norwegian Petroleum Safety Authority (PSA) is also looking into this new standard with great interest.

Other key players involved in the work of promoting and developing Asset Management are the Institute of Asset Management, which is a non-profit organization that "exist to advance the science, practice and discipline of Asset Management for the public benefit" (The Institute of Asset Management, 2014), and The Asset Management Council, which is formed by the Technical Society of Engineers, Australia. It is a national non-profit organization whose vision is "enabling benefits for all from effective use of assets", and they "provide independent information and guidance on asset management across the multitude of industry sectors and professional roles in asset management, both in Australia and globally" (Asset Management Council Ltd, 2014). Lastly there is also reason to highlight The Global Forum on Maintenance and Asset Management (GFMAM), which "has been established with the aim of sharing collaboratively advancements, knowledge and standards in maintenance and asset management (Global Forum on Maintenance and Asset Management, 2014).

As it is the employees of the organizations that actually "do" the asset management by their performing of day-to-day activities in the organizations the results of the asset management practices will vary dependently on the knowledge, willingness, competence and teamwork effort they contribute with towards reaching excellence in asset management. Experience shows that there often is a big difference between having a great plan for optimal management of assets, and the way things end up being performed when the plan is set to motion. While a good plan and framework for effective asset management can serve as a facilitator, one is dependent of strong leadership as well as extensive collaboration efforts across departments and disciplines of the organization in order to actually achieve it.

The definition of an asset

There exist numerous definitions and approaches to the word asset throughout the available literature on the subject. (Standard Norge, 2014) however define an asset as an "item, thing or entity that has potential or actual value to an organization". This definition is then followed by explanatory text regarding the terms value and asset. Value can take form of financial or non-financial nature and it can be tangible or intangible. It is also important to be aware of the fact that the value of an asset can change, and take both negative and positive form throughout its life-cycle.

The definition of asset management

(Standard Norge, 2014) define Asset Management as "the coordinated activity of an organization to realize value from assets". This definition is followed by explanatory text regarding the word activity and the term realization of value. Activity can take many forms, both tangible and intangible. Examples of activities in relation to realizing value from assets can be different sets of approaches, planning and implementation of plans. When it comes to generating and harvesting value as a result of improved asset management this often involve the balancing opportunities and risk as well as cost and performance.

The relation between an asset management system and asset management

An organization needs a system for coordinating, controlling and performing their asset management related activities. (Standard Norge, 2014) state that "an asset management system is a set of interrelated and interacting elements of an organization, whose function is to establish the asset management policy and asset management objectives, and the processes, needed to achieve those objectives. In this context, the elements of the asset management system should be viewed as a set of tools, including policies, plans, business processes and information systems, which are integrated to give assurance that the asset management activities will be delivered”. In other words one can say that a system for asset management is an overall structure defined and implemented in order to achieve an effective and efficient management of assets through a set of controlled processes. It is important that one do not misunderstand the nature of an asset management system as limited to an electronic information management system, i.e. a software system that manages asset information, procurements, work planning and control, inventory management and so on. The asset management system may contain these things, but it should not be limited to it alone as the asset management system should also include ways of harmonizing contributions and connections from different functional assets within the asset management system. In many cases the different assets within the asset management system can and will affect each other, and they can also affect different functional units through a set of different ways. From this it can be seen that in order to achieve optimal asset management by combining the attributes of all assets in an organization, a holistic approach to the management of all these assets incorporating the strategy of asset portfolio management, must be taken.

Figure 3 below is gathered from the document “Asset Management –an anatomy” and illustrates the relation between the different terms related to asset management.

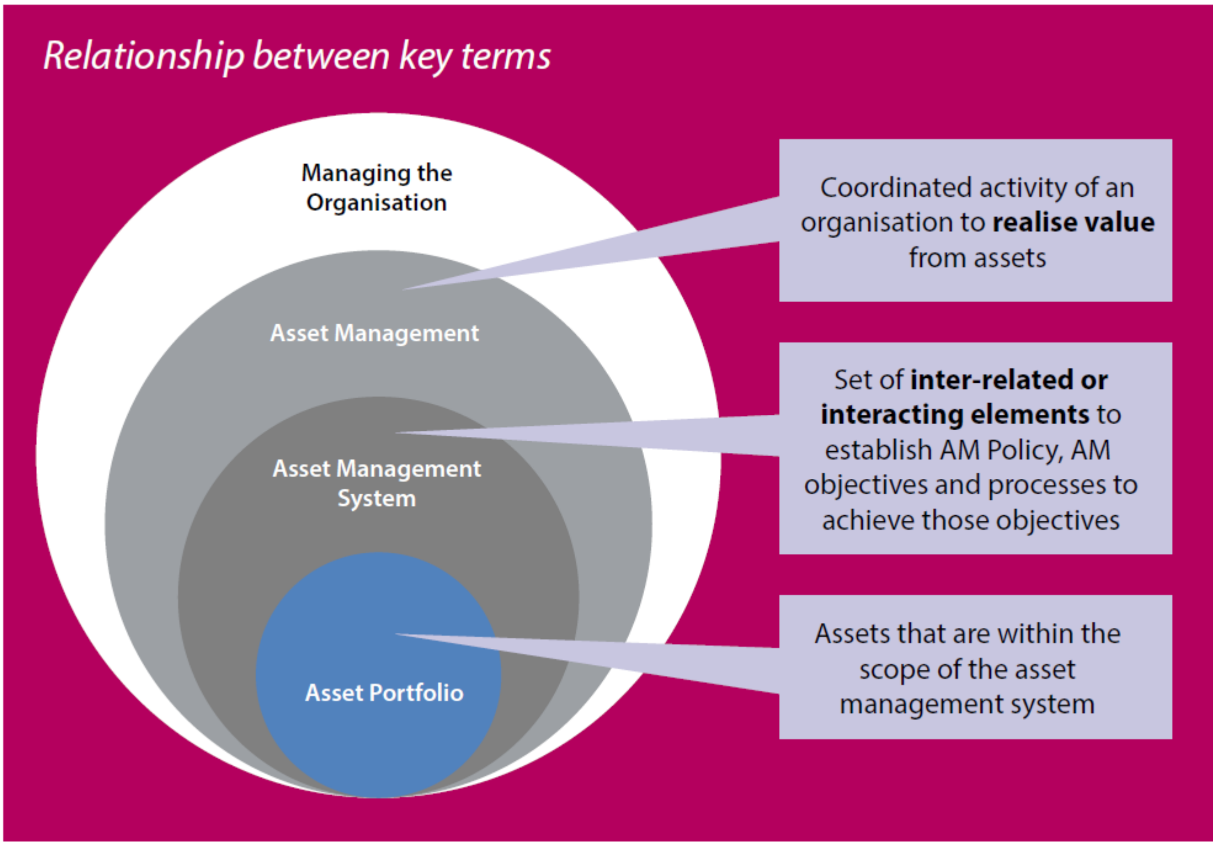


Figure 3 The relationship between key terms related to asset management (The Institute of Asset Management, 2014)

2.1 The key elements of an asset management system

The implementation of an asset management system will affect the entire organization, including the relation to all relevant stakeholders. In relation to systems engineering (Parnell et al., 2011) refers to Freemans definition of stakeholders as "any group of individuals who can affect or is affected by the achievement of the organization's objectives". In today's highly competitive industry the importance of stakeholders like customers, employees, business partners and the authorities have been substantially increased in relation to the more traditional stakeholders like managers and owners of the organizations. The implementation of an asset management system will lead to an integration of most of the organizational activities, which would otherwise have been segregated in departments and sections. In this way the organization can be managed in a more effective and efficient manner as a result of its holistic approach (Standard Norge, 2014). One can say that the organization goes from a traditional structuring comprising of different departments and sections which can be seen as functional silos, into a more process-oriented way of thinking where traditional organizational boundaries have been mitigated (Liyanage, 2012). The implementation of such a management system calls for a thorough understanding of how it will affect the organization, and good plans for the implementation must be established before the implementation process is initiated. ISO55000 have established 7 requirements in order to enable this needed planning (Standard Norge, 2014). Figure 4 below is gathered from this standard, and illustrate the relationship between the key elements of such an asset management system.

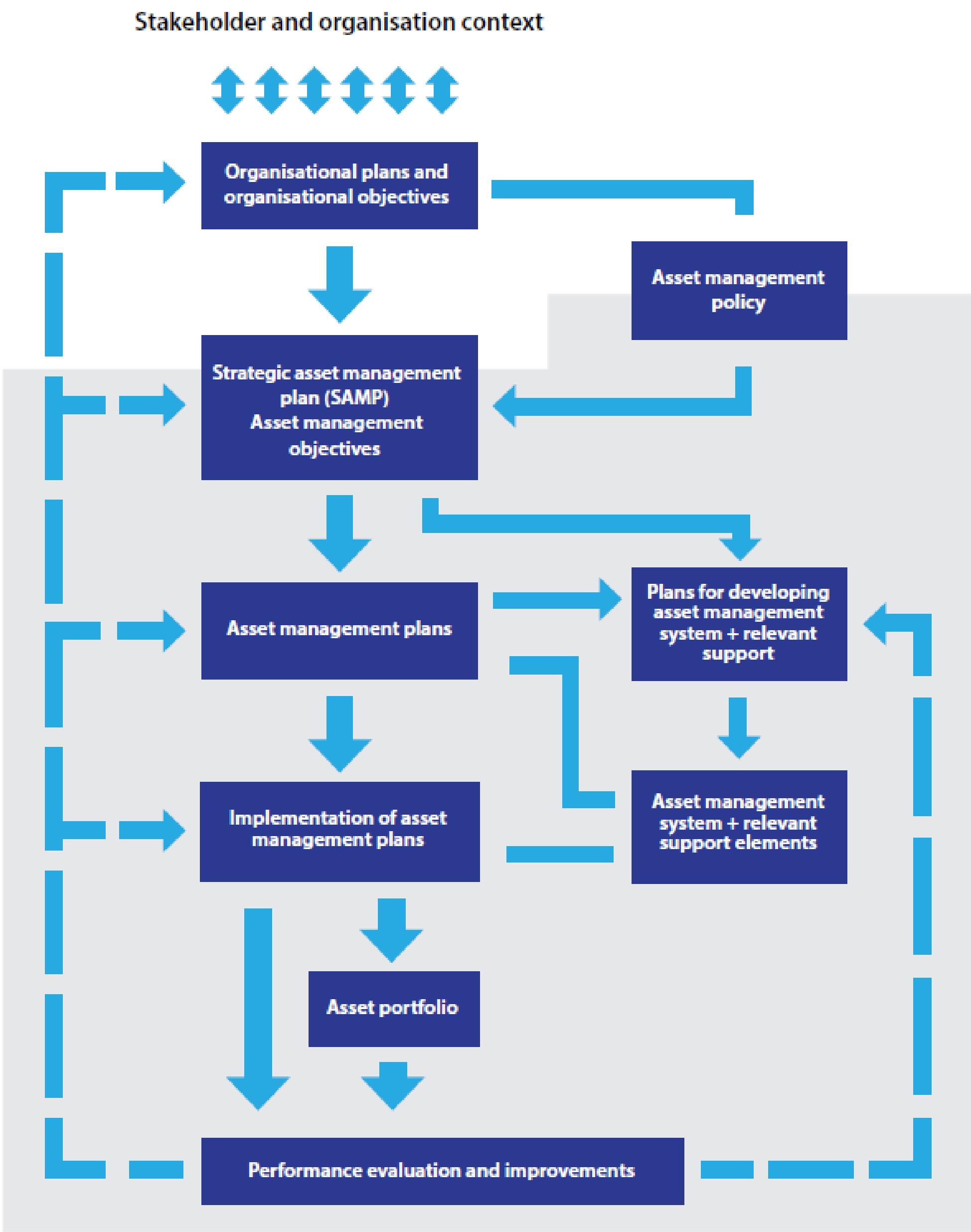


Figure 4 The relationship between key elements of an asset management system (Standard Norge, 2014)

Context of the organization

The starting point when an organization is going to implement an asset management system is to identify the internal and external context of the organization. The internal context can be exemplified by the organizational core values, goals and vision. It is important to be aware of the fact that the culture in the organization will affect this internal context. The external context of the organization is affected by its owners, customers and the business environment in which it is meant to be involved. Regulatory demands and financial structures, as well as social and environmental contexts must also be taken into consideration. The expectations and needs of the stakeholders will form the basis for the organizational aims and implicitly its asset management system.

Leadership

The top management of the organization is responsible for developing an overall strategy for the asset management system, and are further responsible for making sure that its objectives are in line with the aims and goals of the organization. Responsibilities regarding the progress of different work tasks should be made clear, in order to enable follow up and reporting on the development of the process. Leaders on all levels of the organization are responsible for developing and implementing plans that are in accordance with this strategy. It is important that the required competence and resources needed to implement the asset management system is in place in order to enable its effective and efficient implementation. It is further important that leaders on all levels embrace and promote the implementation of the system, and act swiftly upon any problems that should emerge in relation to the implementation of the system. An example of emerging problems can be conflicts related to the new asset management system in opposition to existing tools and systems for management. This is in fact highlighted as the one factor which prevents the implementation of new digital measures in organizations involved in the O&G industry the most (Accenture and Microsoft, 2015). It is lastly important that leaders on all levels clearly communicate the goals and benefits of the asset management system to all employees, customers, service providers and others so that a common understanding of the means and goals is established, enabling a successful implementation. At the same time it is important to be able to receive and adapt to feedback given from the affected stakeholders, so that the system can be improved or adjusted to best fit the organizational needs.

Planning

The overall goals and aims of the organization lay the foundation for its activities, including its asset management activities. These goals and aims are generated by the organizations strategic level planning activities, and the principles for how the organization is meant to achieve its goals should be clearly documented in the strategic asset management policy. The plan for how the organization is to implement these measures should be documented in the strategic asset management plan (SAMP). The forming of a well-functioning SAMP is of high importance, as it lays the foundation for the asset management activities that are to take place in the organization. More explicitly, the SAMP should be used as a guide when it comes to the forming of asset management plans. These plans should include the specific asset management actions that is to be performed for each asset, and the result and impact of these actions should be of a measurable type, so that one can make use of experience in order to improve and alter plans and actions for future development. In this way the experiences can be utilized in order to ensure that the development of each asset is in accordance with the overall organizational goals and aims. As one are able to quantify how well the development is going according to the preset plans and expectations, one is better able to increase efficiency and effectiveness by decisions engineering and performance management. Asset reports in relation to performance and development can also be exploited to generate a better understanding of the financial situation in the organization. It may also improve planning of forthcoming investments and emerging problems or possibilities.

Support

The forming of and development, as well as the continuous improvement of, the asset management system require a collaborative effort by personnel from different departments and disciplines of the organization. The asset management system will in many cases gather large amounts of data from different types of operations and interactions from both within and without the organization. This can be seen in relation to recent developments where the application of what is called" Big Data" and "The Internet of Things" have been rapidly evolving as a tool to add real value to organizations (Tieto, 2015, Marr, 2015). The process of transforming this data into useful information so that one is able to form correct decisions in an effective manner will in many cases require substantial resources. These resources, as well as all the other resources involved in the asset management system as a whole, must be coordinated and managed. The requirement for competence amongst the contributors should be clearly defined in order to ensure the desired quality and results of the processes being performed. The competence of the involved personnel must also be maintained and developed according to the defined requirements in order to be able to implement, maintain and continuously improve the asset management system.

Operation

The goal for the organization's asset management system is that it functions as an aid in controlling, planning and directing the asset management activities of the organization. In order to enable this it is important that the operational demands of each asset is included in the asset management system. This can for instance be the implementation of technical standards, statutory demands and functional policies and so on. The operational context or even the nature of assets may change during their life cycles. This may call for alterations to the asset management plans, which again should be reflected by the implementation of these altered plans in the asset management system. In this context it is important to be aware of new risks, as well as new possibilities that emerge. A clear plan for management of change must be present, and this should include a way of handling these risks and possibilities. Such issues can for instance be addressed by performing risk assessment in relation to the new plans.

Lastly it is important to be aware of the fact that all asset management activities should be included in the asset management system, also the ones that are not performed by the organization itself. In many cases certain operational functions of assets may be outsourced, or third party personnel may be the ones that are responsible for performing the specific asset management activity. Also these should be included in the control of the asset management system. It is important to be aware of the increased level of complexity that outsourcing of asset management activities gives to the organization, especially when it comes to defining responsibilities.

Performance evaluation

Performance evaluation and management is both equally important as it is complex. All organizational activities should be subject to performance evaluation, going from evaluation of individual asset performance to how well the management of the assets is performed. Also the performance of the asset management system itself should be subject to evaluation. The evaluation processes should be performed continuously, but can also be planned and executed with given intervals. One important requirement for a successful performance evaluation program is the identification of relevant drivers subject to monitoring and evaluation for the different assets and processes (Maskell, 1991). The gathering of data, and transformation of this data into meaningful information is a key to effective performance measurement and assessment. One should seek to identify which drivers enabled the reaching of the predetermined goals, or alternatively which drives led to not reaching the set goals, so that actions can be taken to improve results in relation to the predetermined goals. It is further important to be able to understand that faulty input to the decision-making processes may also be the reason for not achieving the desired asset management performance. If this is the case one must be prepared to revise operational plans and decision-making processes in order to utilize the assets in better ways. Lastly the performance evaluation may prove that the predetermined goals are not adequately proportioned in relation to the achievable performance of the asset, as it may either underperform or over perform in relation to them over time. If this is the case the set goals in the asset management system should be considered revised.

Improvement

In todays' complex and rapid changing industrial environment it is obvious that changes in the operational context will in many cases lead to the need for development and change of the asset management system. In addition to this changes to the asset portfolio as a result of procurement and implementation of new assets, or the removal of other assets calls for revision and improvement to the asset management system. All changes and improvements must be made subject to risk assessment and control prior to implementation, in order to prevent unwanted effects like the potential or actual occurrence of nonconformities. The continuous improvement approach is applicable to all levels and processes in the organization, spreading from the assets, through the asset management processes as well as to the asset management system level. As aforementioned performance evaluation processes may identify opportunities or threats to improvement, and the findings can be utilized in order to optimize performance by improving the existing systems. Management reviews and audits by external parties such as hired consultants or audits performed by the authorities should be used as aids to improve and further develop the existing systems. In such processes it is important to ensure that the implemented changes are in line with the overall organizational goals and aims, so that they prove beneficial and appropriate when employed. Should there occur incidents or emergency situations in relation to specific assets in the organization, it is important to consider the possibility that inadequate procedures or flaws to the asset management system may have been underlying causes that needs to be addressed. Should this prove to be the case it is important to perform investigations and reviews, which may lead to the implementation of relevant changes to the existing systems, in order to mitigate or ideally eliminate the risk of reoccurrence of the same situation or similar cases in the future.

2.2 The key benefits of an asset management system

For many organizations it can be hard to identify drivers that justify the implementation of a whole new system for managing its assets, as it will require a great deal of effort to successfully implement such a complex system. An asset management system is meant to be a holistic system for planning, controlling, executing and revising all activities an organization choose to undertake in relation to their assets throughout their entire life-cycle perspective. This can further be used as a tool in ensuring that all these activities are in line with the organizations overall goals and aims.

ISO55000 have identified the following four areas where benefits of the implementation of an asset management system can be seen (Standard Norge, 2014).

- *The creation and implementation of an asset management system is beneficial in itself*
    - The implementation of an asset management system will open up possibilities in relation to risk reduction, improvement of processes as well as early identification of opportunities as soon as the implementation process is started. Such quick-wins can be utilized in order to gain more support for the implementation process throughout the organization.
    - As asset management is data-intensive new applications and processes for handling the data may improve the organizational understanding and thereby the decision-making processes being performed in the organization.
    - The implementation process can bring new perspectives to the organization, which in turn can lead to new and better ways of managing the assets in the organization.
    - Due to the life-cycle perspective of an asset management system the implementation can lead to improved functional integration of the organization.

- *Management on top level of the organization obtains new insights and achieve cross-functional integration*
    - The creation of an asset management system can lead to improved insight and understanding of the assets when it comes to their specific challenges and possibilities.
    - An asset management system will provide benefits related to the more streamlined sharing of information and improve communication as a result of its integrating nature.
    - An asset management system serve as an aid to forming long-term decision-making processes from a holistic view, which can lead to better whole-life asset management of entire asset portfolios.

- An asset management system provide a framework for a holistic approach to the integration of standards, regulations and codes which affect the assets in various ways.

- *Financial functions and decisions can be improved as a result of better data sharing and connectivity throughout the organization*
  - An asset management system can serve as an important facilitator to balancing short, medium and long-term objectives and goals as a result of the improved flow of information throughout the organization.
  - An asset management system enable integrated decision-making processes related to both financial and operational risk of the assets, and can thus serve as a facilitator to balance risk, costs and the performance of assets.

- *Organization-wide benefits as a result of the implementation of an asset management system*
  - An asset management system can lead to improved integration of data from various systems and platforms, and by this improve decision-making processes related to managing of assets.
  - An asset management system can give improved sharing of information and collaboration both between different parts of the organization as well as with other relevant stakeholders.
  - An asset management can facilitate improved utilization of human capital in the organization related to achieving organizational goals, as general knowledge related to good asset management practices enabled by the system can be further developed and employed.

2.3 The key elements of asset management

It is up to the system owners to decide on how one can manage assets in the best way to generate the optimal amount of value. This will evidently depend of the nature of the organization in question, and what it and its relevant stakeholders defines as its desired value and value generators. Examples of different types of values can be reduced operational risk, improved yield on financial portfolios, that the organization is able to perform its operations while at the same time enforcing minimal impact on the environment and so on. According to (The Institute of Asset Management, 2014) there exist a key set of elements that define good asset management, as opposed to when organizations are merely able “to manage an asset”. These key elements are also highlighted by (Woodhouse, 2010). These key elements are:

- *Integrated* –At the heart of good asset management lies the principle that all parts and elements of the organization affect each other through complex interactions. There exist a need for the organization to function as a whole rather than a set of different departments generally moving in the same direction.

- *Systematic* –the concept of an asset management system must be applied on all levels and parts of the organization in order to enable good asset management.

- *Systems-Oriented* –Good asset management looks at the assets from their natural systems context, in order to be able to generate value.

- *Multi-disciplinary* –Asset Management from a holistic point of view crosses both departmental, disciplinary and geological boundaries and evolve around generating the best possible value –independently of the nature of the value. This value can take many forms and will often vary within the different parts of the organization. Different types of value may be increased economical profit, improved safety or quality of products.

- *Sustainable* –There must be established plans that ensure optimal value-generation throughout the life cycle of the asset, while at the same time including important aspects related to environmental issues.

- *Risk Based* –Being able to plan for, manage and understand implied risks in decision-making processes is an important factor of good asset management.

- *Optimal* –Good asset management include that one is able to balance objectives so that cost, performance and risks can be balanced on both short and long terms.

Alignment as an underlying concept for asset management

In order to reach the desired goals and aims of the organization it is important that all employees and relevant stakeholders not only have a clear opinion of what they are to do, where and when they are to do it and how they are to do it in accordance with the plans and priorities of the organization, but they also need a strong understanding and relation to why they are doing it. This focus is better described as "line of sight" by (Woodhouse, 2010). It relates to the fact that in order to be able to improve and develop the organization in relation to its determined goals and aims it is imperative that the employees hold a deeper understanding of the activities they perform. By understanding the meaning of their tasks they will in turn will be able to propose innovative solutions and improvements to the different work processes that are being performed. They will further be better able to coordinate and prioritize their work tasks in order to reach the organizational goals and aims. A clear line of sight between the strategic goals and aims of the organization, as in "where are we going and why are we going there", and the day-to-day asset management activities being performed by the workers in the organization, as in "how do we get there", needs to exist. From this it can be seen that the line of sight also must exist from the top managerial level to the bottom line of the organization as well. It is equally important that the goals and aims of the organization are naturally reflected in the asset management activities that are being performed in the organization on the day-to-day basis. Feedback, evaluation and continuous improvement are therefore also key elements of the asset management system.

2.4 The key benefits of asset management

Asset management relate to being able to reach the organizational goals and aims through effective and efficient value making by managing the assets of the organization in an optimal way. The form and nature of this value making is dependent of the organization and its assets, but ISO55000 have identified the following 9 key benefits that can be achieved through the application of asset management. These possibility of gaining these benefits are enabled by the implementation of an asset management system as earlier described.

- Improved financial performance
- Informed asset investment decisions
- Managed risk
- Improved services and outputs
- Demonstrated social responsibility
- Demonstrated compliance
- Enhanced reputation
- Improved organizational sustainability
- Improved efficiency and effectiveness

From the diversity of these benefits it can be seen that in order to achieve them it is required that all disciplines, departments and parts of the organization contribute equally and in line through a collaborative and continuous effort.

2.5 A conceptual Model for Asset Management

The Institute of Asset Management have developed a conceptual model for asset management consisting of 6 subject groups, as described in Figure 5. These subject groups comprise of 39 sub elements as described in Figure 6. This model is meant to form a basis for the holistic approach to the subject of asset management. It focuses on that asset management evolve around the integration of the included groups with its sub elements in order for the organizational goals and aims being achieved.

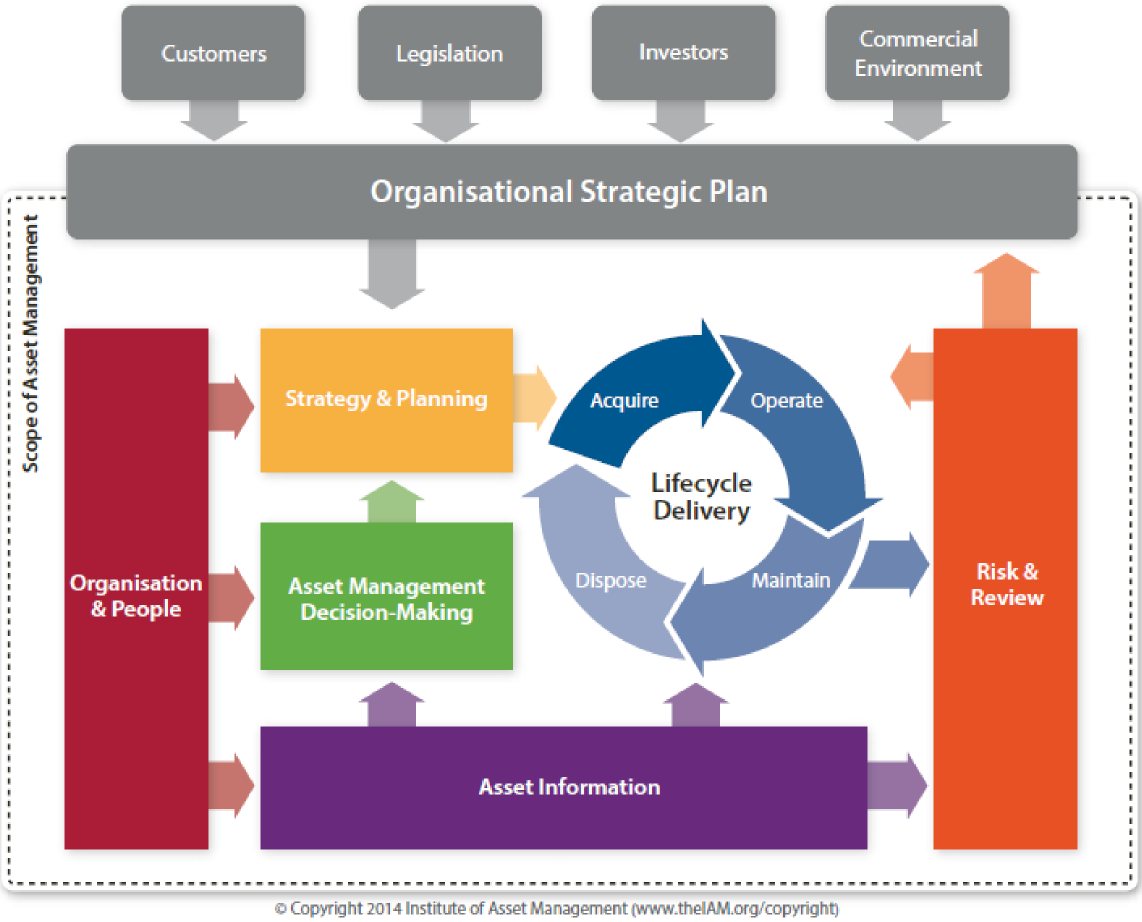


Figure 5 The IAM Conceptual Model (The Institute of Asset Management, 2014)

Strategy & Planning	Asset Management Policy
	Asset Management Strategy & Objectives
	Demand Analysis
	Strategic Planning
	Asset Management Planning
Asset Management Decision-Making	Capital Investment Decision-Making
	Operations & Maintenance Decision-Making
	Lifecycle Value Realisation
	Resourcing Strategy
	Shutdowns & Outage Strategy
Lifecycle Delivery	Technical Standards & Legislation
	Asset Creation & Acquisition
	Systems Engineering
	Configuration Management
	Maintenance Delivery
	Reliability Engineering
	Asset Operations
	Resource Management
	Shutdown & Outage Management
	Fault & Incident Response
	Asset Decommissioning & Disposal
Asset Information	Asset Information Strategy
	Asset Information Standards
	Asset Information Systems
	Data & Information Management
Organisation & People	Procurement & Supply Chain Management
	Asset Management Leadership
	Organisational Structure
	Organisational Culture
	Competence Management
Risk & Review	Risk Assessment & Management
	Contingency Planning & Resilience Analysis
	Sustainable Development
	Management of Change
	Asset Performance & Health Monitoring
	Asset Management System Monitoring
	Management Review, Audit & Assurance
	Asset Costing & Valuation
	Stakeholder Engagement

Figure 6 The 39 subject groups of Asset Management (The Institute of Asset Management, 2014)

Even though the Institute of Asset Management highlight the fact that one should not consider the dissimilar elements of the model as discrete subjects, but rather see them as interconnecting elements of a whole in order to be able to achieve good asset management, the author have chosen to emphasize the element "Asset Management and Decision Making", and some selected sub elements in the following text. This follows as the forming of well-informed decision-making processes lay the foundation for the development of strategies, the way operations are being performed and further how a maintenance strategy and a maintenance program is developed. The focus on this element over the others must be seen in relation the scope of this thesis, where one part of this is related to the forming of decision-making processes regarding the improved operation and maintenance management of offshore assets, focusing on the utilization of CBM strategies. Several other subject groups and subjects are however also relevant, but not given any further discussion in this part of the thesis. In the case study of CDE the IAM Conceptual model is applied for the identification of improvement potentials related to asset management in section 5.1.

It is underlined that in order to successfully implement an asset management system in any organization one need to consider all the elements of the model with an equal degree of effort. For organizations that are interested in implementing this model for asset management in their organizations the document "Asset Management –an anatomy" present a thorough explanation of the 6 main elements and their 39 subgroups (The Institute of Asset Management, 2014).

Asset Management Decision Making

In order to be able to utilize assets in the most optimal way through making the best possible decisions it is necessary to have access to the right type and amount of information and knowledge at the time it is required (Frankel, 2008). According to Frankel this is often referred to as knowledge management, where the knowledge is administered in a well-developed and well-managed decision-making framework in order to enable effective asset utilization by well-informed decisions engineering. The decision-making framework should reflect the organizations asset management policy, which again should be founded in the organization's asset management strategy. Such a strategy must include considerations in relation to one's own organization, customers and competitors, as well as the market environment in which one operate. It is further important to be aware of the fact that asset management decision-making processes are equally important at all stages throughout the lifecycle of assets, be it in relation to subjects like acquisitions, operations, modifications or decommissioning.

The required knowledge can be related to a number of aspects, varying from knowledge related to the asset itself, such as design related issues, technical constraints, the need for upgrades and modifications and so on. Other examples of knowledge needed in relation to decision-making processes can be regulatory obligations and statutory demands as well as knowledge about current and future developments in the market situation and so on.

In order to obtain and consider the information needed to make good asset management decisions it can prove beneficial to perform a "SWOT analysis". The SWOT analysis follows an integrated approach which includes both key organizational and environmental variables, and its goal is to confront the organizational strengths and weaknesses as well as external opportunities and threats in order to detect possible strategic options (Böhm, 2008). Strengths and weaknesses often relate to being able to recognize the criticality of assets, as well as obtaining and considering knowledge regarding the condition of the assets. Opportunities often present themselves as possibilities related to improving the condition of assets, either through implementing new technology, performing modifications or implementing new skills in the organization that may improve the asset management capability, performance or utilization. Opportunities can also be mergers, new acquisitions or new builds that can improve the competitive position of the organization in the market which it operates. Threats often relate to upcoming challenges that may affect asset performance in a negative way. Being able to foresee these are important, as identification of these threats render the possibility of establishing preventive actions that may mitigate or ideally eliminate their consequences. Threats can also be economic recessions in the markets, competitors that are able to offer equal or better services at lower prices resulting from improved asset management processes and so on.

Capital investment decision-making

Decisions related to investment programs, and their inherent magnitude and timing, will have a great impact to the success or failure of an organization. It is therefore of the utmost importance that capital investment decisions are based on thorough analysis. However, this is not the reality in many cases. Often decisions are based on assumptions and historical data related to expenditures from similar investments being performed at earlier stages. In this perspective it is important to understand that several factors may have changed since then, rendering the comparison with the historic data invalid. In addition to this there may exist uncertainties regarding deterioration rates and maintenance costs in relation to assets. In order to prevent capital investment decisions being taken on erroneous assumptions a number of different actions may be taken. A comparison between the continued operation of existing assets with a given set of operational expenditures (OPEX) against the possibilities of reduced OPEX by renewal of the existing assets, or the implementation or acquisition of new assets must be done. If the latter solution is chosen the organization will face higher capital expenditures (CAPEX) in a shorter perspective but obtain the possibility of lower OPEX in the long run, and thereby the possibility of increased profits. In order to ensure good capital investment decisions one can perform life cycle costs (LCC) analysis (Markeset and Kumar, 2000). A sensitivity analysis can further be performed to determine the quality of such an analysis. This will help to identify how the variation of key aspects will affect both CAPEX and OPEX in relation to the asset. When performing analysis it is important to mitigate risks and uncertainties in relation to the data that forms the basis for the analysis. Monte Carlo simulation is an example of a technique which can be applied to resolve such issues.

In many cases there may exist external factors that affect the timing of capital investment decision-making in negative ways. Such factors can be the relation to other assets or an asset portfolio, financial limitations or regulatory demands. The understanding of such implications and their impact is necessary in order to be able to optimize the timing of the capital investment decision-making process.

Operations and maintenance decision-making

In many cases the OEM will recommend a set of maintenance activities for the supplied equipment in order to ensure its safe and efficient operation throughout its lifecycle. These recommendations however often surpass the actual need for maintenance on equipment, as they are general recommendations intended to cover the needs of all customers independently of how and where the equipment is being used. Such recommendations are often based on running hours or certain time intervals. In many cases the industry follows these general recommendations, which often leads to an excessive set of maintenance tasks being performed, as they are executed regardless of the actual maintenance needs of the equipment. This again leads to an unnecessary high OPEX, as a result of unavailability of equipment being maintained, used man-hours and spare part consumption (Jardine et al., 2006).

In the O&G industry there is an increased demand for reduced OPEX, and this calls for rationalization of the maintenance management system. A maintenance strategy must be established, and several techniques can be applied in relation to this. (Norsk Standard, 2011) have defined that "failure modes, failure mechanisms and failure causes that can have a significant effect on safety and production shall be identified and the risk determined in order to establish a maintenance program". One widely used technique used for assessing maintenance needs when implementing a reliability centered maintenance (RCM) system is the failure modes, effects and criticality analysis technique (FMECA) (Rausand and Høyland, 2004). This qualitative reliability tool is meant to systematically identify all possible failures in relation to each individual equipment, in order to be able to form a maintenance strategy to avoid the occurrence of these failures. In addition to this a criticality is assigned for each equipment's main and sub functions including its inherent failure states, so that the best maintenance strategy can be chosen. For equipment with low criticality it is common to choose CM tasks, or a "run to failure" strategy. For equipment identified to have medium or high criticality more thorough analysis is required. A risk matrix as shown in Figure 7 below can be used as an aid in this process to determine the likelihood and consequences of risks in relation to different objectives. Such objectives can for instance relate to areas like risk to safety, production or oil spill to sea.

The application of FMECA studies is both time consuming and require a great deal of effort. On the other hand it can give great value as it forces the user to fully understand the system studied, including its different components, their complex interactions and failure modes. However, as it can be a costly process the need to perform such analysis must be clearly identified prior to the start of the process.

Likelihood	Category	Consequence			
		Catastrophic	Major	Marginal	Minor
		1	2	3	4
Frequent	A	1	1	2	2
Likely	B	1	2	2	3
Occasional	C	2	2	3	3
Unlikely	D	2	3	3	3
Remote	E	3	3	3	3

Figure 7 Criticality Matrix (Norsk Elektroteknisk Komite, 2009)

One definition of risk-based decision making is that it is "a process that organizes information about the possibility for one or more unwanted outcomes into a broad, orderly structure that helps decision makers make more informed management choices"(ABS). This way of thinking is applied in the risk based maintenance (RBM) philosophy. This technique identify maintenance needs, highlights essential areas and focuses on the critical elements that influence success when it comes to maintaining assets. This include identification and systematic evaluation of risk, and its inherent causes, probabilities, effects and consequences which again will form a basis for risk mitigation measures. One key element in this respect is the identification of the accepted level of risk versus the cost of the maintenance tasks performed in order to control the level of this risk. For organizations that are involved with O&G activities on NCS this must be seen in relation to the "as low as reasonably practicable" principle (ALARP). (Petroleum Safety Authority Norway et al., 2013) describe that "In reducing the risk, the responsible party shall choose the technical, operational or organizational solutions that, according to an individual and overall evaluation of the potential harm and present and future use, offer the best results, provided the costs are not significantly disproportionate to the risk reduction achieved." In other words this means that any available technical solution that can reduce the risk shall be implemented, unless its costs can be proven to be grossly disproportionate with the possible benefits gained.

Other studies which can be used to assess the consequences of an initiating event or potential accident is the event tree analysis (ETA), as described by (Aven, 2008) or the fault tree analysis technique (FTA), as described by (The International Marine Contractors Association, 2002). The selection of applied techniques will vary from case to case, but in order to be able to apply them in such a way that they give the desired results a certain degree of knowledge on the subject is required by the involved personnel. As a result of this it can prove beneficial to make use of external expert knowledge when performing such processes, in order to ensure and optimize the quality of the efforts taken.

When deciding on a maintenance strategy, which forms the basis for operations and maintenance decision-making processes, it is important to acknowledge the weaknesses of the applied techniques for identifying the needs. In many cases it can be beneficial to use a combination of techniques, and it can also prove beneficial to revise the framework for operations and maintenance decision-making processes at given intervals. In this way one will be able to include and consider the effects of implementation of novel technology, the dissimilar needs of aging or new assets, as well as changes to the operational environment. In addition to these effects also statutory demands may vary and change, imposing the implementation of new measures.

A structured framework for design and implementation of a maintenance strategy based on the guidelines provided in NORSOK Z-008 is described in the case study of CDE in section 4.2.

Lifecycle value realization

The different stakeholders in an organization take different perspectives in relation to what is the optimal asset utilization over a given time interval. Even though this interval often spans from the procurement of an asset through its shutdown and decommissioning phase, certain situations related to contractual issues or other factors can result in this interval being shorter than this. A plan for optimizing lifecycle value realization should comprise of different elements in relation to how one can boost asset performance throughout its different lifecycle stages. In this context both social, financial and environmental issues should be included. Factors like customer satisfaction related to quality of services and performance, employee satisfaction levels as well as the reputation of the organization are aspects that can affect the lifecycle value realization of assets.

Resourcing strategy and resource management

This subject relate to the identification of what resources and capabilities the organization should have in order to be able to manage and perform their asset management plans, and the safe and efficient performing of the operations of the organization. Strategic decisions must be made on whether one should outsource parts and elements of the organization, or if one should develop own resources in the organization, i.e. develop in-house competence and facilities related to certain subject areas. Such decisions are dependent on what is defined as core capabilities and area of operations for the organization.

In order to manage the organization’s operations in an efficient manner a well-defined resourcing strategy is needed for other areas as well. Examples of such areas can be the management of spare parts and logistics, as well as the managing of resources related to facilities or special equipment needed to perform operations.

Shutdowns and outage strategy and management

For many businesses and organizations the performing of planned shutdowns of plants and machinery is a necessary evil in order to be able to maintain equipment or perform needed modifications. A well-formed strategy for the performing of such shutdowns enable their effective, efficient and safe performing. Current industrial development show that the performing of planned maintenance stops are intricate, due to the performing of many parallel processes on various equipment within a limited area and inside a very limited time period. The tasks that are being performed are in many cases complex, and often require the assistance from external specialist knowledge. From this it can be seen that the effective management of such processes are crucial in order to maintain the required level of safety for the involved parties, as well as ensuring that the different work processes are coordinated properly. In this way they can be performed in an efficient manner without any conflicts.

It this relation it is important to comprehend that the management of shutdown is not merely related to the on-site management tasks being performed during the actual shutdown. Planning of the tasks well ahead of their performing may prove to be an even more important part of the management, as this can serve as an important facilitator to fully exploit the window of opportunity of performing parallel activities like maintenance tasks and so on. The management tasks related to planning can also be related to acquiring spare parts and special tools and equipment, gathering of information, coordinating activities with service providers and so on and so forth.

2.6 Asset management practices in the O&G industry on the NCS

This section of the thesis describe developing trends in the asset management practices performed by the actors involved in the O&G industry on the NCS. From a general point of view it can be claimed that the industry have a strong focus on compliance to statutory demands as well as a strong focus on safety in operations, and that they have not focused enough on how to improve the efficiency of operations while at the same time obtaining acceptable levels of safety in operations. The following chapters in this section highlight several important areas which are identified to hold substantial potential for improvement related to such aspects.

Implementation of novel digital solutions for improved asset management and performance

In the Norwegian O&G sector there seems to be an understanding of the term asset management to be a novel and populist term looked into by some players with interest, while one flippantly can suggest that others continue their day-to-day business in a similar fashion to the one they always have. As the Norwegian O&G industry generally can be said to be a conservative business sector with a strong focus on utilization of well proven managerial and technological solutions in order to ensure the highest level of safety in their operations, new ways of managing assets can be seen as a threat to existing departments and structures in the organizations, as well as the overall safety of operations. The fact that the implementation of novel business structures based on digital technologies, leading the way for better asset utilization, will require a great deal of effort throughout the O&G industry can be exemplified by the results presented in the recent survey “Oil and Gas Digital and Technology Trends Survey” performed by Accenture and Microsoft. In this survey the biggest perceived barrier to realizing value from digital technologies was identified to be existing workflows and processes creating bottlenecks (Accenture and Microsoft, 2015). In the survey novel collaboration technologies were highlighted as an important area that could be increasingly applied in the upstream O&G industry to create a more efficient workforce and to enable faster decisions being made.

The implementation of novel digital technologies can lead to a re-engagement of the work force through empowerment of the employees, and it can help to eliminate organizational barriers between the different departments of organizations. It may also revitalize the desire to deliver better value for the money in the organizations (The Institute of Asset Management, 2014). From this point of view there are indicators showing an awakening regarding this subject in the O&G industry, as those who have embraced this new approach to managing business from a process oriented point of view seem to obtain substantial benefits from doing so.

The previously mentioned survey further revealed that 86% to 90% of the respondents said that the increasing of their analytical, mobile and Internet of Things capabilities would enable them to increase the value of their business (Accenture and Microsoft, 2015). The rapidly increasing relevance of the afore mentioned Big Data thinking approach as a facilitator to enable business success can be exemplified by the way the company Shell have embraced this strategy. By their implementation of a data-led strategy, enabled by the application of advanced computer analysis to the rapidly growing amount of available digital information, they have been able to significantly improve their efforts in search for oil and gas. This entail the application of more than a million sensors for the gathering of data related to exploration of possible hydrocarbon deposits. This enable them to get a far more accurate picture of what lies beneath the sea bed, and by their extensive existing knowledge obtained from other comparative oil fields around the world, and automated digital processes for comparing the vast amounts of data, they are enabled considerably improved decision making processes as to where they should actually initiate the drilling of their exploration wells. They employ Big Data to ensure the efficient and proper working of their machines. This is especially important since their drilling equipment is operated in harsh conditions for prolonged periods of time. By fitting the machinery with sensors that collect data about the performance of the machines, they are able to compare it with previously obtained baseline data. This render the opportunity of replacing parts in need of it in an efficient manner, leading to a reduction of operational downtime, and thus reducing unwanted overheads. Lastly Shell apply Big Data for the streamlining of the logistics related to their downstream business area. As Shell’s business areas involve end-to-end management of hydrocarbons, including exploration and production, transport and retail they obtain substantial benefits from optimizing capacity exploitation of their refineries as well as reducing transportation costs by the effective management of all their assets from a holistic approach to all related processes (Marr, 2015).

Due to the large degree of interdependencies and need for greater cooperation and seamless sharing of information between different stakeholders the traditional management philosophy for assets operating on the NCS is now challenged. This firstly is related to internal organization of companies, where traditional management practices are to keep management processes segregated in different departments like for instance engineering, production, finance, human relations and so on. This approach to managing processes is now being challenged by the recognition of the fact that all different departments and business functions have complex interactions and affect each other in various ways (Liyanage, 2012). This calls for a new and holistic approach to management. Secondly the managing of relations with external stakeholders are subject to new ways of thinking. This has become evident as stakeholders like third parties and external service provides, OEM's and clients now play important roles when it comes to decision-making processes related to activities that needs to be performed to counteract emerging challenges and negative trends. If such processes are not properly managed by a holistic and well-funded asset management approach it can lead to increased operational risks as well as other challenges. As the involvement of different stakeholders have been substantially increased, it has become very important to clearly define responsibilities between the different parties involved. Experience shows that such responsibilities in some cases can be unclear, emerging as a direct result of the rapid forming of new alliances and forums for decision-making processes, which have not been subject to proper evaluation and management of change processes. From this it can be seen that clear and formalized lines of communications related to these subjects needs to be established. This aspect is further made challenging as experience also shows that the lines of communication between the companies involved on the NCS and the service providers may often take a form of one way communication, where the service providers perceive that their potential in aiding the customer in not fully released. This come as a result of lack of exchange of information and not having a clear two-way communication.

Recognition of equal importance of all processes and business areas for obtaining improved asset management

Traditionally some decision making processes have been regarded as more important than others. One example of this is the misconception that production related decisions are more important than maintenance related issues, as the latter to some degree has not been regarded as value-generating processes, but rather been considered as necessary evils whose extent should be kept at a minimum in order to obtain maximum utilization of. Similarly it can be said that cost related decisions have been seen superior in relation to safety and environmental decisions (Liyanage, 2012). The same way of thinking can also be seen in relation to CAPEX compared to OPEX. This follow the fact that while the installation and implementation of new equipment and electronic solutions can give negative cash flow resulting from high CAPEX in the short to medium term perspective, it can in a long term perspective serve as an aid to substantial reductions to OPEX, which will improve the performance and financial results. Stakeholders like company owners may for instance choose the former solution based on various selfish strategies or from the simple lack of funding (Ross, 2011).

Forming of alliances and technological clusters

From a general point of view one can claim that there seems to be an improvement potential related to more extensive and efficient collaboration with service providers and vendors throughout the Norwegian O&G industry. The unreleased improvement potential related to the forming of tighter collaboration with service providers can be exemplified by the fact that Statoil have achieved a 35% increase in efficiency of operations on their asset Statfjord since 2013 by improved collaboration and integration with their service provider Archer (Frafjord, 2015). Several other initiatives have now been taken by other actors in order to achieve similar benefits.

The forming of federated technological multi-disciplinary clusters where business-to-business relationships are formed seems to be a new and fruitful way of establishing alliances between actors involved with the Norwegian O&G industry. Such alliances seems to be mutually beneficial for all related parties, who are enabled harvesting on improved collaboration related to different strengths and weaknesses, including the sharing of facilities, information, human capital and technology. By doing this one is enabled to present the best possible solutions to the business sector in which one is involved. This new way of thinking within the Norwegian O&G industry can be exemplified by the establishment of the Norwegian Centers of Expertise, as illustrated in Figure 8 below. One of these centers related to the O&G industry called Norwegian Offshore & Drilling Engineering (NODE) has now developed into being one of the two first global center of expertise (GCE) situated in Norway (GCE NODE, 2015) . GCE NODE comprise of some 70 partnering companies which develop and deliver advanced technology and systems for offshore drilling and operations within the global O&G industry. Their vision is to contribute so that the O&G industry in south of Norway will become a world leader in delivering services to the global O&G industry by establishing conditions for effective collaboration and building specialist knowledge within the fields of mechatronics, robotics and logistics and management (Innovation Norway, 2013).

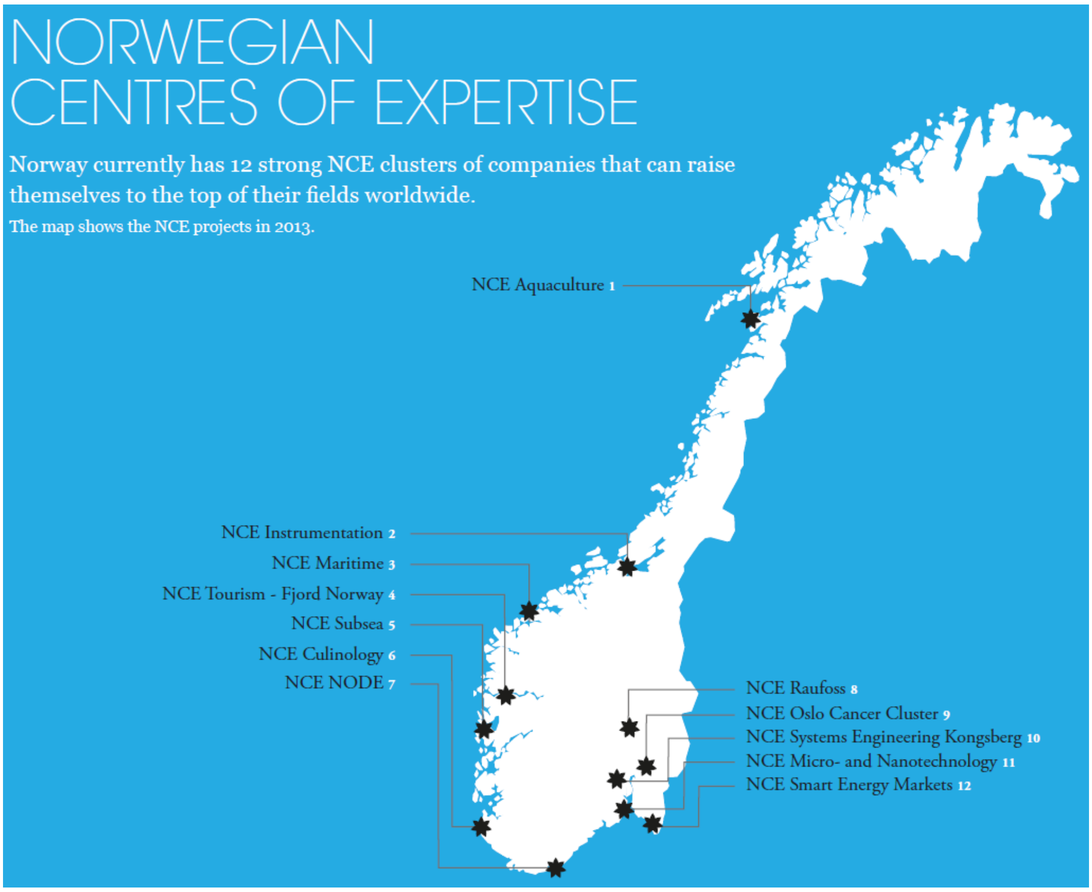


Figure 8 Norwegian Centers of Expertise projects 2013 (Innovation Norway, 2013)

Even though GCE NODE comprise of companies which in many cases can have conflicting interests, and in some cases even are competitors, the participants in the initiative have recognized the fact that in order to retain a top-position in the highly competitive industry through the application of novel and advanced technology they are better off cooperating towards reaching their common goal. The forming of GCE NODE erase organizational, geographical and technological barriers, and enable the partaking organizations to better release their potential through various types of loose couplings with their other relevant stakeholders (Perrow, 1999). This recent development of performing operations in what can be described as an ever changing interactive environment, have in other words transformed the focus of asset management to also include other relevant stakeholders which are not a part of the organizations themselves. A strong focus on clear and good cooperation and communication must be maintained with parties such as the asset operators and owners, customers, regulatory and statutory authorities, service providers, OEM’s, spare part vendors, technology developers and engineering contractors as well as logistics providers. In addition to this improved cooperation with training centers, schools and universities can serve as an aid into being able to educate and connect with personnel having the required competence and knowledge to further develop the work in the alliances.

Focus on intellectual capital and effective application of novel technological solutions

One of the most important elements related to asset management is to enable empowerment of the workforce through well-designed human-machine interfaces (HMI) that enable the operators to understand the given signals from the systems in order to be able to make the right decisions for maintaining safe and effective operations. This aspect has become ever more relevant as the human capabilities of offshore personnel now is being challenged by the increasing complexity of the operations being performed and the advanced technical systems that needs to be operated. It is therefore paramount that the workers are in line with the high level of safety standards that prevail throughout the Norwegian O&G industry, and lastly that they maintain a high level of situational awareness in their performing of complex tasks which often include a series of complex interactions with other related activities.

In order to achieve this the needed human intellectual capital, knowledge and resources for understanding the systems being operated offshore must be available for the organizations (Roos et al., 1998). Due to the level of complexity of systems one today see an increased use of specialist services from OEM's and third parties for sorting out any problems with equipment. This development hold both several challenges and benefits. With the implementation of advanced communication technology the actors involved with activities on the NCS are given the opportunity of receiving extensive assistance from experts physically located elsewhere than where the physical problem lie. This can for instance be the provision of expert assistance from onshore support centers via electronic network solutions for sorting out problems with equipment located offshore. From this aspect it is important to be aware of the fact that the application of such technological solutions can (and most probably will) fail at some point, leaving the sorting out of the problem to the available personnel offshore. From this it can be seen that the now extensive and widespread use of external specialist expertise can pose a threat to the overall safety of offshore installations on the NCS. This challenge must be treated seriously by the actors involved. The implementation of measures in the asset management strategy to avoid such threats have become important focus areas for all actors involved with activities on the NCS.

Standardization and common platforms for exchange of information and documentation

Due to the rapid development of novel technological solutions in the Norwegian O&G industry the past recent years a lot of the focus around creating excellence through asset management has naturally been related to being able to successfully implement such technology. Experience however shows that a number of other factors also needs to be in place in order to be able to release the potential given by the introduction of the technology itself. Such factors can be well developed information sharing processes and presentation of available data, interoperability solutions, integrated decision processes and work management, cross-disciplinary operational risk management and so on. The rapid development within these areas have made it ever more evident that a standardization of information sharing, processes and databases is important in order to enable a seamless integration between the different departments throughout the organizations, so that assets can be managed in the best possible way. Based on these needs several initiatives for improvements of these aspects have been taken.

Due to the high demands for safety in operating the high-risk assets involved with the O&G activities on the NCS, as well as the ever growing complexity in the applied technical solutions the industry have seen a rapid increasing demand for the documentation of processes and equipment. That this effort has given positive results is made clear by the fact that it is now claimed that it has never been safer to be working on the NCS than it is today (Lewis, 2015). In their annual report on safety related issues called "Risikonivå I Norsk Petroleumsnæring" the PSA write that 2014 is the year with fewest reported incidents, as well being the year which had the lowest potential for major accidents since the reporting started in 1996 (Petroleum Safety Authority Norway, 2015).

While it is safe to say that the extensive demands for documentation has been a contributing factor to these positive results, other issues related to the subject also needs to be addressed in order to be able to continue this development in the future. A key player involved in the O&G industry now raise the question whether the demand for documentation of processes meant to improve the safety now have progressed so far that they in fact end up giving no results towards this goal at all. He exemplifies this by referring to the documentation demands related to a tender his company delivered recently. The value for the delivery of the service was 35000NOK, while the documentation required to deliver the tender ended up filling 397 pages (Ånestad, 2015). From this point of view one can claim that the demand for documentation now have become so extensive that the industry is coming close to the point where these demands are coming out of proportions. This view is further illustrated in an article published by NRK, where it is claimed that up to 80% of the time being spent in the O&G industry is not used towards value generating processes (Stenberg and Gjesdal, 2014).

Also the need for standardization of processes seems to be an area for significant improvements to asset management throughout the O&G industry on the NCS. In the recent Norwegian offshore conference "Subsea Valley" one of the main topics discussed was in fact standardization and related issues. In this conference one of the main challenges that the service provider industry face today was identified to be the frequently changed specification requirements of equipment by the major oil companies. It was pointed out that in order to satisfy the extensively specified requirements of the oil companies the service providers were prevented from delivering the most cost-effective solutions, and thus being imposed to unnecessarily drive up the costs for all related parties (Ekeseth, 2015) .

One of the major oil companies that have taken this challenge seriously is Statoil, who have now recognized a need for improved efficiency in their operations (Laustsen, 2015). As a result of this they have initiated the Statoil Technical Efficiency Program (STEP). This ambitious project, which is aimed at giving Statoil annual savings up to 13billion NOK, comprise of 6 focus areas, two of them being the simplification of technical demands documentation and the standardization of processes so that the obtained knowledge more easily can be utilized again for similar future projects (Kongsnes, 2014, Aadland, 2015). In a presentation of the STEP program in the Johan Sverdrup project given by Statoil three guiding principles, as shown in

Figure 9 below, was presented. By the implementation of these principles into their asset management strategy the overall aim is to achieve substantial savings when performing this project (Røstadsand, 2014). From this it can be seen that they have gone from a focus on installing the most optimal and thus expensive solutions, to an approach more related to the identification of what will be sufficient and adequate solutions. This view is also promoted in the recently published newspaper article under the title "Mener oljebransjen må gå fra Mercedes til Toyota"(Ekeseth, 2015).

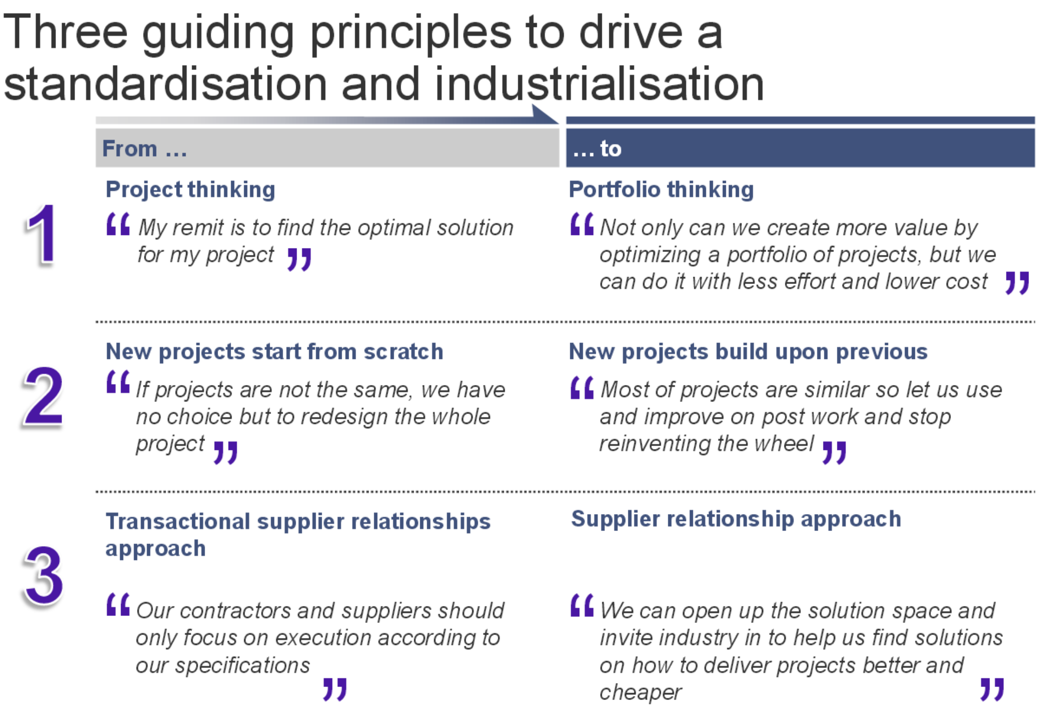


Figure 9 Statoil Guiding principles for standardization and industrialization -STEP in Johan Sverdrup (Røstadsand, 2014)

In 2007 Oljeindustriens Landsforening (OLF) commenced with an initiative towards the standardization of exchange of technical documentation and information between service providers, contractors and operators on the NCS. The goal is that the exchange of all relevant documentation involved with projects and delivering of equipment and systems can be more effectively managed by implementing it into a common library database called Equipment Hub, or EqHub. This is a noncommercial initiative run and operated by the organization Exploration & Production Information Asset Management Association (EPIM). It is estimated that the annual economic benefits following this standardization process are in the order between 100 and 170 billion NOK, where 40-60% are related to the standardization of information regarding equipment (Zachariassen, 2011). Even though this initiative has been met with several challenges from the industry, it seems that it in the future can serve as an important aid towards more easy exchange of documentation and information between different stakeholders in the industry, and thus serve as an aid to improved value generation throughout the industry (Zachariassen, 2011).

The application of EqHub has already been embraced by the company Total E&P, as they have included it as one of their technical requirements for service and equipment providers contributing to their development of the Martin Linge field on the NCS. In doing this they ensure that all the delivered standardized equipment fulfill the requirements set in ISO 15926. EPIM now hope that the application of EqHub for reducing costs related to documentation processes involved with equipment deliveries, and ensuring a harmonized deliverable of all standard equipment information in this project, will be a success story. Such a success may pave the way for other actors to recognize the initiative and choose the same solution for their future performing of projects (EPIM, 2014).

The recognition of the need for improved asset management throughout a lifecycle perspective of offshore assets operating on the NCS can further be illustrated by the novel development of a joint effort throughout the Norwegian O&G industry called the Integrated Lifecycle Assets Planning (ILAP) project. This initiative is based on the findings by a NOSOK work group which revealed that the improved efficiency of information sharing within the industry held the potential of reducing CAPEX with 25% and OPEX with 20%. Considering the large number of actors partaking in the extensive activities on the NCS this sum up to the potential of some 50 billion NOK of annual savings throughout the industry (Langeland, 2015). The stakeholders in this initiative include, but is not limited to, authorities, vendors, operators, organizations, suppliers and various contractors. Some of the key contributors in the project are Statoil, Eni, Conoco Phillips and Lundin. The goal of the project is to establish a common international standard for the exchange and sharing of plan data in all phases of the lifecycle of assets between all relevant stakeholders. According to a presentation given at UiS in March 2015 the standardization shall involve planning activities for (Langeland, 2015):

- Asset management in order to optimize lifecycle value for physical assets
- A standard for data optimization and interoperability between stakeholders
- Project management in all lifecycle phases of physical assets
- The standardization shall be adapted for and applicable to all stakeholders related to the O&G industry

The potential of the ILAP project is to improve planning efficiency, reduce the number of HSE related incidents and achieve more days with production through safer, faster and better decisions enabled by high quality planning.

3. Condition Monitoring and condition based maintenance

Introduction

The rapid development of advanced information and communication technology (ICT) and its now widespread application throughout the O&G industry have opened up new possibilities in relation to use of sophisticated condition monitoring techniques. Such novel automated condition monitoring techniques which include the application of continuous data sampling, processing of the data, transferring of data to analytical centers onshore by use of satellite or broadband technologies emerge as new possibilities that may significantly reduce the need for maintenance activities offshore. This development must be seen in relation to what OLF describe as the rapid development of IO on the NCS, which gives indirect or direct potential for increased value of NOK250 billion on the NCS (Oljeindustriens Landsforening, 2007b). As systems and equipment expert groups situated in specialized onshore centers can process and analyze data before sending recommendations to the end user offshore the need for offshore personnel may be reduced to a minimum. In addition to this the end users in the offshore organization gain the benefits of knowledge and advice from expert analysts, which serve as an aid for improved operation and maintenance decision-making processes.

This section of the thesis provide an introduction to the history and development of condition monitoring, and furthermore the possibilities it gives in relation to implementing CBM strategies for equipment. It explains the fundamental techniques of condition monitoring as well as describing areas that are applicable to CBM. A model for implementing CBM is provided and discussed. The implementation of IO in offshore organizations enable the application of novel e-operations and e-maintenance solutions, like for instance advanced diagnostics and prognostics and remote health assessment of equipment. A contextualization of the application of such techniques in the O&G industry is provided, and its advantages and disadvantages are discussed. An example of how problems related to the integration of data and use of different monitoring equipment can be overcome is presented by the introduction of the Open System Architecture for Condition-Based Maintenance (OSA-CBM). Lastly an introduction to the Watchdog Agent Technology is presented, in order to highlight one of the novel technological solutions that have now been commercialized.

The history and development of condition monitoring and CBM

In earlier times condition monitoring was limited to the inspection of machinery and equipment by human labor using their natural senses like sound, smell, taste, touch and vision to detect emerging problems. As machines grew more complex and systems became more advanced the application of sensors like pressure gauges and various process related monitoring equipment was installed so that operators was enabled easy assessment of the technical condition of systems (Moubray, 1997). This development came as a natural response to increasing demands for improved productivity, higher safety and more reliability of equipment. As time went by operational experience was applied in order to foresee and plan maintenance needs, and to develop maintenance programs that prevented machinery breakdowns. This was the early stages of RCM. By the monitoring and assessing of equipment state while equipment was in operation one was enabled to perform maintenance tasks when they were actually needed instead of performing them on a regularly scheduled basis. This development lay the foundation for modern CBM strategies (Moubray, 1997)

With the computer age the condition monitoring sensors were implemented in machine control stations, allowing the operators to assess the condition of entire plants of equipment without having to move around the plant. In todays advanced and complex working environments advanced HMI's present the system operator with enormous amounts of condition monitoring data. In many cases the systems have now become so advanced that they are able to perform self-assessment processes, so that they are able to present the system operator with suggestions for appropriate actions when an intervention is needed. An increasing focus has been given to the forming of systems so that they can fit the human, taking in human factor elements like anthropometry and the human capabilities for effective detection of errors. Now the challenge with managing complex ergo systems have come to evolve more about how one can be able to present relevant information to the human operator so that he is enabled to take the appropriate actions based on the information he is presented with by the HMI, and thus avoid falling into the cognitive error paradigm (Bridger, 1995, Redmill and Rajan, 1997).

3.1 The relation between error states, failures and faults

In the context of applying condition monitoring and CBM to intervene with emerging problems and challenges in equipment it is important to both comprehend and be able to segregate the terms errors, failures and faults. For the work with this thesis the author have chosen to use the definitions and limitations to these terms as described by (Rausand and Høyland, 2004). According to their definition an *error* is a divergence between a calculated, observed or measured value and what the true or theoretically correct value actually is. If an error occur the performance of the equipment is still within the acceptable levels of performance. An error can be caused by problems with instrumentation or other disturbances to the measurements. If this is not the case, the error state may be the first sign of a deterioration in the equipment that may develop further into an undesirable *failure* event. This occur when the performance fall below what is defined as the acceptable limit. This can be the result of a number of situations, where age and degradation, internal or external and direct and indirect problems are some. If this failure event is not dealt with it may develop into a *fault*, which is the state where the equipment fails to perform its function. The relationship between the three terms are described in Figure 10 below.

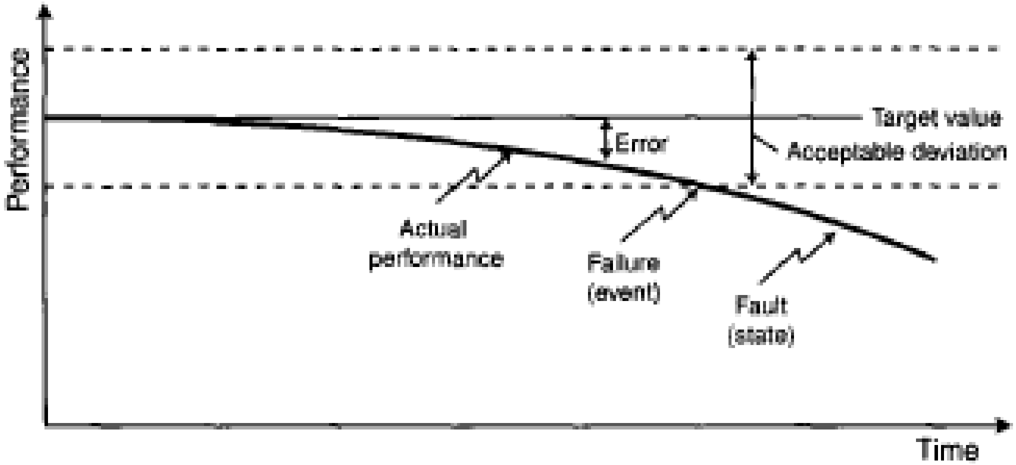


Figure 10 Relationship between failure, fault and error (Rausand and Høyland, 2004)

(Moubray, 1997) defines the interval from a potential failure occurs; i.e. when it becomes detectable, until it develops into a fault as the P-F interval, as shown in Figure 11 below. By application of various types of condition monitoring the idea is to be able to intervene with a potential failure within the P-F interval, so that one can avoid any unplanned shutdown of equipment. It is important to comprehend that the length of this P-F interval may differ greatly dependent on the type of failure mode and the specific equipment type in question. Through identification of the equipment's inherent failure modes, as well as their probabilities of occurring by performing processes like the aforementioned FMECA analysis, one is given the opportunity to design a CBM system where timely inspection intervals may be designed to suit the different types of equipment.

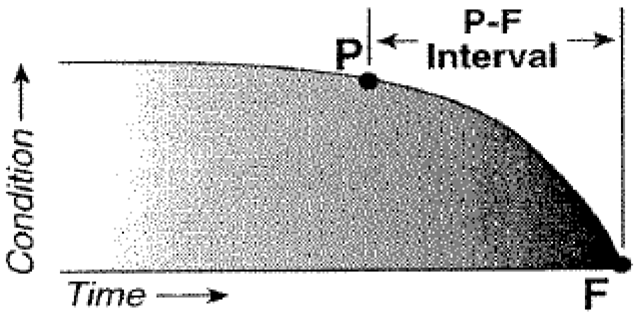


Figure 11 The P-F interval (Moubray, 1997)

3.2 The definition of condition based maintenance and condition monitoring

(British Standards Institution, 2010) define CBM as "preventive maintenance that include a combination of condition monitoring, inspection, testing and the ensuing maintenance actions." In other words one can say that CBM involves all maintenance related activities performed on a preventive basis as a result of the detected needs by various means of inspections, monitoring and collection of data. The analyzing and interpretation of this data forms the decision basis upon which maintenance tasks that needs to be performed. From this it can be seen that CBM in some cases is referred to as predictive maintenance.

Condition monitoring include all manual and automated activities related to obtaining information about the actual technical state of equipment. Such activities can be inspections at given intervals or continuous or semi-continuous monitoring and gathering of data. It may also involve the application of remote analysis or special equipment like sampling fluids or other types of materials (The international Organization for Standardization, 2003). A combination of techniques may also be applied in order to obtain the desired knowledge about the physical condition of equipment. In order to be able to maximize the output it is important that a solution which is suitable for the specific equipment type is chosen, and that relevant parameters are monitored. It is further important that the personnel that assess and interpret the obtained data hold the required knowledge to establish the correct decisions when it comes to creating suitable maintenance tasks to act upon any emerging negative trends or challenges.

3.3 Condition monitoring techniques

(Moubray, 1997) defines four main categories of condition monitoring techniques, and these techniques will be given an introduction in this section of the thesis.

The use of specialized equipment to monitor other types of equipment

By installing sensors and equipment in order to establish a picture of the technical state of other types of equipment, one is able to obtain the necessary information to determine the needs for maintenance tasks or other types of interventions. Such interventions can be related to various alterations to the running state and work load of machinery. Today many OEM's include various types of continuous condition monitoring equipment as a standard installation when delivering equipment to customers. One can say that the general development throughout all industries is that an increasing amount of parameters are being monitored automatically, and recommendations are presented to the system operator through various HMI's. This follow as a natural development to the ever increasing availability of equipment and sensors and the significant cost reduction in relation to such equipment one have seen during the recent years. This can be exemplified by the extensive application of condition monitoring equipment in the automotive industry. Condition monitoring sensors related to parameters such as tire pressure, engine oil level, engine temperature and turbo pressure have now become standard equipment on a number of different cars. If an error condition is discovered in one of these parameters the driver is either directly notified by the HMI in the driving display in the dashboard, or a signal is sent to the advanced engine safety system telling it to shut down or reduce the power output if needed to prevent further damage to related equipment.

During the last decades various OEM's delivering equipment to the O&G industry have embraced the application of condition monitoring in order to enable their customers early detection of error states. In doing this the render customers the possibility of timely intervention with errors before they can develop into failures or faults. By the application of condition monitoring equipment the customers are also enabled to ensure the optimal operation of equipment within normal running parameters. This will lengthen the lifetime of equipment and improve the equipment performance at the same time as reducing maintenance costs to a minimum.

There exist a number of different techniques to monitor all sorts of parameters depending on the specific equipment in question. (Moubray, 1997) have classified the areas of condition monitoring by use of condition monitoring equipment into the following 6 sub categories.

Dynamic effects

An inherent property of all equipment which include moving parts is that they emit various amounts of energy in the form of noise, vibrations or pulses. If the level of emitted energy differs from what is normal it may be caused by errors or failures in machine parts such as ball bearings, wear out of engine parts, misalignment, imbalance and so on. Ultrasonic devices and special equipment for the detection of acoustic emission can be applied to detect deterioration leading to errors or failures in equipment. Vibration monitoring is a widespread condition monitoring technique throughout the industry today. This come as a result of its excellent properties in relation to the early detection of failures in equipment types like bearings as well as in other equipment types related to for instance various gears and motors. Fast Fourier Transformation can be applied for the analysis of vibration spectra related to parameters like velocity and acceleration, as well as frequencies and amplitudes of the emitted vibration. Time-wave form analysis may give important information about the nature of the failure, which can be related to aspects such as misalignment, eccentricity, roller or cage defects in bearings and so on. From this it can be seen that by the application of vibration analysis one can be able to pinpoint the exact location and cause of an error or a failure in equipment. In Figure 12 an example of a vibration analysis performed on the main shaft of the top drive installed on the drilling rig COSL Pioneer is shown. This specific example will be further discussed in section 5.3.

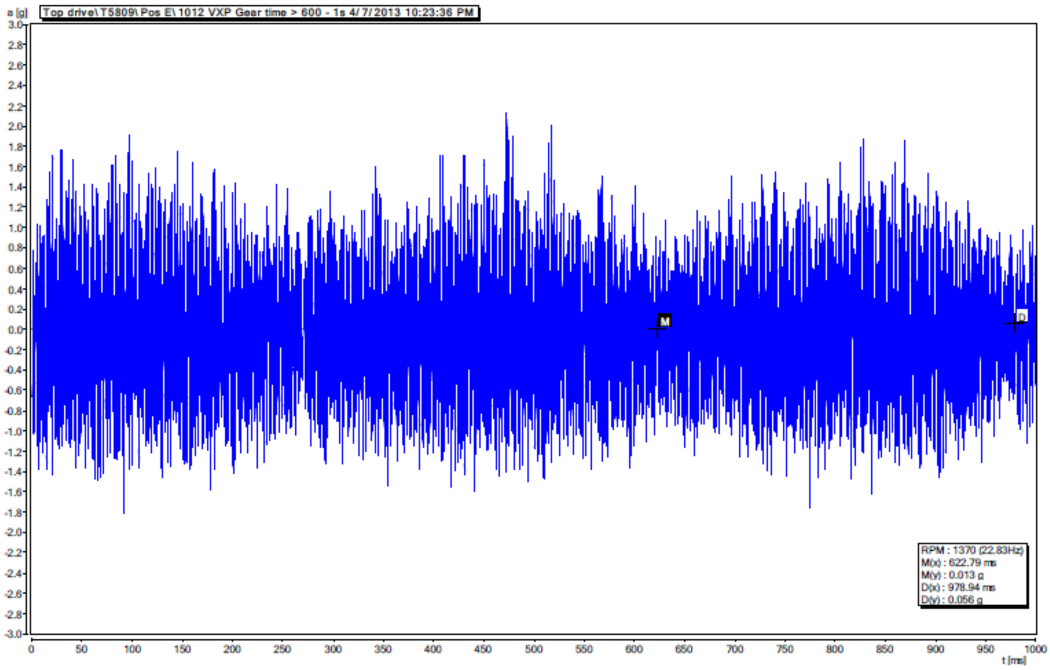


Figure 12 Vibration analysis performed on the top drive main shaft on COSL Pioneer (Karsten Moholt, 2013c)

Particle effects

In order to enable the continuous operation of rotating machinery and other processes various types of lubrication oil, hydraulic oil and cooling fluids are applied. When the machinery gradually deteriorates different types of particles are absorbed in the fluids resulting from effects like abrasion, friction, erosion or corrosion in the various machine parts. In addition to this ingress of external contaminants like for instance other process fluids, water or dirt may change the property of the lubricating or cooling agent. By performing either continuous or periodic oil sampling one can detect the type, size, number and shape of particles in the fluid. By this one can determine the origin of the particles and in some cases the processes that led to their creation, and thereby determine in which specific system part the deterioration process is taking place. Oil sampling can also be used as an aid to determine oil change or filter change intervals, as the fluid itself will lose some of its characteristic properties over time as a result of compression, temperature changes and other types of wear.

To contextualize the importance of condition monitoring of particle effects it is worth to mention the vastly increased application of hydraulic fluids for energy transmission throughout todays' industrial markets, and in the O&G industry in particular. This development come as a result of the many advantages given by the application of hydraulic fluids for the transmission of energy, as opposed to traditional measures using moving mechanic parts and gears to perform the same tasks. Examples of its now widespread application are the use of centralized high pressure units (HPU) which deliver pressurized oil to perform tasks like the rotation of machinery. Examples of such can be hydraulic motors for rotation of thruster engines and anchor winches as well as the application of actuators and hydraulic cylinders and so on. Another advantage that have boosted this development is the ability of step less speed adjusting of movable parts by the application of proportional hydraulic valves. In addition to this come the fact that hydraulic oil is an incompressible fluids which give the possibility of very precise operation when applied. With the complex and accurate operations now being performed throughout the industries this feature have been recognized as being especially valuable.

Chemical effects

By analyzing samples of various process fluids like for instance oils or cooling agents one can detect failures in other parts of the system which give will give effects to the properties of the fluid. Sampling of cooling agents will for instance give important information about level of inhibitors to prevent corrosion, the level of conductivity in the fluid, freezing temperatures and so on. Oil sampling will give answers to ingress of contaminants like particles, acid, soot and so on that may lead to a deterioration of the fluid and prevent it from performing its tasks in an adequate way.

Physical effects

As a result of wear and tear the physical abilities of various equipment, machines and their parts may deteriorate and develop weaknesses, deformations, cracks, fractures or other unacceptable levels of wear. These can for instance be the results of general wear, wrong use of equipment, heat, vibrations, overload and faults in materials or bad design. Such failures can be detected by performing various types of non-destructive testing (NDT) like magnetic particle inspection (eddy current), the use of liquid dye penetrants, ultrasonic equipment, x-ray testing or boroscopy. Such techniques now have a widespread application throughout the industries, and it is mostly performed manually on a scheduled basis. In the O&G industry this type of condition monitoring is typically applied for verification of the technical state of different types of equipment, like for instance lifting appliances and drilling equipment.

Temperature effects

As a result of increased friction, misalignment, blockage, cavitation or other types of failures the emitted temperature from different types of equipment and machinery will increase, and be detectable as an abnormal condition by condition monitoring equipment. Different types of techniques and equipment exist, but the most common are in-line temperature sensors for continuous monitoring and infrared cameras for periodic inspections. The procurement costs for advanced thermography equipment have now been significantly reduced due to the rapid technological advances in this area. This has now opened up for a more active use of the technique, and it has now got a widespread application area throughout the industry. Whereas its earlier application was limited to detecting hotspots in electrical cabinets and buses by specialist operators, it is now also applied on a series of different pumps, engines, pipes, coolers and other types of equipment by different types of personnel, enabled by the ever increasing simplicity of the user interfaces.

Electrical effects

By various means of special test equipment it is possible to determine the state of electrical equipment like motor windings, batteries, electrical conductivity of breaker contacts and so on. Thermal effects, vibrations and corrosion are key factors that may lead to the deterioration of electrical equipment. Increased power consumption in relation to power output may be an indicator of this. Testing of electrical components by use of meggers and capacity testing of uninterrupted power supply (UPS) battery packages are examples of typical periodically performed condition monitoring tasks, while electrical motor current and bus voltage and frequency are typical parameters that are often subject to continuous condition monitoring.

Assessment of product quality

In todays' industrial environment demands for quality in products are extremely high. As a result of this the monitoring of products and product quality can help identify failures in one or more machines involved in the production process. This is especially important for organizations involved in the manufacturing industry, but may also be used by other types of organizations.

In the O&G industry many products are not tangible but exist of the delivery of functional services. One example of a functional service is the performing of drilling services. The assessment of the quality of this product can be achieved by considering parameters like for instance the time consumed for tripping in and out of wells as well as the rate of penetration (ROP) achieved by the drilling team. Other parameters that can serve as aids for the determination of quality of services are the number of accidents that lead to loss of operational time, often called lost time incidents (LTI), or the technical availability of assets.

Primary effects monitoring

Use of process control equipment to monitor parameters such as power consumption, temperature, flow rate, pressure and so on may give vital information about the technical state and performance of equipment. In order to utilize this technique in an effective way it is important that the measuring equipment gives a representative indication of the state, i.e. that the measuring equipment is calibrated. It is furthermore important that normal reading values, often referred to as baseline data, are established and understood, so that one will be able to detect a deviation from these normal parameters. The personnel that performs the readings must inherit the required competency in relation to assessing the obtained information. It can be useful to mark off normal parameters in gauges and similar equipment in order to ease the process of detecting failures. If this is done it is important to be aware that different running states will give different readings, which can both be normal but dependent on the different running states.

In todays' industry this is a widespread technique for the monitoring of equipment. From this aspect it is worth pointing out that it is essential that the time between inspections are well within the expected P-F interval, so that the operators will be able to intervene with emerging challenges in a timely manner.

The use of human senses

The use of human senses to detect failures and emerging challenges within various types of equipment has always been, and still remain, a very effective, easy and versatile method. This technique however have several weaknesses. The ability to detect failures will be dependent on the objectivity and the mental awareness of the inspection personnel, and this will be dependent of the level of experience the inspector have obtained from earlier cases. It is also a fairly insensitive technique as it is hard to obtain quantifiable data from the mere sensual observation of equipment. As a result of these factors the inspector may first detect a failure condition when it have been able to develop for some time, in opposition to when dedicated measuring equipment is applied. The upsides with this technique are however obvious as the human capability to both understand and assess the relation between different failures, and how they affect each other, far surpass the ability of any available equipment. A human will also be better be able to determine the severity of a failure as opposed to other types of condition monitoring which is normally limited to the mere recording of operational data and the presentation of this to a human for further assessment. Novel technical solutions, which have the capability of performing advanced diagnostics and prognostics, are however available. Such advanced technical solutions will be further discussed in section 3.8.

3.4 Technical and operational feasibility of condition monitoring

If the condition monitoring techniques applied are appropriate they can be very effective and a great aid to the equipment user in relation to early detection of deterioration or upcoming problems. If the applied techniques are not feasible, or they are implemented in an unsystematic way, the results may be high installation and operation costs and disappointing results. At worst the effort may prove to be a waste of both time and money. When considering the feasibility of condition monitoring it is important to comprehend the fact that even though condition monitoring is technically possible, it may prove not to be a feasible solution from an overall perspective, and should therefore not be applied.

In order to apply condition monitoring as an effective technique for determining the maintenance needs of different equipment types some prerequisites must be met. Factors like physical access to installation of the condition monitoring system, the complexity of the data acquisition system and the level of data processing needed before the user can get readable and useful information must be considered. Cost related issues regarding installation, operation and data processing must be evaluated, and other or existing means of performing the condition monitoring task in an adequate way must be considered. The P-F interval needs to be both well established and seen as fairly consistent, and the length of the P-F interval must also be long enough to enable both detection of the failure condition and to carry out the needed maintenance tasks well before the failure state can develop into a fault. It must be practical to monitor the equipment at shorter intervals than the P-F interval, and lastly the condition monitoring task must be able to give quantifiable data that can be used to indicate the development of a clear failure condition. If this is not the case other methods for determining the technical condition of equipment and establishing maintenance tasks should be applied. Figure 13 below is obtained from ISO 17359; "Condition Monitoring and diagnostics of machines -General Guidelines" and show examples of different condition monitoring parameters and their application in various types of machinery.

Parameter	Machine type								
	Electric motor	Steam turbine	Aero gas turbine	Industrial gas turbine	Pump	Com-pressor	Electric generator	RIC engine	Fan
Temperature	•	•	•	•	•	•	•	•	•
Pressure		•	•	•	•	•		•	•
Pressure (head)					•				
Pressure ratio			•	•		•			
Air flow			•	•		•		•	•
Fuel flow			•	•				•	
Fluid flow		•			•	•			
Current	•						•		
Voltage	•						•		
Resistance	•						•		
Input power	•				•	•	•		•
Output power	•	•	•	•			•	•	
Noise	•	•	•	•	•	•	•	•	•
Vibration	•	•	•	•	•	•	•	•	•
Acoustic techniques	•	•	•	•	•	•	•	•	•
Oil pressure	•	•	•	•	•	•	•	•	•
Oil consumption	•	•	•	•	•	•	•	•	•
Oil (tribology)	•	•	•	•	•	•	•	•	•
Torque	•	•		•		•	•	•	
Speed	•	•	•	•	•	•	•	•	•
Length		•							
Efficiency (derived)		•	•	•	•	•		•	

• Indicates condition monitoring measurement parameter is applicable.

Figure 13 Examples of condition monitoring parameters for different machine types (ISO, 2011)

In order to apply condition monitoring for the assessment of technical state of equipment and the establishment of maintenance tasks in an effective manner, some organizational requirements must also be met. Firstly the method of condition monitoring must be known and acknowledged by all levels in the organization, from the top management to the maintenance engineers that are to perform the tasks. A system for managing the obtained condition monitoring data and transforming this into actionable tasks in a systematic manner must be established. The required level of resources to perform the established maintenance tasks must be assigned, and it is further important that these resources hold the necessary knowledge and competence in order to perform their given tasks in a safe and efficient manner.

3.5 A brief study of the implementation of a CBM strategy

A series of international standards have been established in order to manage the implementation of CBM. Appendix 1 is an overview of pertinent international standards on the subject, based on the article “A new standard for condition monitoring” and the publication “Standards Related to Prognostics and Health Management (PHM) for Manufacturing” (Vogl et al., 2014, Mills, 2011). From the extent of available international standards on the subject one can conclude that the implementation of CBM strategies for equipment is very relevant throughout the industry, due to the possible substantial benefits it may provide. These standards and their content will however not be discussed in detail in the following, as it lies outside of the scope of this thesis. It is however worth to mention that ISO 17359:2011 is an umbrella document for a series of other standards related to condition monitoring and diagnostics. This standard include a methodical approach flowchart, as shown in Figure 14 below, for the implementation of condition monitoring techniques founding a basis for a CBM strategy for equipment. Based on the flowchart a brief explanation of this generic implementation procedure for CBM will be given in the following sections of this thesis.

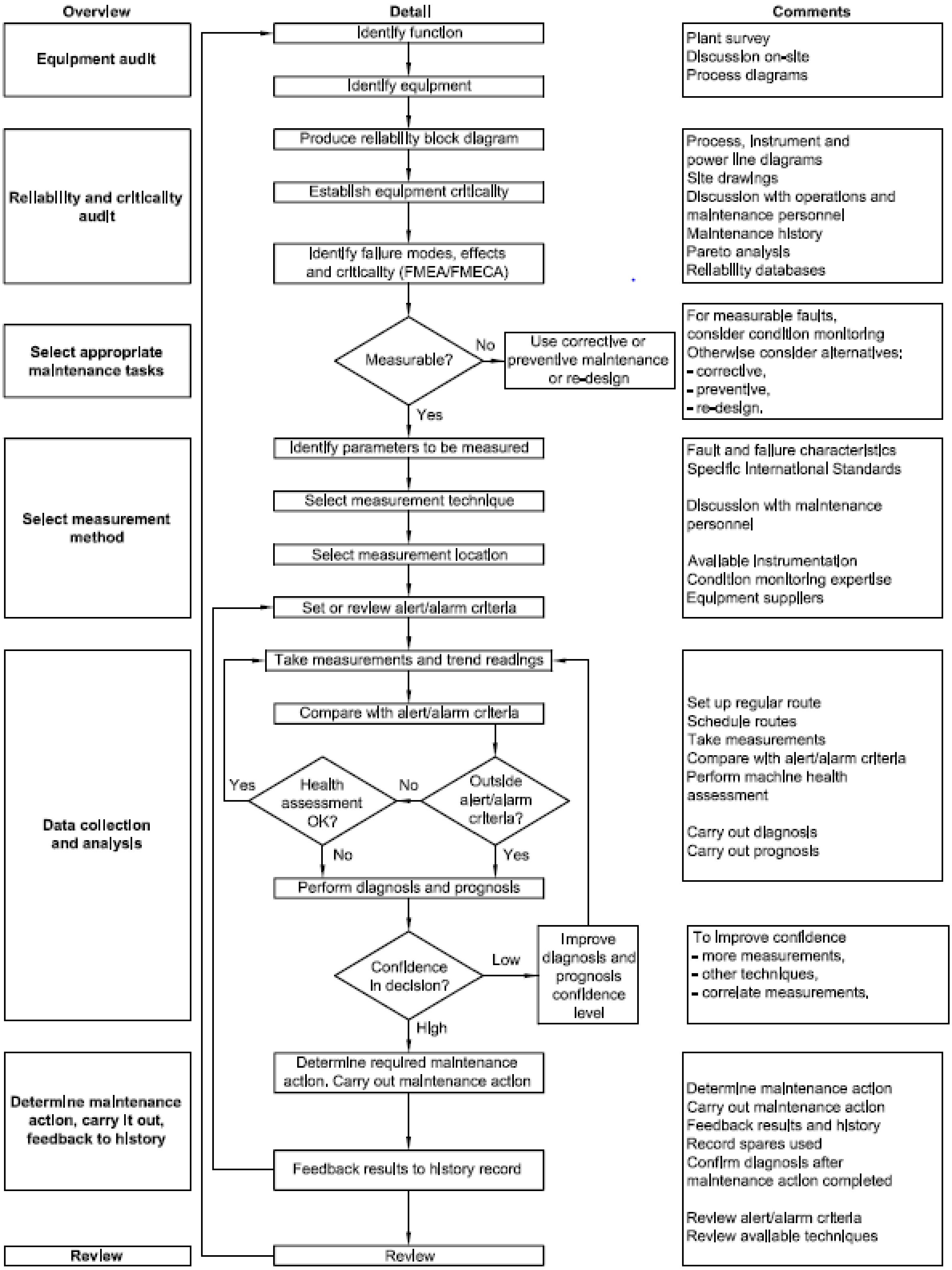


Figure 14 Condition monitoring procedure flowchart (ISO, 2011)

Identification of equipment and equipment function

When considering the eligibility of equipment for implementing condition monitoring it is appropriate to first identify the different types of equipment involved, as well as determining the equipment's requirements and functions, as well as identify their normal operating conditions. This equipment audit will serve as an aid in the effective performing of the following steps of the procedure.

Reliability and criticality audit

The determination of the reliability of the equipment will serve as an aid when it comes to targeting the condition monitoring processes to equipment where this will have the desired effects. In addition to this it is recommended to create a prioritized list of equipment and systems that are to be included or excluded from the condition monitoring program. The classification can be based on factors like:

- Safety and environmental impacts resulting from equipment faults
- Costs related to machine down-time or lost production costs
- Costs related to secondary impacts on related equipment resulting from faults in equipment
- LCC of equipment and systems
- Costs related to maintenance and spare parts
- Mean time to failure (MTTF)/ Mean time to repair (MTTR)
- Acquisition, operational and maintenance cost of condition monitoring equipment

It can also prove beneficial to perform the previously described FMECA at this point, as this will identify key parameters to monitor in relation to possible errors and failure states of the equipment in question. A list of relevant technical condition monitoring parameters for different equipment types is shown in Figure 13.

Selection of alternative maintenance tasks

If the identified errors and failure modes do not exude any measurable or quantifiable parameters or symptoms, or if such symptoms reveal themselves at a time which will not enable measures to be taken within the P-F interval, other maintenance strategies must be applied. Such strategies can for instance be CM, PM or the modification of equipment so that the identified failure causes are entirely designed-out if possible.

Choice of measurement methods

As aforementioned a series of different condition monitoring techniques are available, ranging from continuous, semi-continuous and periodical techniques involving dissimilar types of equipment and methods. The choice of method is dependent of the nature and specific needs of the equipment where it shall be applied. There are however some general points that needs to be taken into consideration when it comes to the choice of method:

- As aforementioned the technical feasibility of the measurement technique must be considered for each specific equipment.
- The location of the measurement equipment is crucial as the sensor must be placed in the part of the system that is expected to give the first identifiable signs of deterioration. If several such spots exist in the same machine, the application of a combination of several sensors should be considered. If a periodic measurement approach is chosen it is important that the measurements are performed at the same place from time to time, and that the measure is taken under similar operating conditions. An aid to obtain this goal can be the establishment of a list of specific sampling points, which are clearly numbered and marked on the various equipment. In addition to this specific procedures describing the operating conditions when the sampling is performed can be created to ensure the quality and usability of the obtained data.
- The measurement interval must be determined. This will be dependent on the lead time for development of faults, i.e. the length of the P-F interval. Factors like safety, criticality and cost will influence the choice between continuous, semi-continuous or periodic measurement techniques.
- The sample rate, i.e. the time between each interval must be determined in a way that the lowest detectable deterioration will be discovered between two consecutive intervals.
- The necessary accuracy of the monitored parameters will determine the requirement for the precision of the measurement equipment. For some types of machinery the most important element is the ability to detect a development in a trend, whereas other types of equipment require a sampling of exact parameters in order to establish a picture of the technical state. In this context it is further important to be aware that if the measured parameters are to be used for performance testing or other purposes there may be higher requirements for accuracy and level of detail in the data.
- The normal operating conditions during measurements must be established in order to eliminate false readings giving invalid inputs to the CBM system. An example of this can be the need for suppressing monitored parameters during startup and shutdown of equipment, as the parameters in these phases naturally will deviate from readings obtained during normal operation. In this context it is also worth mentioning that the establishment of baseline readings, i.e. samples taken when equipment was new and operating under optimal running conditions, can serve as a great aid in detecting deteriorating conditions at later stages of the lifetime of equipment.
- In relation to the measured parameters it is necessary to establish a set of alarm criteria. A balancing must be performed between early detection and warning of deteriorating

trends and unnecessary and irrelevant alarms. Time delays for the triggering of alarms should be considered implemented where this is suitable, so that natural temporary changes from normal running parameters as a result of operational changes will not give irrelevant alarms. The alarm types should be classified so that the system operator can easily assess the level of severity in relation to the alarm. Such classification can for instance be a low level alarm or a "lowlow" level alarm, which can also be used for other purposes, like for instance automatic shutdown functions. Either increasing or decreasing values can be triggering factors, dependent of the application and nature of the condition monitoring. These alarm criteria should be subject to revision and improvement when one have obtained a certain degree of operational experience. Similarly their given limits should be improved over time as an iterating process as the system operator obtains more operational experience in relation to what is the most adequate alarm level.

Data collection and analysis

One commonly used method for data collection is to obtain various measurement parameters by periodic inspections. These inspections are performed with a higher frequency than the expected or known deterioration rate that will cause errors and failure states. Then the obtained results are compared with previous sampled results or baseline values of the same parameters. By the implementation of the measured parameters into a remote or centralized condition monitoring system the necessity of manual inspections can be reduced or fully removed. If abnormalities in relation to normal readings are detected there is a need for performing diagnostics and prognostics in relation to the obtained data. Here one can choose to focus on the error or failure itself in order to rectify the situation, but it is also advisable to pursue the detection of the cause for the error or failure. If one is successfully able to identify the cause for the error or failure one can move on to performing adequately targeted maintenance activities. If there is uncertainty in relation to the cause of the failure, more thorough analysis and improvement of the diagnostics may be required. Such tasks can be repeated sampling of data, comparison of data to previous known deterioration cases or baseline data, performing additional sampling of data at other points in the system or the application of more advanced or alternative techniques to verify the obtained results. A sensitivity analysis can also be performed by the combination of altering the operational state of the equipment and performing new sampling of data. If these techniques do not produce the desired results in the form of giving answers to the cause of the error or failure it may be necessary to seek advice from personnel with expert knowledge on the equipment, like for instance vendors or service providers.

Determining maintenance activities

The least demanding reaction to obtained data from condition monitoring is naturally to do nothing at all. Even though this may seem as an irresponsible approach this it may be the appropriate one based on the criticality of equipment and the severity of the error or failure. If such an approach is chosen the continued condition monitoring will be the action chosen for follow up, in order to be able to consider the performing of certain actions at a later time when one have obtained more knowledge on the development rate of the deterioration. In other cases it may be sufficient to alter operational parameters such as for instance the workload of equipment so that the monitored values are moved within acceptable levels. In cases where this is not desirable or possible it can be necessary to perform inspections or CM tasks. If this is the case it is important that operational values and parameters obtained through condition monitoring both before and after the maintenance task is carried out is reported in the Computerized Maintenance Management System (CMMS). In this way one is able to generate useful historical data for the equipment, which can serve as a tool for improving maintenance intervals and future maintenance tasks. It is further important to note the downtime of the equipment when performing maintenance tasks, as well as documenting the consumed spare parts and resources into the CMMS so that work tasks can be more easily planned in the future. Another substantial benefit of generating a maintenance history for the equipment in the CMMS is the ability to detect repetitive failures in the same equipment, which can be indicators of bad design, operating equipment out of design values or other related issues that needs to be dealt with.

Review and audit of the system

New technological solutions which were not available or considered unfeasible at the time the condition monitoring system was established may on review be considered as feasible. This can result from things like reduction in procurement costs of equipment or the invention of new technological solutions and so on. From this it can be seen that review and audit of the system focusing on the effectiveness of the techniques applied should be performed on a regular basis, so that improvements can be made. This approach is in line with good asset management practices described in part 2, as well as being in line with the continuous improvement approach which is widely applied by the actors involved with the O&G activities on the NCS.

As aforementioned it is also useful to evaluate the alarm criteria and limits in order to improve the early warning of emerging challenges. The alteration of alarm criteria and limits may also become necessary as a result of natural degradation of components and equipment, while it at the same time is deemed appropriate to continue operation of the equipment in question. In such cases, and after CM tasks has been performed it can be necessary to establish new baselines to be able to discover deviations from normal running parameters. This follow as the normal operational parameters of the equipment may be substantially altered by the maintenance tasks being performed or as a result of acceptable degradation.

Training of personnel

When establishing a CBM strategy it is important that all involved personnel are given the required training to perform their tasks in a safe and efficient manner. Several factors are important, where the understanding of the condition monitoring technique itself often prove to the most important one. Competence in relation to the operation of monitoring equipment must be obtained, as well as the competence to be able to interpret the obtained data by condition monitoring. Based on this interpretation the forming of adequate maintenance tasks in order to be able to rectify identified deterioration can be complicated, as it will require a great deal of equipment and system understanding from the involved personnel. In order to give the system operators the required level of knowledge one may initiate training and development programs (Rahimi et al., 1988).

3.6 Advantages and disadvantages with a CBM strategy

In many cases maintenance activities are merely based on expectations to the MTTF or mean time between failures (MTBF) and is performed independently of the actual technical condition of the equipment. There can be many reasons for this, like OEM recommendations, statutory demands or other precautionary principles. However, there seems to be a common understanding throughout the industry in relation to maintenance that as few as possible CM-tasks shall be performed, while at the same time performing as little as possible PM-tasks. In addition to this maintenance activities should be performed at a time which suits the equipment owner, and as late as possible before equipment failures occur. The implementation of condition monitoring in order to establish a CBM strategy for equipment can serve as a facilitator to achieve this. It is however important to assess the need for such a strategy before it is initiated. If the deterioration rate, i.e. the P-F interval of equipment is well established as a linear function with time a PM strategy may prove to be the most appropriate. For many types of equipment however there do not exist, or there has not been established a clear relation with deterioration as a function of time. In such cases condition monitoring can be applied in order to be able to perform predictive maintenance when it is actually needed.

When considering the implementation of a CBM strategy it can be beneficial to be aware of the potential upsides and downsides related with doing this. A short presentation of some possible key advantages and disadvantages are presented in the following. It is underlined that the presented list below is not exhaustive, as other advantages and disadvantages may exist.

Advantages

- *Reduced maintenance costs*
    - As equipment is maintained only when it is actually needed the total number of maintenance tasks will be reduced.

- *Damage limitation*
    - As one obtain the possibility of continuous assessment of equipment health one can intervene with emerging failures before they can harm equipment or give secondary damage to related machinery.

- *Avoidance of production losses and increased production performance*

    - Being able to operate equipment within optimal running parameters for prolonged periods of time as one is given the opportunity to perform necessary adjustments to equipment operational parameters when needed.

- *Improved safety*
    - By continuous assessment of condition and health of equipment the probability of unforeseen breakdowns is significantly reduced, leading to improved safety.

- *Improved lifetime of equipment through the achievement of operating within optimal parameters throughout the lifecycle of equipment*
    - One is given the required information to adjust operational parameters according to equipment needs while the equipment is in operation.

- *Minimized spare part costs*
    - Parts are only replaced when there is an actual need for it.

- *Better budgeting and planning of maintenance related costs*
    - Can predict upcoming maintenance tasks and needs for spare parts.

- *Reduced costs related to labor as maintenance needs are reduced*
    - General reduction of consumed man hours for maintenance tasks following a general reduction of maintenance needs. Overtime related costs can be mitigated as maintenance tasks are predicted.

- *Prospect of being able to postpone or cancel statutory classification activities*
    - By presenting documented knowledge to the healthy state of equipment one may obtain the benefit of postponing statutory maintenance activities.

Disadvantages

- *High initial cost*
    - Procurement and installation costs can be substantial.

- *Complex to integrate after design and construction*
    - If condition monitoring equipment is not designed-in during the design phase extensive work may be needed to implement it at later stages. Problems related to access and integration to related systems may also become a major challenge.

- *False readings from instruments*
    - Faulty sensors or badly designed solutions can give false readings which can be time consuming to sort out.

- *Require high level of training of involved personnel*

- Maintenance and operation personnel needs to be given adequate training in use and maintenance of chosen solutions, as they need to understand the concept and interdisciplinary technicalities of the system.

- *Require system for management, analysis, as well as presentation of large amounts of data*
  - Systems for handling the data, transferring it and processing it into useful information that can be used for actionable tasks must be in place. Such systems may be both complex and costly to acquire and operate.

- *Changes to organizations and how maintenance management is performed*
  - Implementation of CBM require managerial support and restructuring of the organization, maintenance management system as well as forming of new maintenance tasks.

- *Unclear responsibilities between different stakeholders both within and from outside of the organizational boundaries*
  - The inclusion of third parties for the transferring and analyzing of data introduce new challenges related to communication and exchange of information. Complex interactions can require new contractual agreements between involved parties.

- *All these negatives calls for a thorough cost-benefit analysis which itself can be a costly and time demanding task to perform*
  - The consideration of implementing CBM will itself require substantial resources.

3.7 The relationship between integrated operations and CBM

The term integrated operations is defined by OLF as "real time data onshore from offshore fields and new integrated work processes" (Oljeindustriens Landsforening, 2007a). In 2004 OLF raised the focus on this concept as a new development scenario for the O&G industry on NCS. They state that the potential for increased value through the implementation of the IO concept can be NOK250 billion for the actors on NCS (Oljeindustriens Landsforening, 2007b). The development and implementation of novel and advanced ICT-solutions opens the possibility of remote operations, inter-departmental and inter-organizational integration, improved efficiency, improved decision-making processes and improved safety in operations. The application of IO for various types of offshore operations is now recognized and embraced by several large actors on NCS, as illustrated in Figure 15 below, gathered from Katrine Hilmen's presentation from the 2014 Moscow World Petroleum Congress.

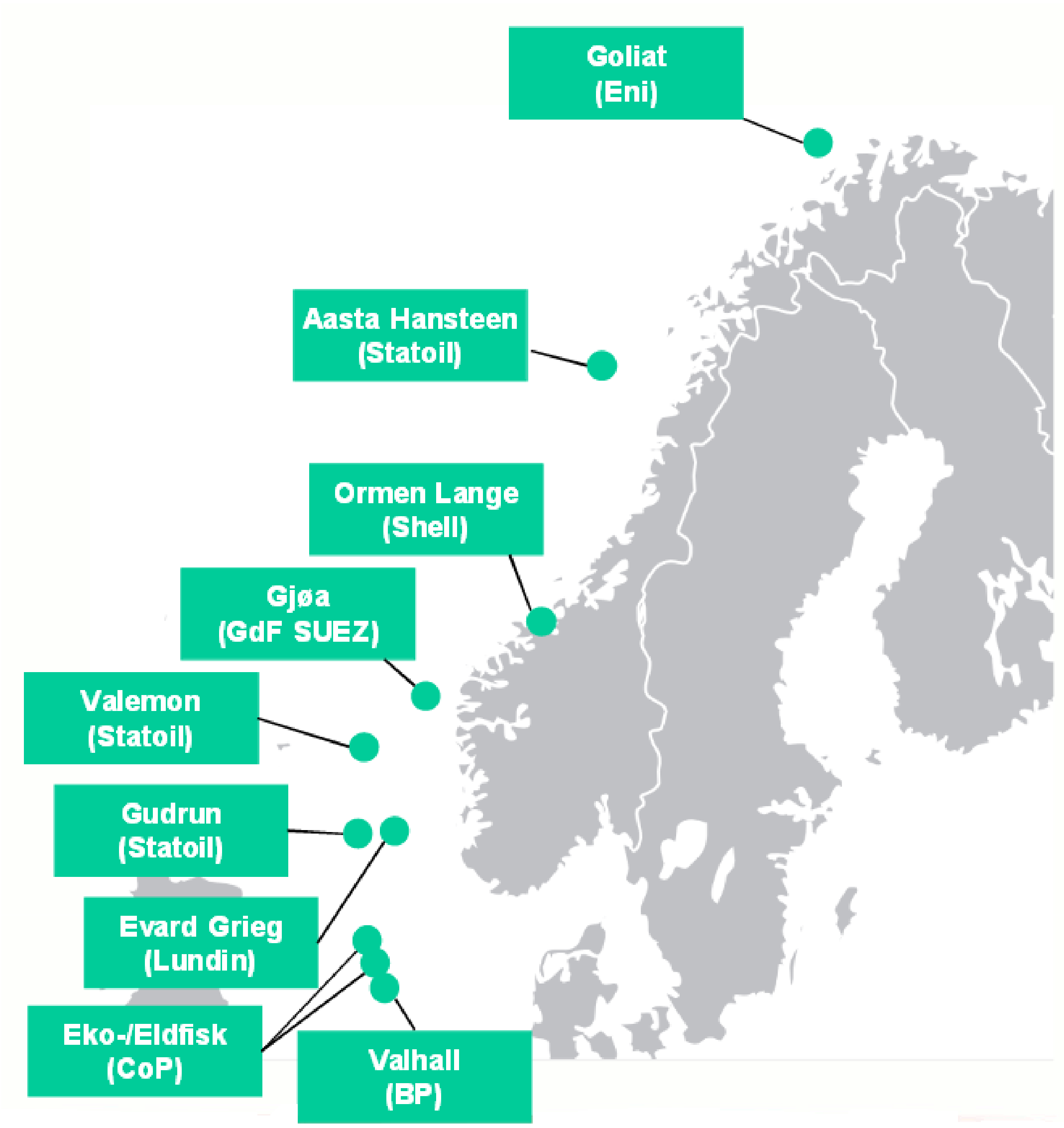


Figure 15 Installations on the NCS which have already implemented IO as a strategy for improved management and operation of their installations (Hilmen and Devold, 2014)

One specific example of an actor that embraces the implementation of IO is Statoil, which on their company web page state that their aspiration is to become a world leading actor within this area (Statoil, 2007). This ambition is reflected in the way Statoil now operate the Kristin platform by extensive application of IO. The management of this asset is performed through the establishment of a parallel structure consisting of two management teams, where one is located offshore and one is located onshore (Statoil, 2008). In doing this they have erased the traditional organizational boundaries between the on- and offshore organizations. This also enable them to harvest on the knowledge held by a significantly larger group of experts than the one situated offshore at any given time. The ability to include involvement from experts independently of their physical location and organizational affiliation have helped them to improve the information intensive performance of their virtual organization.

In the document "Integrated Work Processes: Future work processes on the Norwegian Continental Shelf" OLF presented a graphical illustration of the development and implementation of IO comprising of two separate generations, as shown below in Figure 16.

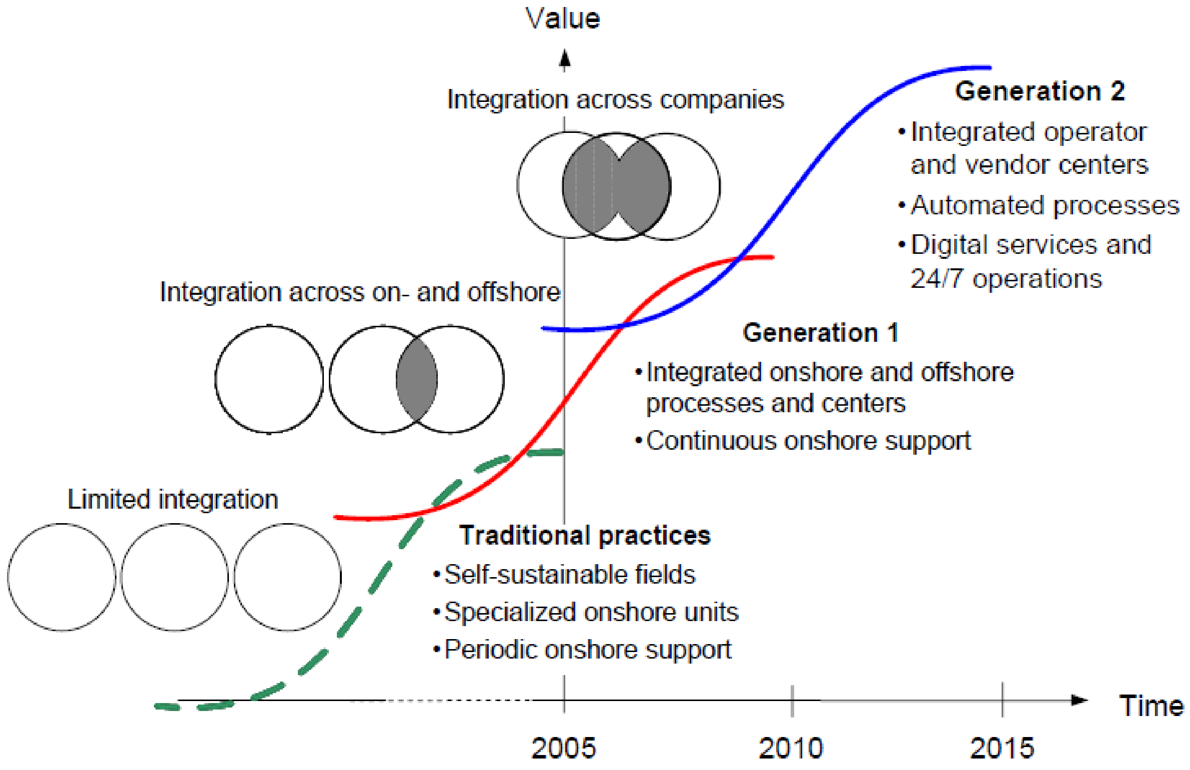


Figure 16 The two generations of IO (Oljeindustriens Landsforening, 2005)

From this it can be concluded that the operation of Kristin mainly involve the 1st generation of IO. Whereas IO to a large degree have been applied for better management of operations this does not seem to be the case for maintenance related issues (Oljeindustriens Landsforening, 2005). There may be several reasons for this, and OLF mentions causes like high work load in organizations, reluctance to be the first one to try new and unproven solutions as well as the lack of organizational structures that fit the concept as some. The use of IO as a facilitator to CBM require a whole new approach to management models and the forming of work processes. This can be seen in relation to part 2 of this thesis regarding asset management, and operations and maintenance decision-making processes in particular.

CBM in combination with IO is applied to some degree by the actors on the NCS, but mainly for few and large equipment types like heavy rotating machinery (Oljeindustriens Landsforening, 2007b). In this aspect it is noteworthy that several OEM's report that they have the ability to provide novel technological solutions for helping customers to better manage their assets, but they experience hesitant customers which decline their offers for various reasons (Oljeindustriens Landsforening, 2007b).

According to OLF the 2nd generation of IO is characterized by network based virtual operational centers with continuous sharing of real-time digital information between different physical locations around the world (Oljeindustriens Landsforening, 2005). 2nd generation IO processes is not yet fully implemented on any installations on the NCS. However, the Statoil platform Gudrun which commenced operations during the fall of 2014, have taken a more aggressive approach to this subject and it seems like the ambition is to implement a larger degree of 2nd generation thinking. This is reflected in the operational strategy which involve a very lean offshore organization whose sole focus is daily operations and maintenance of the offshore asset, and an onshore organization that manages the operations, handles administrative issues and collaborates with vendors from the onshore operations center. The implementation strategy for Gudrun was also to entail existing infrastructure from neighboring fields in order to maximize value. The produced oil and gas is processed on the Sleipner A platform, the gas goes from there to the continent through existing pipelines and the oil goes to Kårstø together with condensate from Sleipner (Statoil, 2014a).

A large potential for increased savings resulting from the future implementation of CBM enabled by IO is still not realized by the actors involved in the O&G industry on the NCS. It is clear that the development of IO serve as an important facilitator for the forming of and implementation of novel data intensive CBM strategies. Such strategies imply the use of service providers for the data management and assessment of technical state as an integral part of the onshore operations management team. In the following section some of the developing trends related to the implementation of such advanced techniques will be further discussed.

3.8 Developing trends related to implementing novel and more advanced condition monitoring technology

According to OLF there is a potential to reduce operation and maintenance costs by 30% through the implementation of CBM. This can be achieved by better exploitation of operational data, reduction of PM tasks and the establishment of campaign based implementation models (Oljeindustriens Landsforening, 2007b). The magnitude of the upsides are further manifested by the prospect of increased efficiency, improved safety and higher operational time of equipment. But determining the steps that needs to be taken in order to reach such an ambitious goal can be both uncomprehensive and complex, and many impediments pave the way leading to progress. The successful implementation of novel, automated and advanced condition monitoring techniques, and the integration of these into a larger system that incorporate other elements such as logistics, spare part planning, resource allocation and so on, can be facilitating factors in order to achieve this goal. The fundamentals of some of the techniques now being applied for this will be described in the following section.

Going from CBM to integrated e-operations

Traditional CBM follows the practice of determining maintenance needs based on information gathered from various condition monitoring techniques, as earlier described. It include the three steps of data acquisition, data processing and maintenance decision making (Jardine et al., 2006). As the availability of new technology increases rapidly novel solutions in relation to advanced diagnostics and prognostics present themselves as important integral parts of CBM. Diagnostics is “the determination of the current condition of a component or system, and prognostics is the predictive ability of future performance degradation and expected failures.” (Vogl et al., 2014). By combining input from different sensors placed in various parts of equipment, processes or machines one can better predict failures, and more importantly, be able to pinpoint which part or element of the system is the root cause for a failure if it should occur. When this information from smart machines is embedded in a network which enable remote monitoring and operation, as well as performing modelling and continuous analysis on the transferred data, one have moved from the traditional CBM practice to also include what is called “intelligent prognostics”. This is defined as “continuously tracking health degradation and extrapolating temporal behavior of health indicators to predict risks of unacceptable behavior over time as well as pinpointing exactly which components of a machine are likely to fail.” (Lee et al., 2006). Through obtaining real-time and continuous insight on both present and future predicted states of equipment and systems one can advance operations to also include what is described as e-maintenance. This approach enable system owners to plan and harmonize maintenance activities with other corresponding maintenance activities and the overall operation of the plant. Furthermore system owners are by this given the opportunity to order spare parts and allocate the needed resources to perform the maintenance tasks at a time suitable for the equipment owner.

In many cases vendors provide customers with relatively smart machines which entail a large number of condition monitoring equipment, rendering the customer the ability to make use of this data for improved asset management. The problem however is that little or no practical use is made of this data. There exist many reasons for this, one being the lack of the necessary tools to interpret and gather the information into a useable form. Other reasons are the lack of technical infrastructure for transferring the data, or the lack of resources or competence to handle it if the data is transferred (Djurdjanovic et al., 2003).

Due to the rapid increasing numbers of various types of data inputs to the condition monitoring system from sensors placed on disparate components, equipment and systems there has emerged a need for standardization of data types and exchange of information. In addition to this there is a need for a standard architecture and framework for implementing different types of hardware and software into the CBM program. Machinery Information Management Open Standards Alliance (MIMOSA) is a “not-for-profit trade association dedicated to developing and encouraging the adoption of open information standards for Operations and Maintenance in manufacturing, fleet, and facility environments. MIMOSA's open standards enable collaborative asset lifecycle management in both commercial and military applications.” (Mimosa, 2015). MIMOSA have developed an architecture for exchange and moving of information throughout CBM systems, namely the Open System Architecture for Condition-Based Maintenance (OSA-CBM). The purpose with developing this system was to stimulate CBM service providers to standardize the information exchange specifications so that one could obtain improved integration and interchangeability of CBM components through the open systems architecture. The OSA-CBM is defined by the application of the Unified Modelling Language, and is versatile, as it separates the exchange of information in the CBM system from the specific technical interfaces that the system integrators apply in order to communicate the information. As a result of this, both equipment vendors and data integrators can implement the standard using the appropriate technology which fit their specific needs. This multitechnological implementation design for CBM comprise of six functionality blocks, as shown in Figure 17 below. This design is in compliance with the ISO 13374-2. OSA-CBM adds data structures and methods for creating interfaces between the different functionality blocks. In other words one can say that this processing architecture both process and transform basic obtained condition monitoring data into actionable information. This information can for instance be utilized for the generation of predictive maintenance tasks.

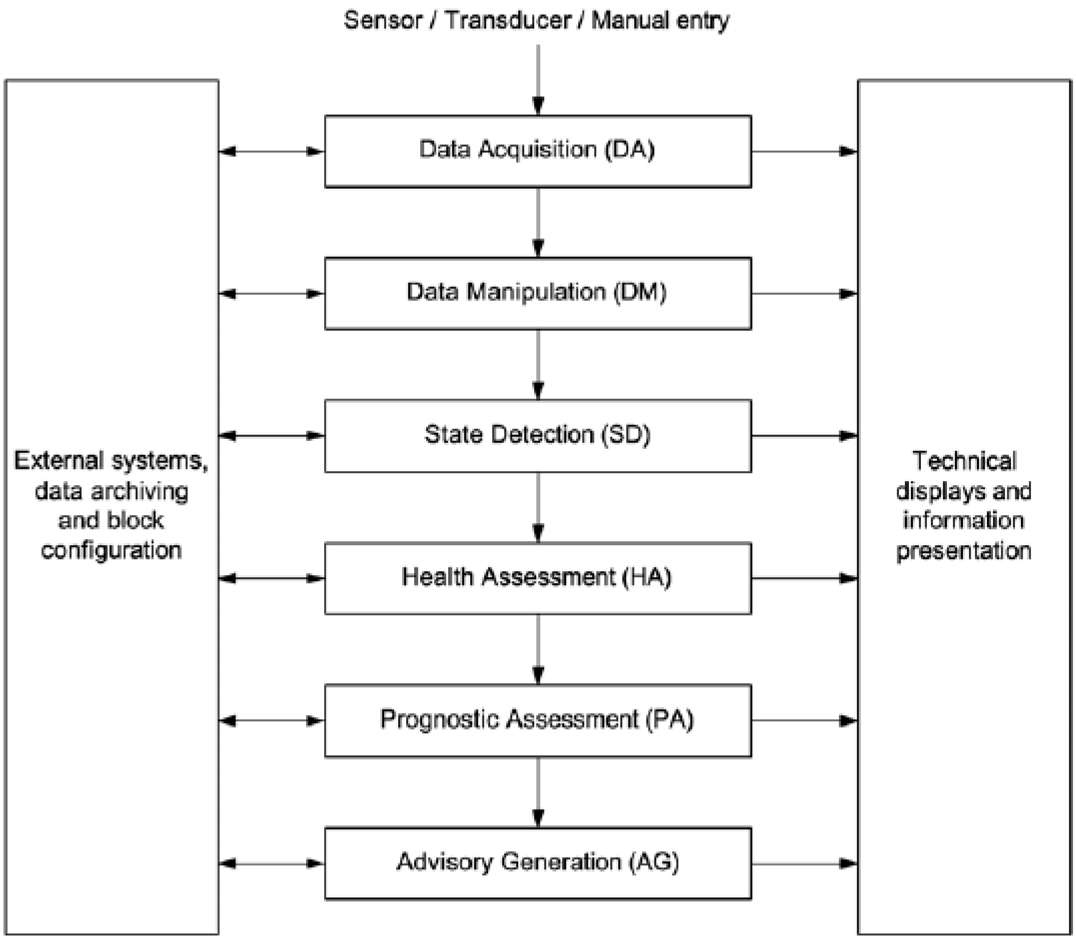


Figure 17Open condition monitoring and diagnostics processing architecture –functionality blocks of OSA-CBM (ISO, 2007)

The functional blocks of this structure will not be given a detailed explanation in this thesis, as this can be found in ISO 13374-2 (ISO, 2007). Figure 17 is however included to illustrate possibilities of developing trends in the O&G industry on the NCS in relation to the subject of improved asset management by the implementation of more advanced solutions for diagnostics and prognostics. One can suggest that through the extended application of the OSA-CBM for improved integration and more easy transformation of obtained data into actionable issues while moving from traditional PM to advanced CBM strategies, one can gain the opportunity of substantial increased value generation, as the involved processes become less resource demanding, more intuitive and more streamlined. This can be seen in opposition to some current practices in the O&G industry on the NCS where the manual transfer, analyzing and reporting on data is still being performed.

The Watchdog Agent Technology

An example of an agent for multi-sensor performance assessment and prediction of emerging challenges is the Watchdog Agent Technology. It assesses the values of a number of parameters, and looks at the relation between them in order to be able to generate a quantifiable presentation of system and component degradation. It combines the human-like reasoning of the fuzzy system with the learning and connectionist structure of neural networks. The application of artificial neural networks are powerful tools for helping to perform tasks like advanced pattern recognition using machine learning (National Instruments, 2014). This is made possible by the continuous comparison of the various sampled values in relation to the established baseline values recorded when the equipment was in a healthy state. As a result of this one is able to exclude the influence of faulty readings, and one have eliminated the need for manual input by expert knowledge in the performance assessment process. The Watchdog Agent also have the possibility to save and learn from operational history, enabling it to recognize earlier known cases of degradation, and apply this in order to present a quantified prediction of the deterioration rate resulting from the occurring error. Hence, the Watchdog Agent can be argued to hold elements of intelligent behavior that makes it possible to answer two very important questions; namely establish a quantified prognostic answer to when the observed degradation will cause the equipment to develop a failure state, or when the error develops into a fault state. The other answer the Watchdog Agent offer is the diagnostic detection of why the degradation process started in the first place, i.e. ferreting out the root cause for the start of degradation (Djurdjanovic et al., 2003).

This novel technology has already been successfully used by a group of researchers at the University of Cincinnati for the prediction and prevention of hydraulic hose failures. In a presentation of this study they state that “the hydraulic hose health monitoring technology can be adapted for a variety of customer segments, including oil, gas, and mining applications. For customers in the oil and gas industry, having a hydraulic hose with this health monitoring capability could prevent many hose failures that could cause serious economic or environmental impacts.”(Lee et al., 2014). From this it can be seen that future application of this technology can prove an important tool in order to be able to maintain safe and continuous operation of offshore assets. As the technology now is implemented in the LabWIEW software program delivered by National Instruments it can also successfully be applied for other types of equipment in the future (National Instruments, 2014).

Part 3: Case study and discussion of possible improvement potentials

Figure 18 CDE official logo and COSL Philosophy stating "Always Do Better" (COSL Drilling Europe, 2008)

This part of the thesis comprise of the sections 4 and 5. Section 4 is a case study of the company COSL Drilling Europe, and is dedicated to describing the way this company is organized, in other words the state of the art in CDE.

Section 5 is dedicated to a discussion of the state of the art described in section 4 in particular, but also incorporate considerations in relation to what is previously described about state of the art in part 2 of the thesis.

4. Case study of COSL Drilling Europe

In the highly competitive O&G industry on the NCS the actors see an increasing demand for high operational time and efficiency in operations, in combination with minimal costs related to operation and maintenance. This section of the thesis provides a case study of the drilling company CDE. The goal is to provide the reader with an informative picture of the current asset management practices performed by one of the actors operating in the O&G industry on the NCS. First a brief introduction will be given to the operational strategy of the company. Secondly the maintenance management and strategy, and the processes related to these will be explained. The asset COSL Innovator will be introduced, as it will be used for further studies in this and the following section 5. Current condition monitoring and CBM strategies for equipment will be explained, in order to demonstrate how this technology enables CDE to perform improved decision-making processes related to management of the asset from an operation and maintenance perspective. This study is further performed to establish a basis for the presentation of possible improvement potentials which are proposed in section 5.

Introduction

CDE is a subsidiary to China Oilfield Services Limited (COSL). The CDE head office is located in Stavanger, Norway. The company owns and operates 3 drilling units and 2 accommodation units, all of which are operating in the North Sea. One drilling rig, COSL Pioneer is currently suspended from its drilling contract with Statoil due to reduced demand for drilling services in the market, and is presently stationed at Coast Center Base, Ågotnes (Statoil, 2014b). The accommodation rig COSL Rigmar is currently without contract, and is now cold stacked in the shipyard Kvina Verft, Flekkefjord as a result of this (Offshore.no, 2015a). In addition to this CDE took delivery of the fully winterized new build SSDR COSL Prospector from Yantai CIMC Raffles Shipyard, China in Q4 2014(Almeida, 2014). This rig is now about to commence drilling operations in the South China Sea under management of COSL China due to the lack of available drilling contracts on the NCS. CDE employ approximately 800 persons.

4.1 Operational strategy

On the company webpage CDE state that "The vision for COSL Drilling Europe is to be the preferred supplier of drilling- and accommodation services in the North Sea"(COSL Drilling Europe, 2015b). The main mission of the company is described as "to build and operate fit for purpose semi-submersible drilling units and provide world-class offshore drilling and well operations anywhere in the world". The core values of CDE which found the basis for all their operations are "honesty, motivation and cooperation".

CDE has been a rapid growing company throughout the last decade, as illustrated in Figure 19 below. Their strategy is to operate compact, versatile drilling units with reasonably affordable operational costs. The three relatively new drilling rigs operating on the NCS are of the same GG4000 design, and the fact that the rigs are near identical gives CDE several benefits related to economies of scale in operations of the non-diversified asset portfolio. Such benefits can be exemplified by their establishing of an onshore warehouse located at Mongstad, which is geographically located near the field of operations for the rigs. The close proximity of the warehouse enables CDE to place a larger amount of spare parts onshore, reducing the need for carrying an unnecessary large stock of spares on board. In addition to this the operation of the identical rigs enable CDE to reduce unnecessary overhead costs as the overall need for carrying items in stock onshore is significantly reduced as the same common fleet spares can be used throughout the asset portfolio. The fact that a large amount of spare parts can be stored in a dry and stable environment in the warehouse onshore, while at the same time keeping the lead time for spares arriving offshore at a minimum, opens the possibility of reducing the carrying costs of spare parts significantly.

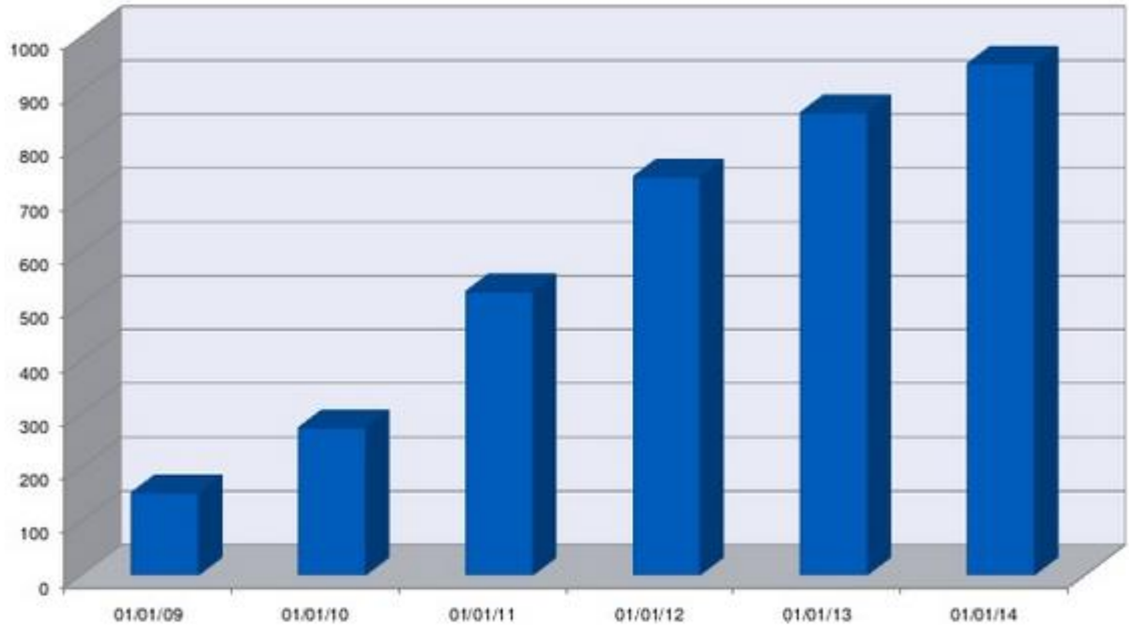


Figure 19 Development of manning situation CDE 2009-2014 (COSL Drilling Europe, 2014a)

Another competitive advantage that CDE have in relation to other companies is the ability to rotate personnel between the different rigs, as the assets are alike and operated in the same way. This advantage has been especially highlighted during the last year, as CDE have been able to utilize personnel from the suspended rig COSL Pioneer to fill in for personnel on their other drilling rigs. This practice have also given several positive synergies in relation to improved experience transfer between personnel from the different rigs as well as improving the working environment in general. The fact that CDE is a relatively small company operated out of Stavanger, Norway opens up for short lines of communication and effective collaboration between the top management in the land organization and the offshore organizations. Personnel on all levels of the organization are encouraged to contribute to the continuous improvement of CDE, in accordance with their philosophy which state "always do better". Through empowering the employees CDE have managed to obtain an organization of highly skilled and motivated employees. The latter is especially valuable seen in relation to the fact that CDE have experienced serious challenges in relation to the declining drilling contractor market during the recent year.

From Figure 19 it is made clear that CDE have engaged a large amount of new employees over the recent years. By focusing on recruiting personnel from a diversity of companies one have enabled the forming of a unique organizational culture, instead of just ending up with adopting one from the organization where the recruited personnel were previously employed. The recruitment strategy is illustrated in Figure 20 below. CDE have a strong focus on sustaining their position as a preferred employer. This has been proven by several cases during the recent year, one being the agreement on a 10% salary reduction for all employees in order to prevent the layoff of some 100 colleagues resulting from the suspension of COSL Pioneer in the fall of 2014 (Topdahl, 2014) .

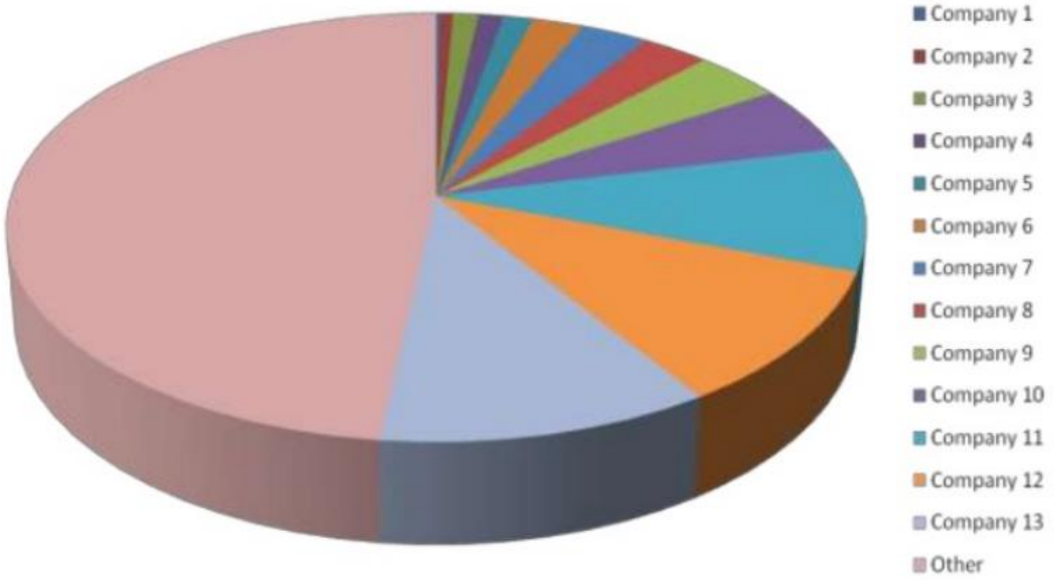


Figure 20 CDE Recruitment Strategy (COSL Drilling Europe, 2014d)

In order to illustrate how reference documents in this thesis gathered from CDE have been accessed, it is meaningful to give a short introduction to the CDE Company Management System (CMS), and this will be provided in the following chapter. This overview is also provided since the systematic way of organizing the company's documentation is an important element of the asset management strategy of CDE.

Company Management System

To enable all employees easy access to the current version of their managing documents CDE have implemented the CMS. This incorporate the use of the document management system "OpenText Document Management eDOCS Edition" (eDOCS DM). On their internet page OpenText state that "employees spend between 30 and 40 percent of their time creating, searching for, retrieving, repurposing and organizing documents -time wasted. In document intensive industries this seriously impact the decision-making process, hindering organizational agility and limiting competitive advantage". They further write that their application eDOCS DM "eliminates inefficiencies caused by the inability to manage and organize the explosion of electronic content by creating a single, highly scalable library for all your work product and matter information." (OpentText, 2015). In CDE the latest issued version of the managing documents are stored on a server which can be accessed from anywhere in the world through the company intranet page. The documents follow a company specific standard for structuring and are classified into the following four levels:

- L1: Overarching management manuals and documents which are applicable to all assets in the company
- L2: Generic manuals, procedures and documents which apply to all assets in the company
- L3: Regional manuals regarding specific types of assets, like for instance drilling rigs
- L4: Asset specific guidelines, operational procedures, manuals and work instructions

The documents are divided into the following types:

- HSE Directive
- Manual
- Work Instruction
- Checklist
- Form
- Procedures

The documents are divided into the following document groups:

- Marketing & Contract
- HSE&Q
- Operations
- Finance & Accounting
- HR/ Administration
- Project

Lastly all documents are linked to the asset or assets they are applicable to, namely:

- COSL Pioneer
- COSL Innovator
- COSL Promoter
- COSL Prospector
- COSL Rival
- COSL Rigmar
- Project
- Office
- Base (warehouse)

It is possible to filter searches by position, free text or by recent updates on the four different levels, or in any combination of these, so that obtaining access to- and finding the document one is looking for is both an intuitive and easy task.

In the internal CDE document "CMS Documents, Issue and Revision" CDE state that all CMS documents "shall be outlined in a manner so that they reflect all relevant quality elements in the Table of Content according to Deming's Circle." Deming's circle follows an iterative four step methodology for optimal planning and control when performing various business processes (Arveson, 1998). It involve the following four steps:

- Plan -which involve the establishment of objectives and the processes needed to be able to produce results that are in accordance with the desired output, in this case the establishment of well formulated and applicable governing internal documents.

- Do –this part involve the actual performing of the task, in this case the preparing of an internal document.

- Check – is related to determining whether the desired output stated in the Plan phase have been reached. In this case it involve the gathering of feedback on the prepared document by relevant parties so that the quality of the document can be verified before it is approved for use.

- Act –if it is identified by the Check phase that the desired objective in the Plan phase was obtained by the Do phase, the new process is implemented. In this case this means that if the new or revised document is found to be more suitable than the existing one it is implemented as a new or improved governing document to the CMS.

The circle is formed as a continuous process, meaning that when the Act phase is complete, the process returns to the Plan phase. In this case it involve the continuous improvement process of the governing internal documents. Experience, changes to equipment, new requirements or other processes may induce the need for revision of documents

Deming's PCDA process, as shown below in Figure 21 gathered from the internal CDE document "CMS Documents, Issue and Revision" have been adopted by CDE to avoid frequent changes to documents, and to optimize their quality and validity. The relevance of this model can further be exemplified by its application in the new ISO 55000 standard on asset management (ISO, 2014).

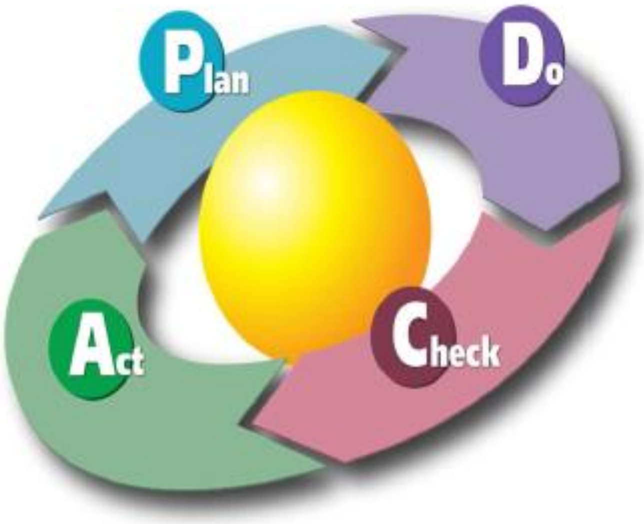


Figure 21Deming's Circle of Plan-Do-Check-Act (COSL Drilling Europe, 2015a)

According to the internal CDE document "Quality Management Manual" The CDE management system framework is based on requirements and recommendations given in the standards ISO 9001 and 14001, as well as on Norwegian HSE regulations and maritime regulations where these are applicable (COSL Drilling Europe, 2014e).

4.2 Maintenance management

The maintenance management model described in Figure 22 below, gathered from the CDE internal document "Maintenance Management Manual" forms the basis for the following brief introduction to the maintenance management practices in CDE.

The input on the left side of the model starts with the identification of the available *maintenance resources*. These are related to the three elements *organizational* resources, available *materials* for performing maintenance tasks and lastly the available *documentation* for assisting in the safe and efficient performing of these tasks. On the other side of the model the *maintenance output* is projected. This relates to being able to produce the desired outputs, while at the same time being able to maintaining a safe operation of the asset. The inherent *risk* of performing the maintenance tasks is sought mitigated by the effective management of processes involved, while at the same time keeping maintenance *costs* at a minimum.

The maintenance management model is to produce quantifiable outputs in relation to health, safety, environment and quality (HSEQ), *regularity* of production, costs related to maintenance as well as the risk exposure with performing the tasks. Such parameters are measured in the MPI's, which will be further discussed in the chapter related to maintenance objectives. If assessment of the MPI's reveals that the maintenance output deviates from the expected or desired output improvement measures must be implemented to the maintenance management process. Such improvements can result from evaluation of the efficiency and effectiveness of current tasks, as well as implementing changes to the managerial maintenance strategy itself.

It is important that the needed *resources* for performing the maintenance tasks are available, and if this is not the case a reallocation must be managed and performed. Lack of resources can for instance be identified by evaluation of the number of overdue maintenance tasks.

The desired *operational integrity* level must be clearly defined, so that it will be possible to implement changes and improvements as necessary if the desired level is not reached. A quantification of the desired integrity level should be performed in relation to the areas of HSEQ and production regularity, so that proper assessment of the fulfilment of goals can be performed.

The onshore maintenance manager is responsible for the *supervision* of the maintenance management, but this task is delegated to the maintenance evaluation group (MEG). Relevant data obtained from the CMMS serve as an important aid in this process, as this enables the assessment of parameters like number of overdue jobs, the ratio between CM, PM and CBM tasks as well as keeping track of resources and spare part consumption. Such data will be presented to the maintenance manager in a monthly maintenance review meeting by the MEG.

The development of the maintenance *program* starts with identifying the *requirements* for the maintenance system. The maintenance system is defined to comprise of the main elements CMMS, MEG and the establishment of relevant procedures and routines. The requirements of the system is to fulfill the maintenance needs related to various stakeholders like authorities, class, CDE and client. The development of the maintenance program will be further discussed in a following chapter.

The primary objective of *planning* maintenance tasks is to ensure that they will be performed according to their specifications within their set due date, while at the same time not interfering with operational activities of the rig. They are to be performed so that the safe and efficient operation of the rig can be maintained at all times. In order to achieve this careful consideration of the operational plans needs to be taken into account when maintenance plans are being made, so that the equipment that is to be maintained can be serviced without any interference with the daily operations. The ability to perform continuous operations while equipment is being serviced lay the foundation for a steady income from the client. The planning of maintenance tasks also involve allocation of the needed resources and personnel, including the availability of spare parts, equipment and the tools needed for performing the maintenance tasks.

The *execution* of maintenance activities shall be performed in such a way that the goal of the maintenance task is obtained both efficiently and safely. This include the use of relevant procedures related to planning, notification of maintenance activities to relevant parties, verified de-energizing of equipment and quality assurance of the task when it is completed. The working area is to be kept tidy and safe at all times.

When a maintenance task is executed it is of the utmost importance that relevant information about the performed activities are systematically reported into the correct systems. It needs to be clearly stated in the work description what types of data is to be recorded into the working history, so that the reporting will be done in a uniform manner each time the task is being performed. Examples of this can be the filling out of forms and data sheets, as well as *reporting* of operational parameters sampled both before and after the performing of maintenance. This is normally reported into the work history in the CMMS. This work is especially important as the availability of documentation lay the foundation for later improvement, as well as giving the opportunity of the verification of maintenance activities to relevant stakeholders like regulatory authorities, client and CDE organization. In addition to this the working history can serve as an aid when planning similar maintenance activities more efficiently in the future, or can be utilized to establish trending of relevant parameters obtained by condition monitoring in order to establish a picture of the deterioration rates of equipment. Improved maintenance budgeting can be obtained by exploitation of historic experience related to maintenance spending. Lastly it is important to identify which maintenance activities are large cost drivers, as they can be made subject to improvement measures.

Maintenance *analysis* can be performed based on earlier performed maintenance tasks, and form the basis for *improvement* processes. It serve as an aid to improve the integrity of the maintenance program by assessing the quality, relevance and costs related to performed activities. Systematic examination of existing maintenance methods, work processes and practices can enable improving their efficiency, or lead the way for developing new processes that can give benefits in relation to improved safety, productivity and reduced maintenance costs.

Maintenance *measures* can be taken for implementing improvements to the existing maintenance system. Such measures can for instance be related to the establishment of a picture of the actual workload in the organization, i.e. a comparison of reported working hours vs. the total available hours. Such measures can be used for optimized performance management, or serve as an aid to optimized planning of operations. If it for instance is revealed that the work load in the organization is too high, resulting in an excessive number of overdue job tasks so that the defined maintenance performance indicators (MPI's) are not being met, an allocation of more resources to the organization may be required. Measures can also be used for the reassessment of equipment criticality, the implementation of added maintenance tasks or the removal of existing ones that fail to serve its purpose, changes in maintenance strategy or maintenance methods for equipment groups. Administrative routines related to reporting, analysis or spare part philosophy may also be subject to such measures.

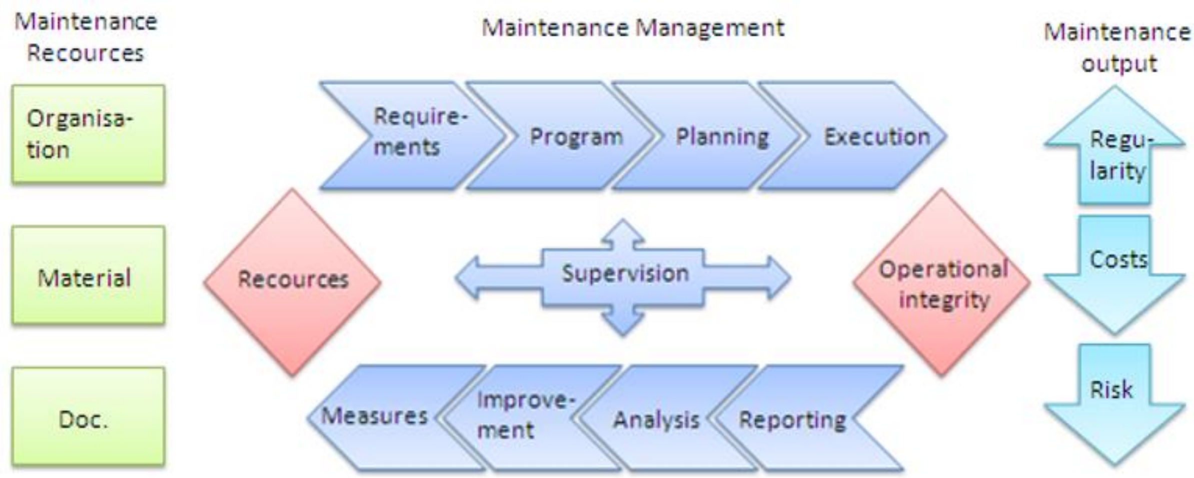


Figure 22 CDE Maintenance Management model(COSL Drilling Europe, 2015c)

Maintenance strategy

In the CDE internal document "Maintenance Management Manual" it is stated that "the implementation of maintenance strategies for equipment units shall be a work process of selecting strategies and methods analytically and systematically based on the Risk Based Maintenance (RBM) philosophy." (COSL Drilling Europe, 2015c). Such a strategy is based on the integration of analysis, measurements and periodic test activities to the more standard PM strategy, in order to optimize the performance of equipment while at the same time keeping the need for maintenance activities at a minimum. It is further stated in the CDE internal document "Maintenance Procedure Manual" that such a process shall be based on the guidelines provided by NORSOK Z-008 (COSL Drilling Europe, 2015h). More specifically CDE have adopted the 3*3 matrix for assigning criticality to equipment types, as described in NORSOK Z-008 (Norsk Standard, 2011). This gives CDE the three notations for criticality:

1. Low criticality
2. Medium criticality
3. High criticality

The areas of criticality are defined in relation to:

1. Health and safety
2. Pollution to environment
3. Operational regularity/ drilling downtime

From this follows the CDE criticality matrix for equipment classification in Figure 23 below.

Criticality Matrix COSL

Criticality	Health & Safety (H&S)	Pollution to Environment	Operational Regularity/ Drilling downtime
3 - High	• Potential for serious personnel injuries. • Render safety critical systems inoperable. • Potential for fire (in classified areas).	• Potential for pollution exceeding 0,75m³	• Stop in drilling > 36 hours
2 – Medium	• Potential for injuries requiring medical treatment. • Limited effect on safety systems controlling hydrocarbons. • No potential for fire (in classified areas).	• Potential for pollution between 0,25m³ and 0,75m³	• Stop in drilling from 12 to 36 hours
1 – Low	• No potential for injuries. • No potential for fire or effect on safety systems.	• No potential for pollution (<0,25m³).	• Stop in drilling < 12 hours.

Figure 23 CDE Criticality matrix for equipment classification (COSL Drilling Europe, 2015c)

A maintenance strategy shall be developed for each equipment unit, and this strategy shall be based on the criticality and failure modes of equipment.

In their selection of a maintenance strategy for different equipment types CDE follow a two phase procedure as described in the CDE internal document "Maintenance Procedure Manual" (COSL Drilling Europe, 2015h). Phase one regards the establishment of a functional hierarchy and performing criticality analysis in order to establish an equipment classification.

Phase one in the procedure consist of the following 4 steps:

1. Perform an evaluation of the equipment in question and decide on which equipment groups that are to be subject for further studies, based on the three criteria safety, regularity and environment
2. Definition of the main function of the equipment and perform a consequence assessment
3. Sub-function definition and consequence assessment in relation to this. Identification of redundancies and possible hidden failure states in the equipment
4. Assign equipment to sub function

The second phase of the procedure is to establish an appropriate maintenance program for the equipment by the application of the classification performed in phase one of the procedure. This include the following 6 steps:

1. If there exist an already approved generic maintenance procedure for equipment types that are classified to have a low criticality on all three areas of criticality this should be chosen

2. If there does not exist a generic maintenance concept for the equipment, and it has been given a low criticality classification on all three areas of criticality, and if there exist no authority or company requirements for maintaining the equipment a "run to failure" maintenance strategy should be chosen

3. If the equipment is given a medium or high criticality classification a more thorough maintenance analysis must be performed, as described in the chapter regarding the working process of establishing a maintenance program below.

4. Selecting a maintenance strategy for each equipment based on the identified risk level

5. Establish maintenance activities and identification of the associated resource requirements

6. Establish work-packages and schedules for the defined maintenance activities

Maintenance objectives

In the process of developing a maintenance strategy for equipment it is meaningful to identify what the desired objectives of the maintenance activities are. In the internal CDE document "Maintenance Management Manual" it is stated that "the maintainable units shall be maintained in such a way that the following objectives are not compromised (COSL Drilling Europe, 2015c):

- Health, safety and environmental objectives
- Quality assurance objectives
- Operational objectives"

These objectives shall be achieved through the implementation of effective maintenance processes. In order to be able to continuously assess the fulfillment of these objectives a set of Maintenance Performance Indicators (MPI) have been established. A list of governing MPI's gathered from the CDE internal document "Maintenance Management Manual" is shown in Figure 24 below.

Maintenance Performance Indicators (MPI)	Accept criteria
TECHNICAL	
Overdue preventive maintenance work orders which has not been treated as a NCR.	0
Overdue corrective work orders	<30
Pending corrective work orders – General	< 200
Number of planned work orders v.s Corrective work orders.	80/20
Rig down time - technical related issues	0
SAFETY	
Safety incidents due to insufficient or lack of maintenance	0
ENVIRONMENT	
Environmental incidents due to insufficient or lack of maintenance.	0

Figure 24 List of governing CDE MPI's (COSL Drilling Europe, 2015c)

CDE states that the achievement of effective maintenance processes shall be facilitated through:

- Effective maintenance administration enabled by the application of established procedures and routines
- Sufficient maintenance management execution, especially performed by the MEG
- Appropriate implementation and administration of all activities in the CMMS

The working process of establishing a maintenance program

The establishment of maintenance programs for equipment is based on the application of acknowledged risk and reliability analysis like criticality analysis and FMECA. In order to enable the effective and efficient use of these analysis techniques CDE have identified that the following prerequisites needs to be met:

- It is beneficial to have maintenance experience from similar equipment and systems
- Experience or knowledge related to deterioration mechanisms and the consequences of failure states in the equipment and systems must be obtained
- The utility value of various maintenance tasks in order to avoid critical failures needs to be identified and understood
- It is beneficial to have experience related to operational maintenance tasks for the different equipment types, so that the most adequate tasks can be chosen for the different equipment types.

Based on the above CDE present Figure 25 below in their internal document “Maintenance Procedure Manual”. This working process for the selection of maintenance program for equipment comprise of the following main elements:

- Data collection of the actual equipment and system design based on information provided by various sources as illustrated in the figure
- The performing of criticality analysis on system and equipment level
- The application of maintenance analysis for critical systems and equipment
- The establishment of a PM program including choice of maintenance strategy and maintenance tasks, job scheduling, allocation of resources and the performing of a spare parts evaluation
- Implementation of the identified and chosen tasks to the CMMS

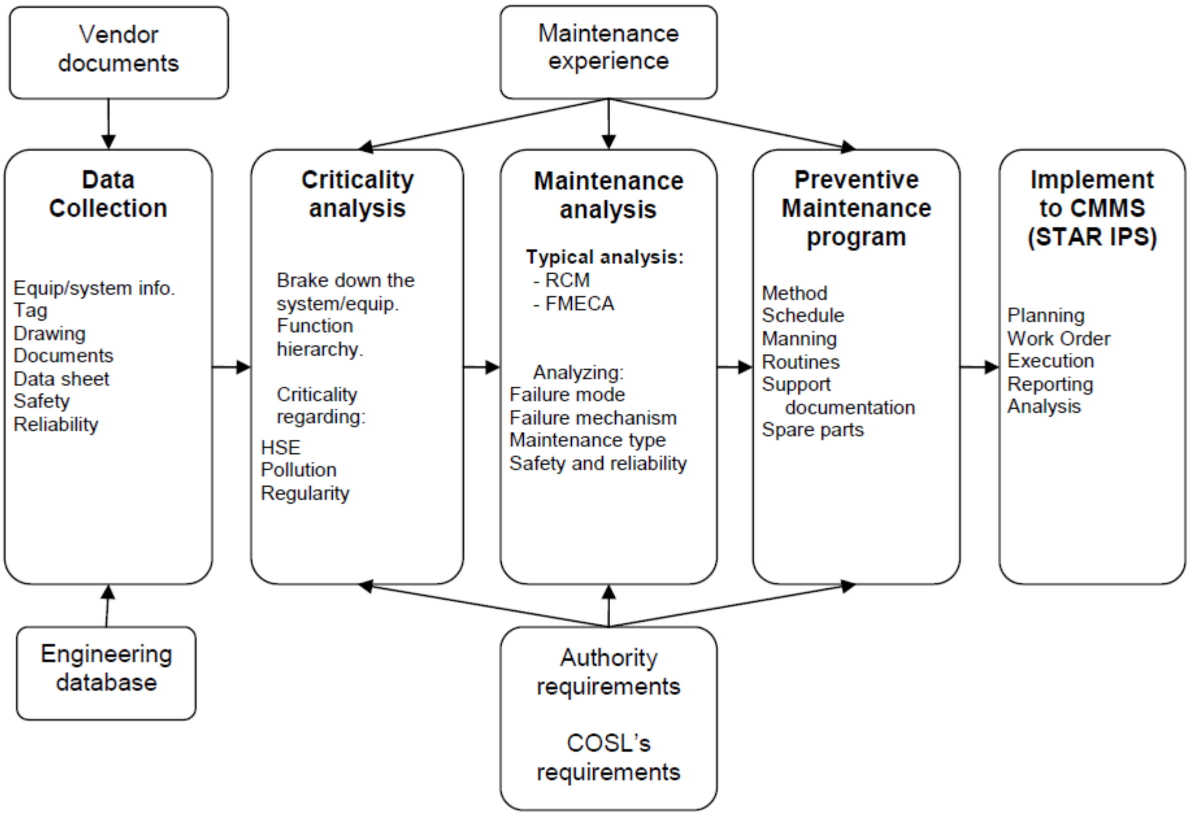


Figure 25 CDE Working Process for Maintenance Program (COSL Drilling Europe, 2015h)

During the design phase of the technical systems in the identical rig COSL Pioneer CDE initiated a parallel process of performing a criticality analysis and establishing a technical hierarchy for all technical systems. The service provider AGR Group was used to assist in this process, and their software program Kamfer was applied for designing intuitive main function and sub function reports for each of the equipment groups, including a criticality assessment of the inherent failure functions of the equipment. The working process was performed as a series of workshops where key personnel involved in the actual maintenance and daily operations of the rig holding specialist technical knowledge and experience, contributed to the identification of failures, assigning of criticalities and assessing the failure effects to the installation (Ringdal, 2009). Two examples of such reports are demonstrated in Figure 26 and Figure 27 below.

Installation:	Pioneer	COSL Pioneer
System:	336	CHOKE & KILL SYSTEM INCL. MUD GAS SEPARATOR

2S	**Main Function Criticality Evaluation**	Revision date	
		A0	03.03.3009
	PIONEER-33601	**CHOKE/KILL MANIFOLD ASSEMBLY**	

Parallel Units:	1	Capacity:	100 %	Redundancy grade:	**A**
			Max Criticality of (S,P,O) =	Criticality:	**2**
				Failure probability:	**MEDIUM**

Criticality Evaluation for HSE(S), Production(P) and Oil Spill(O) Hidden Failure(H) Y:Yes,N:No

	Effect on system	Effect on installation	S	P	O	H
Does not work	MF shut down or unavailable. Valves and hoses cause of failure.	May be critical for safety, MF is part of well control. No immediate effect on oil spill or drilling downtime. Valves can be serviced without creating critical situation. Similar equipment have a history of being serviced often.	2	1	1	N

Data source: Kamfer 04.03.2009

Figure 26 Example of Main Function Criticality Evaluation (Ringdal, 2009)

Installation:	Pioneer	COSL Pioneer
System:	336	CHOKE & KILL SYSTEM INCL. MUD GAS SEPARATOR
Main Function:	33601	CHOKE/KILL MANIFOLD ASSEMBLY

3O	**Sub function criticality evaluation**	Revision date	
		A0	03.03.3009
	PIONEER-33601HOSE	**Hoses Moonpool Drape**	

Parallel units:	1	Capacity:	100%	Redundancy grade:	**A**
			Max Criticality of (S,P,O) =	Criticality:	**3**

Criticality evaluation for HSE(S), Production(P) and Oil spill(O) Hidden failure(H) Y:Yes,N:N
-

	Effect on system	Effect on installation	S	P	O	H
Does not work	Hose leaking or break. Hoses used for circulation of mud in case of kick during drilling operation. BOP closes in case of a kick, hoses only circulation.	Critical to oil spill. If hose is leaking/breaking, will get oil mud to sea. Critical for drilling downtime if hose break, must stop drilling operation, may have to pull BOP. May be critical for safety, hose is part of well control.	2	3	3	N

Data source: Kamfer 04.03.2009

Figure 27 Example of Sub Function Criticality Evaluation (Ringdal, 2009)

Based on this criticality evaluation CDE initiated the working process of performing RCM assessment and establishing maintenance programs for the different equipment types on the rig. In order to ensure the quality of this process CDE chose to perform it in association with specialist expertize on the field gathered from the service provider DNV. The work followed a three stage process and was founded on the guidelines in IEC Standard 60300-3-11 edition 2, which form the core of what is defined in NORSOK Z-008 (Holmes, 2011). This work was also in accordance with the stated maintenance strategy of CDE. The work process comprised of the three stages illustrated in Figure 28 below.

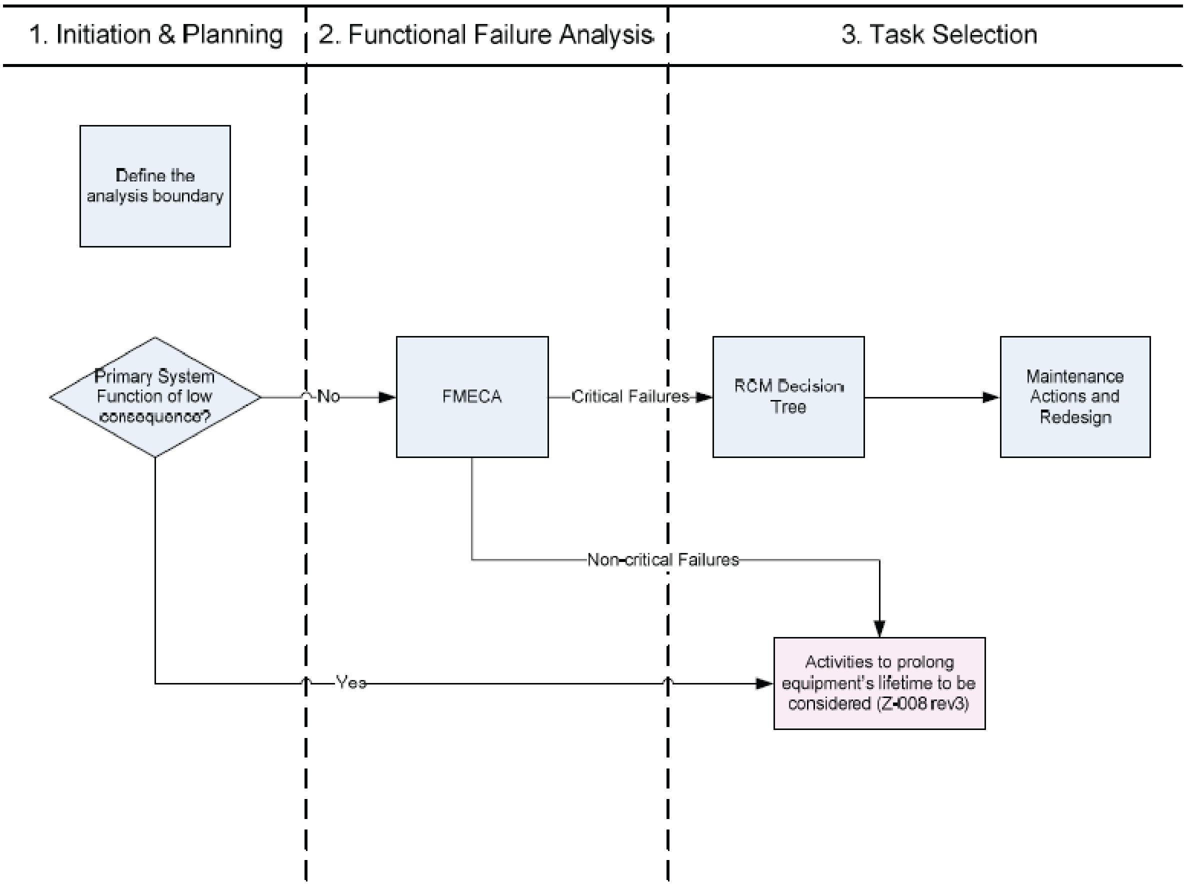


Figure 28 Overview of the Maintenance Activity Definition Process (Holmes, 2011)

The first stage of the process was the *initiation and planning* phase. In this phase elements that were identified to have no benefit from the RCM process was eliminated, and implemented in the maintenance system directly without any RCM assessment. Such elements relate to equipment with low consequences to all areas of criticality, maintenance tasks that will be performed according to regulatory nature independently of technical state and maintenance tasks that will be part of daily inspections and so on.

The second phase consisted of performing a *functional failure analysis*, i.e. FMECA for the different equipment groups. The work included the identification of the functional failure types of the different equipment. Typical examples of such were:

- Complete loss of function
- Failure to function according to acceptable level of performance
- Intermittent functions or in function when not demanded

One of the main tasks for the workshops was the identification of the conditions that could cause the development of each specific physical and reasonably likely failure modes. This identification was to include a precise description of the physical item that had failed, as well as a description of the failure mechanism, in order to enable the implementation of effective maintenance tasks that could prevent the development of such failures. If the workshop discovered that the identified failure modes posed an unacceptable risk to the rig risk mitigating measures would have to be implemented. Such risk reducing measures was especially applicable to failure modes that were given a medium or high criticality according to the matrix shown in Figure 23.

The third and final part of the process was the *selection of adequate maintenance tasks*. The goal of this process was to decide on the most applicable and effective maintenance tasks in order to reduce the probability and hence the risk of the failures in question. If no such tasks were identified a redesign or change of operation was considered. The selection of suitable PM tasks followed the application of the decision logic described in Figure 29 and Figure 30 below. By asking a series of simple questions the technical feasible maintenance tasks that would address the failure modes most efficiently were identified and selected. If different tasks were considered to give equal results in dealing with the failure mode and the consequence of the failure a cost-benefit analysis was applied to decide on which of the tasks was the most desirable.

The following different types of tasks were considered:

- Application of condition monitoring
- Scheduled replacement of equipment
- Scheduled restoration of equipment
- Failure finding
- Alternative actions

When a decision had been made for implementing a specific task it would have to be implemented in the CMMS. Important details needed in the process of establishing job schedules include:

- Intuitive task title and a concise description of the task
- Connected resources including which personnel is to perform the task and the number of hours planned to perform the task
- Inclusion of the expected spare parts needed to perform the task
- An exhaustive list of all special tools required to perform the task
- Job scheduling meaning at which intervals the work order (WO) will be created. This can for instance be operational hours of the equipment, fixed scheduling based on elapsed time or technical condition of equipment.

In addition to this a spare parts strategy was developed based on the identified criticality of equipment. Cost-benefit analysis were performed for those spare parts that were not required onboard at all times according to statutory regulations or contractual commitments to the client.

While the goal of the maintenance program is to reduce the probability and risk of negative occurrences resulting from failures and faults in equipment, the maintenance strategy was developed to reduce the negative consequences if such a negative event occurred. The availability of needed spare parts in a timely manner serve to this purpose. The expected lead time for acquiring the necessary spare parts in the case of an unanticipated failure was used to assess the need for carrying the spares onboard. An important factor that helped reduce the need for carrying spare parts onboard the rig was the establishment of a local warehouse at Mongstad. The development and application of this spare part strategy will however not be further explained as it lies out of the scope of this thesis.

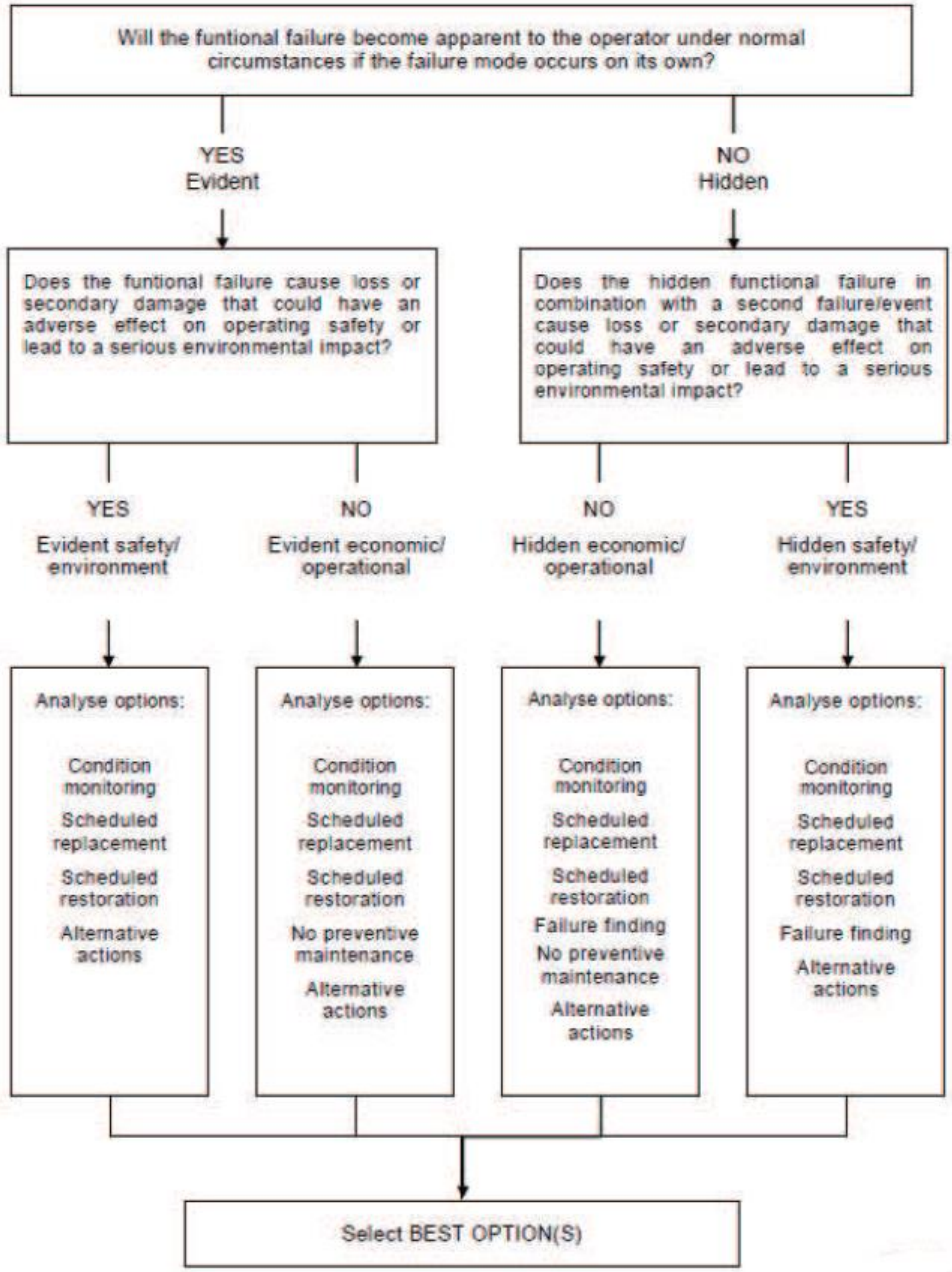


Figure 29 RCM Decision Tree (Holmes, 2011)

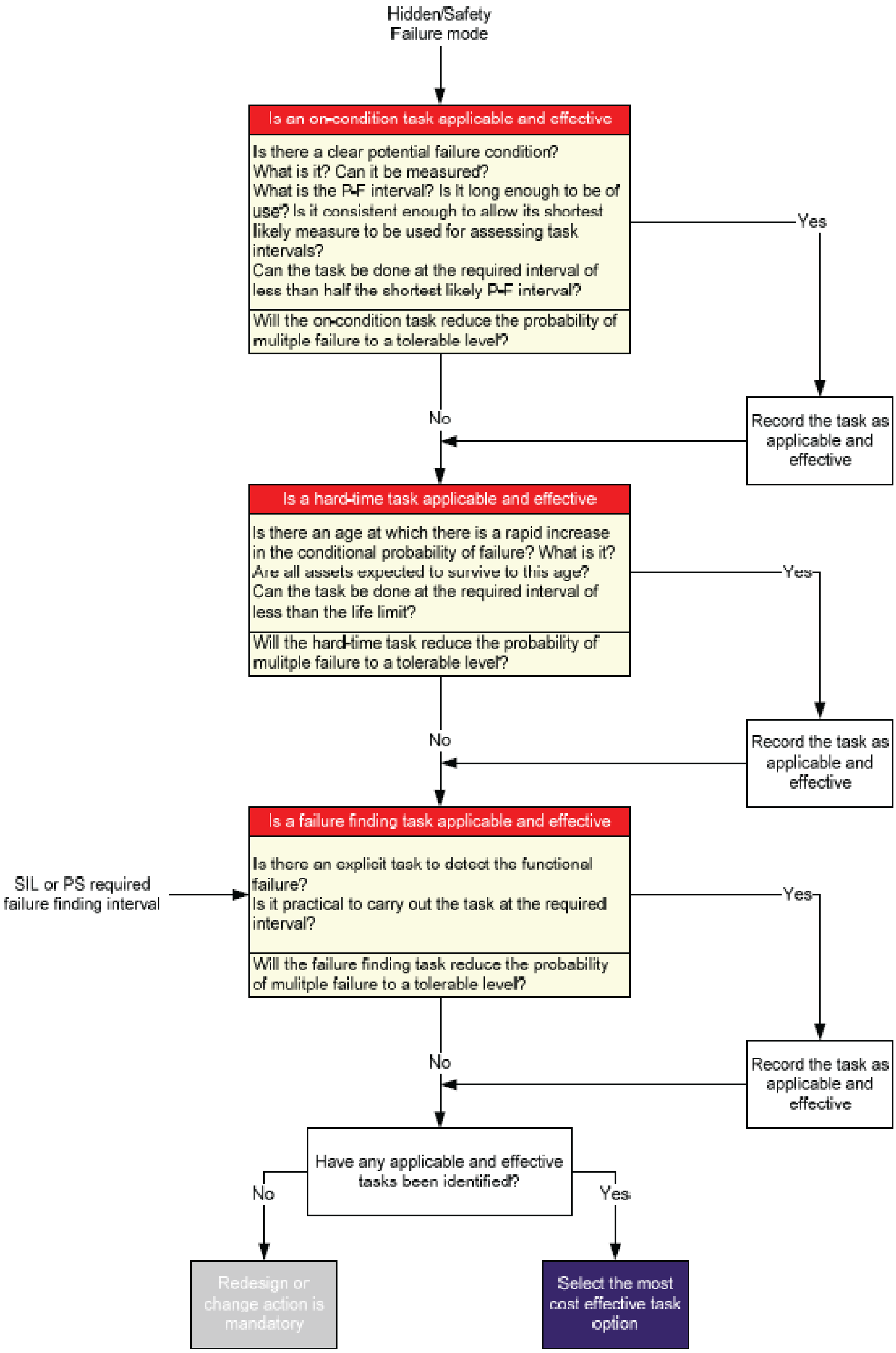


Figure 30 RCM Decision Logic (Holmes, 2011)

4.3 Computerized Maintenance Management System

CDE have defined that "the maintenance system shall utilize work processes and functionality's organized together in such a way that the predefined maintenance objectives are reached." They further state that the maintenance system shall comprise of the following elements:

- CMMS
- Maintenance management execution by the onshore Maintenance Manager and the MEG
- Maintenance administration enabled by the utilization of established procedures and routines

CDE have chosen to use the CMMS Star Information and Planning System (STAR IPS) delivered by SISMarine for the efficient management of their maintenance tasks, handling of logistics, spare parts, purchases and reporting. On their company web page SISMarine state that "STAR IPS is an easy-to-use business application designed to help rig owners and managers operate their fleet in a safe and efficient manner" (SISMarine, 2015). Through the implementation of this user friendly and intuitive system CDE is able to keep track of the maintenance and purchase history of all systems and equipment. This is a particularly important part of the continuous improvement process of the maintenance system, as well as enabling easy access to relevant documentation when requested by regulatory authorities for documenting compliance with regulations. WO's are generated from predefined job schedules on a regular basis by the offshore technical manager. The employees can easily access these pending WO's by performing searches in the CMMS filtered on department, position, type of jobs (CM/PM) and due dates. The job tasks are executed according to the instructions given in the WO, and the employees report spare part consumption and work hours into the job history. When the job status is set to complete it is reviewed by the offshore technical manager before it is closed and filed to the work history library. All work history is easily accessible for all employees, lending them the possibility of performing future similar tasks more efficiently based on the relevant information in the work histories.

The storekeeper who manages the spare parts inventory on the rig generate consumption reports from the CMMS on a regular basis. The report identifies which parts that needs to be reordered based on preset maximum and minimum levels for the items. In this way the computerized administration of spare parts inventory, purchasing and logistics is performed in an effective manner.

CDE recently added the application of barrier management forms that are filled out each time maintenance test jobs is performed on safety critical systems. This quality management system enable the tracking of deterioration trends by reporting of key values into the forms, so that optimizing of maintenance tasks and intervals is possible. At the same time one have obtained the ability of easy access to documentation of the technical integrity of the rig.

Star IPS have a built in report generation system so that one can keep track of the status of pending WO's, overdue maintenance, spare parts and man-hour consumption and so on. This enable improved asset management as this data can be utilized to assess the overall performance of the maintenance organization in relation to the defined MPI's described in Figure 24.

4.4 A brief introduction of the asset COSL Innovator

COSL Innovator is a semi-submersible drilling rig (SSDR) designed with two pontoons and four columns, with operational specification for water depths up to 750meters. The asset is designed for world-wide operations in harsh environmental conditions. Station keeping is managed by an 8-line mooring system or by dynamic positioning (DP), which is maintained by the application of 6 fixed pitch variable speed thrusters. In addition to this a combination of the two methods can be applied, which is position mooring with thruster assisted mooring system dependent on automatic remote thrust control, also called POSMOOR ATA (DNV, 2014). Power generation is obtained through the application of 6 main engines, which are connected to three separate power systems in pairs. This design give the asset a DP3-classification. The COSL Innovator comprise of a series of subsystems which will be further explained in the following section. A graphical illustration of the asset is provided in Figure 31 below.

Figure 31 Graphical illustration of SSDR COSL Innovator (COSL Drilling Europe, 2010)

Subsystem classification of COSL Innovator

For all intents and purposes the classification of systems installed on COSL Innovator are segregated in accordance with the standard developed by the Norwegian organization Skipsteknisk Forskningsinstitutt (SFI). The SFI system helps managing of technical accounts for each system, subsystem and subgroups enabling the effective and efficient management of equipment and its connected spare parts throughout all lifecycle phases. CDE uses a nine digit system, where the first three digits describe equipment groups according to the current SFI group system, and the last six digits describe unit level according to CDE standard. In some cases it has been necessary to apply an 11 digit system as described in Figure 32 below.

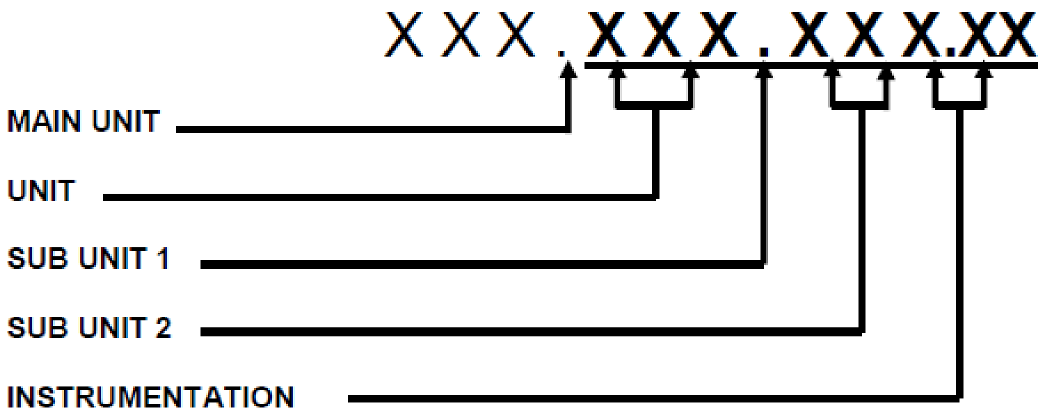


Figure 32 CDE SFI coding structure (COSL Drilling Europe, 2015h)

However, in the following a more general description of the main technical systems of COSL Innovator will be provided independently of this coding system, in order to establish an informative picture of the complex asset. Some of the described systems will be used for further studies in relation to the implementation of condition monitoring and CBM.

Station keeping system

The rigs station keeping system consist of the following main parts:

- DP Vessel Control System delivered by Kongsberg Maritime
- 6 fixed pitch variable speed thrusters driven by electric motors delivered by Wärtsilä and Siemens
- 8-line mooring system delivered by Rolls Royce

Main machinery and auxiliary systems

The rigs main machinery and auxiliary systems consist of the following parts:

- 6 12V32 main engines delivered by Wärtsilä connected to 6 main generators delivered by Siemens

- Emergency power generator delivered by Mitsubishi
- Electrical distribution system including switchboards, wiring and electrical components, mainly delivered by Siemens
- Various technical auxiliary systems like fuel oil transfer system, cooling systems, compressed air systems, steam system, evaporation system, ballasting system, bilge systems, hydraulic systems, heat ventilation and air conditioning systems etc.

Safety equipment

The rigs safety system consist of the following main parts:

- Various fire detection and washdown systems like firewater system, deluge and water mist system
- 4 lifeboats
- 2 man over board watercrafts
- 4 liferafts

Drilling systems

The rigs drilling system consist of the following main parts, all delivered by National Oilwell Varco (NOV) where other is not specified:

- Drillers control cabin based on the Cyberbase technology, 2 operator stations
- Derrick delivered by Nymo
- Drawworks with active heave compensation system
- Electric topdrive
- Rotary table
- Piperacker
- Iron roughneck
- Catwalk machine
- Manipulator arm
- Work basket, man rider winches and utility winches
- Pipehandler crane (knuckleboom crane)
- 2 platform cranes delivered by NOV Molde Crane
- 3 mud pumps
- 5 shale shakers
- Mud mixing and additive system

Subsea equipment

The rigs subsea system consist of the following main parts:

- Blow out preventer (BOP) delivered by Schaffer

- BOP Control system delivered by NOV
- Various overhead cranes for handling of equipment in the moonpool area
- BOP elevator and skidding system
- X-mas tree (XMT) cantilever transport and skidding system
- Various man rider and utility winches and work baskets

Various third party equipment

There are several third parties partaking in the drilling operations that CDE perform for the contractor Statoil. These include:

- ROV system operated by Subsea7
- Work Over Control System (WOCS) for XMT system operated by Aker
- Cementing module operated by Schlumberger
- EC-drill concept for managed pressure drilling operated by Enhanced Drilling
- Drilling IO control room including contractor Statoil and service companies as Baker Hughes, Halliburton and Schlumberger

4.5 The application of condition monitoring on COSL Innovator

On COSL Innovator findings related to condition monitoring are often used as important input when it comes to forming decisions regarding CM tasks. The application of condition monitoring opens up the possibility of early detection of deterioration so that preventive measures can be taken before the errors or failures develops into a fault in equipment. Such measures can be the creating of corrective WO's. A corrective WO can be given a specific due date well within the predicted P-F interval of equipment, so that the problem can be handled before it give negative effect to the equipment itself or secondary damage to other related system components.

Condition monitoring can also be used as an aid in the forming of new PM tasks. If the monitored parameters indicate that there is a need for performing specific actions in order to obtain the optimal operation of equipment, the information obtained by condition monitoring can be applied for developing new maintenance tasks in relation to specific equipment.

Continuous condition monitoring

As described above the COSL Innovator comprise of a large number of advanced technical systems and equipment. Many of the technical systems can be monitored and operated from the vessel control system (VCS). The VCS is continuously manned by an engine room operator (ERO), whose role is to ensure the safe and efficient operation of the technical systems by giving various commands based on the needs and requirements of the operations, while continuously monitoring the health and state of equipment by assessing the continuously monitored operational data. Vital parameters from equipment like main engines, pumps, compressors, boilers and heaters as well as valve positions are being continuously monitored. Most of these parameters have a set alarm limit to enable the ERO to perform the necessary actions should an alarm state occur.

In addition to the technical systems also a series of equipment related to the drilling operations utilize continuous condition monitoring to ensure safe and efficient operations. One example of such a systems is the continuously manned mud control room, where tank and mud pit levels as well as the state and health of the mud pumps are being monitored. Another example is the condition monitoring equipment installed on the various equipment on the drillfloor. The monitoring of all this equipment is integrated in the smart drilling instrumentation (SDI) system, and the monitored parameters are presented to the system operators though the HMI of the Cyberbase Drilling system.

Lastly it is worth mentioning that a number of parameters related to the performing of drilling operations are being continuously monitored by various personnel in the IO room. These relate to data obtained from the well through the application of an advanced bottom hole assembly, based on the technology of transferring data by generating pulses in the mudflow. This technique is referred to as logging while drilling (LWD) or measurement while drilling (MWD). Also the rheology of the mud is being continuously monitored by the mud engineer, in order to be able to maintain its functions by applying various chemicals when needed. These types of condition monitoring techniques, and their area of application will however not be further discussed as it lies out of the scope of this thesis.

Regular condition monitoring

In addition to the continuously manned VCS an extensive manual inspection round is performed by the motorman at the start of every 12hour shift. During this round a large number of technical conditions is manually monitored and assessed so that one is enabled the possibility of early detection of any irregularities that may lead to unwanted error or failures. Examples of conditions that are being monitored by the means of aural, tactile or visual senses are pressure gauges, temperatures, tank levels, oil level or any abnormal sounds. In addition to this the detection of unusual smell as well as general visual inspections of equipment and machinery can serve as aids for the early detection of leakages or other anomalies. This technique can however be inadequate as failure states may be overlooked, changes in parameters from day to day as a result of deterioration or failures may not be discovered as it is not always the same personnel that perform these inspection rounds. This problem has been partially countered by establishing a weekly routine for noting the most relevant parameters in a technical form. By doing this one is given the ability to systematically compare the results with previously obtained data on a weekly basis.

Periodic condition monitoring

For many systems PM in the form of periodic condition monitoring tasks are performed to verify the technical state of the equipment. A typical example of this is the oil sampling program for COSL Innovator. The asset comprise of an extensive number of hydraulic systems for transferring energy to various systems, and it is of the utmost importance that the quality of the oil in these systems is in a healthy state at all times. In addition to this it is vital to maintain the safe and optimal operation of the main engines, which is dependent on the correct function of the engine oil. When performing oil sampling it is important that the sample is taken from a specific sample point in the system, and that it is noted on the sample under which running conditions the sample was taken. In addition to this it can be appropriate to make a note on the sample stating the reason for the sample being taken, as the laboratory technician then will know what to focus on during the actual analysis of the sample. In order to ensure that the oil sampling process is performed in a similar way from time to time, the internal CDE level 3 document “Procedure for Oil Sampling” have been established, and a numbered list of oil sampling points with corresponding tags in the field have been made so that the samples can be treated and followed up in a systematic way. CDE have a frame agreement with the oil analysis specialist company Invicta for handling the analysis of the oil samples. On their company web page they illustratively state that by analyzing only 50ml of oil from a system, one is able to verify the technical state of equipment, and they further write that “an oil sample is like a blood sample from the machinery” (Invicta, 2015). To illustrate this an example of an oil analysis report from the thruster gear oil systems on COSL Innovator from the first quarter of 2013 is provided in Appendix 2. From this it can be seen that parameters such as water content, number and size of wear particles, particle counting, and content of non-magnetic metals is analyzed. This particular oil sample identified that the particle contamination for the HPU steering system of thruster 2 was above the defined limits. This enabled CDE to perform the necessary corrective actions in order to prevent the development of a failure in the system. The analyzing of other parameters may be required for other types of equipment. This is exemplified in Appendix 3, which is the oil analysis of Main Engine 1 from March 2015. Here the metal type of the particles are identified so that one is able to pinpoint which engine parts are starting to deteriorate. In this way CM tasks can be performed where they are needed in order to prevent the development of failures and faults. Also other parameters such as the oil viscosity, acid and base number and the flash point of the oil are interesting parameters, as they can provide important information about any ingress of cooling water or fuel dilution to the oil, which can be lead to failures that may cause serious damage to both personnel and equipment.

Periodic condition monitoring for determining the technical state of equipment is applied on a number of different systems on COSL Innovator. Some examples of such systems are megger testing of electrical motors, thermographic photography of switchboards as well as various temperature readings in systems and so on. In addition to this extensive use of NDT is applied for lifting appliances and various types of drilling equipment on a regular basis as a result of statutory verification demands.

Need based condition monitoring

During normal operations equipment may fail to perform its function as intended between its given maintenance intervals. If this is the case certain need based condition monitoring tasks can be established, in order to be able to ferret out the root cause for the failure. One example of such a task used by CDE is the installation of the MERA iPack. This is a fully automated and intelligent fluid monitoring device which can be installed in hydraulic oil and gear oil systems. It continuously monitor the condition of the fluid and present information about the hydraulic fluid to the user of the system through an intuitive HMI. The benefits of the system is the ability to continuously monitor the condition of the fluid, specify alarm limits as well as the ability to filter out both water and particles from the oil. The unit is portable and easy to hook up with all systems (MERA, 2012).

Other examples of need based condition monitoring is the installation of clamp on flow reading instruments to verify the flow delivery from pumps and the application of light emission reading instruments for determining the need for light bulb replacement.

4.6 The application of CBM on COSL Innovator

As a result of the above described challenges with condition monitoring tasks CDE have implemented the application of advanced CBM techniques for two of the most extensive systems on COSL Innovator, namely the main engines and the thruster systems, both delivered by Wärtsilä. An explanation of the two systems will be provided in the following, highlighting the possible benefits gained by its implementation as well as describing some challenges related to the systems. In addition to these two systems there is an opportunity for online assistance from the OEM NOV in relation to fault finding on some of the advanced drilling systems delivered by them, and this system will also be given a brief explanation.

Wärtsilä CBM

In their company webpage Wärtsilä state that they “enhance the business of its marine and oil & gas industry customers by providing innovative products and integrated solutions that are safe, environmentally sustainable, efficient, flexible, and economically sound” (Wärtsilä, 2015). One example of this is the advanced technical solution they have delivered to COSL Innovator for condition monitoring, dynamic maintenance planning (DMP) and CBM. By continuously monitoring a series of operational parameters on the engine installation one is able to increase the engine availability, reliability and the efficiency of the installation. The implementation of DMP enables fine-tuning of operational parameters and adjustments of the maintenance intervals of main components.

The concept is based on careful real-time analysis of operational data automatically gathered from a number of sensors placed in various parts of the engines. The operational data that is recorded relates to parameters like pressure measurements, temperature measurements, load measurements, speed measurements, assessment of the control and monitoring systems and so on. As the data gathering and transfer process to the Wärtsilä CBM center is fully automated it does not require any active involvement from the offshore maintenance crew. All the data is however easy accessible for the offshore crew through the HMI called Wärtsilä Operator's Interface System (WOIS) if this should be needed (Wärtsilä, 2011). To be able to apply the data in a systematic manner so that one can obtain valuable conclusions and effective decision making a great deal of processing and analysis must be performed. This analysis process is performed by expert engineers placed in the Wärtsilä CBM center in Vaasa, Finland. They have extensive knowledge about the system, as well as vast amounts of baseline data gathered from both this specific installation, as well as from a number of similar installations from all over the world. This enable them to establish a picture of the actual technical state of the equipment in the form of diagnostics, as well as predict any emerging challenges in relation to deterioration in the form of advanced prognostics. In addition to the data gathered from the engines the Wärtsilä engineers also have access to the oil sample results from the specialist analysis performed by Invicta, so that they can be even better able to pinpoint the reason for any negative trends. The Wärtsilä experts are responsible for contacting CDE regarding any emerging challenges in a timely manner. In any case they present CDE with a monthly report presenting the last month's operational data and any detected emerging challenges or developing negative trends. The monthly report from Wärtsilä to CDE for February 2015 is provided in Appendix 4 to exemplify this process, and from this it can also be seen which parameters are continuously being monitored. In this particular case it was discovered that the cooling water temperature on Main Engine 5 was slightly out of optimal parameters. Investigation of the problem revealed that a non-critical deaeration valve in the cooling system was blocked. This exemplifies that by including the external expertize in Wärtsilä to the CDE organization through the CBM system, one is able to detect error states at an early stage so that they can be prevented from developing into failures or faults. In addition to this Wärtsilä presents CDE with a maintenance proposal on a half year basis. This proposal predict which maintenance tasks that needs to be carried out based on the calculated expectations with regards to running hours and the prognostic rates of deterioration. The proposal also include a list of all the spare parts needed in order to perform the recommended maintenance tasks so that these can be obtained by following normal purchase routines well ahead of the time they are required onboard, thus giving the opportunity of improved spare parts and logistics planning (Wärtsilä, 2012).

A graphical illustration of the communication system of Wärtsilä CBM is provided in Figure 33 below.

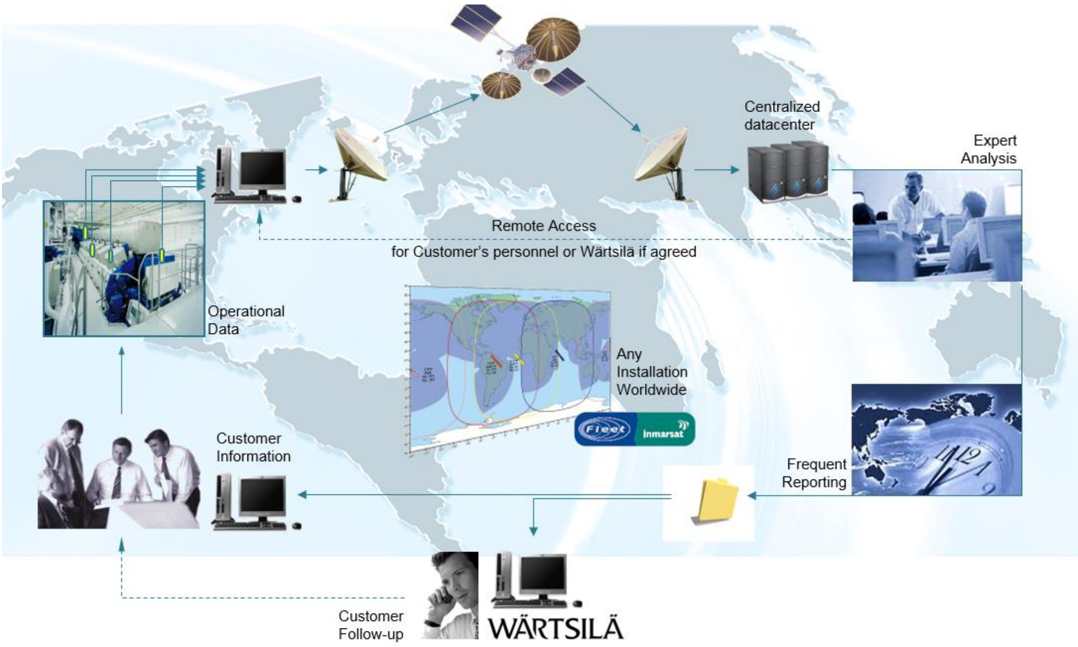


Figure 33 A graphical illustration of the Wärtsilä CBM Communication system (Wärtsilä, 2008)

Whereas conventional equipment maintenance is based solely on running hours and predetermined generic expectancies of deterioration rates this new approach open up the possibility of postponing maintenance tasks until there actually exist a need for them. The ability to predict the time at which the maintenance task is to be performed also enables optimal planning in relation to allocation of resources and spare parts, as well as avoiding negative effects related to unplanned downtime on equipment. The schematic principle of Wärtsilä CBM is illustrated in Figure 34 below.

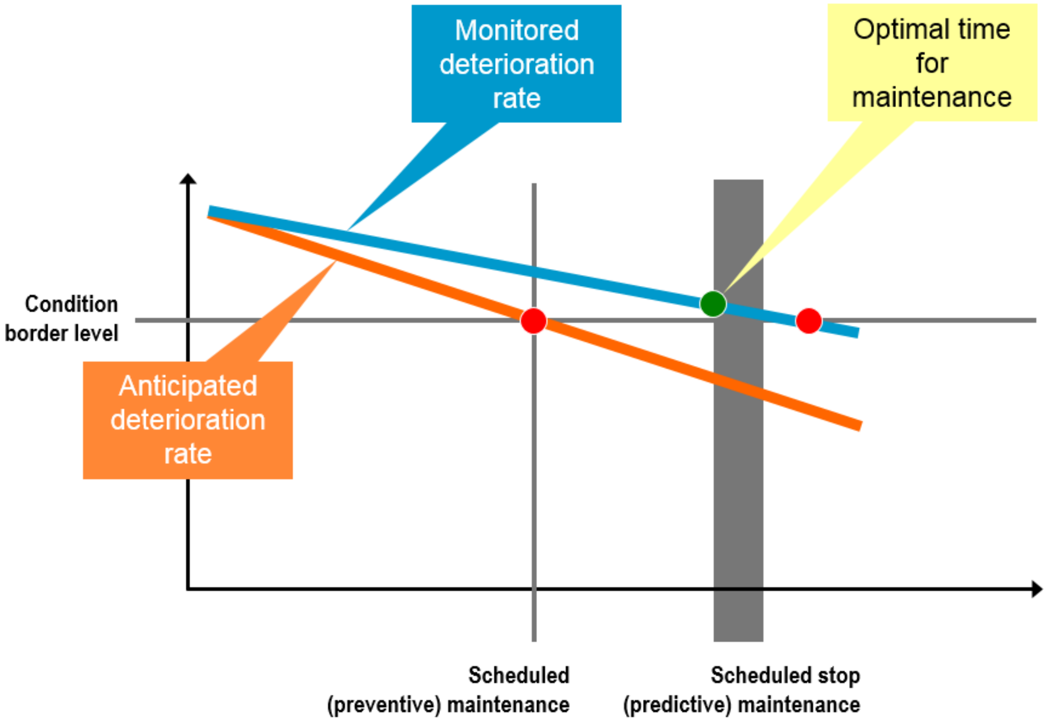


Figure 34 Schematic Principle of Wärtsilä CBM (Wärtsilä, 2008)

As CDE obtain information about the technical state of the engines through the CBM system, the generic maintenance schedule developed by Wärtsilä can be made subject for reevaluation. As Figure 35 below indicate there now exists a possibility for prolonging the major overhaul interval from the standard interval set at 24000 running hours for the installation on COSL Innovator up to 36000 running hours. This figure is based on that the engines are operated by diesel oil (DO), the average load is below 75%, and that an inspection of one cylinder is performed at the standard interval in order to physically verify the technical state of the engine.

Fuel	**Overhaul interval with CBM, max intervals (std intervals in parenthesis)** Note: before extending the overhaul intervals with CBM, one cylinder must be inspected at std interval. Future intervals can then be predicted based on inspection results and CBM info	
	Average load > 75 %	**Average load < 75 %**
HFO 2	(12) 20 000	(16) 24 000
HFO 1	(16) 24 000	(20) 32 000
DO	(20) 32 000	(24) 36 000
NG	(20) 32 000	(24) 36 000

Fuel	**Std overhaul interval**	**CBM max**
HFO 2	16 000	24 000
HFO 1	16 000	24 000
DO	24 000	36 000
NG	24 000	36 000

Figure 35 Flexible maintenance schedule enabled by the implementation of Wärtsilä CBM (Wärtsilä, 2008)

At the time of installation on COSL Innovator Wärtsilä predicted that there existed a possibility for accumulated savings up to 1,300,000 EUR during the first ten years of operation resulting from the implementation of Wärtsilä CBM and DMP, as shown in Figure 36 below. Even though this is a predicted figure and not give an accurate presentation of the actual monetary savings it is a good illustration of some of the benefits gained. These benefits are related to elements like for instance:

- Improved safety as the risk of unplanned stops is significantly reduced by obtaining real time information about the technical state of equipment

- Reduced operating costs and improved environmental impact as a result of reduced fuel consumption, reduced maintenance costs and increased component life time as one can operate within optimal parameters throughout the lifecycle of equipment

- Reduced number of unplanned stops of equipment as a result of improved monitoring and prognostics related detection of deterioration

- Reduced number of failures as a result of improved diagnostics of technical condition by the implementation of Wärtsilä expert analysts

- Improved maintenance planning as a result of prediction of deterioration rates which enables reduced need for carrying spare parts and improved allocation of maintenance personnel well in advance of need to perform maintenance tasks

- The possibility to prolong major overhaul schedule from 24000 to 36000 hours based on inspections and condition monitoring

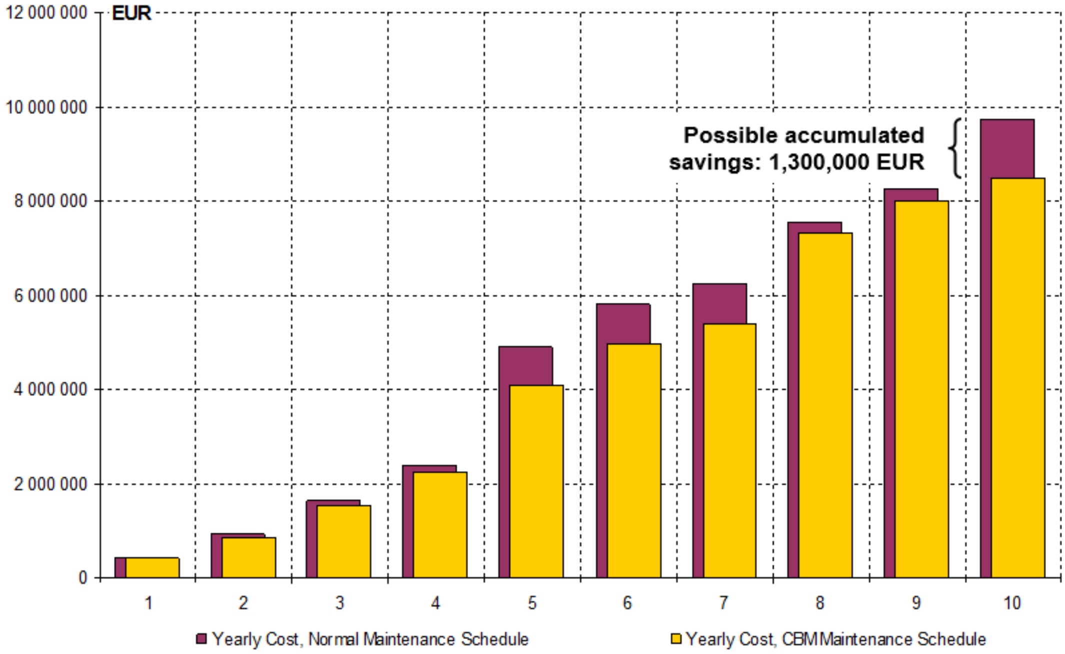


Figure 36 Possible accumulated savings by the implementation of Wärtsilä CBM (Wärtsilä, 2008)

Karsten Moholt CBM for thrusters

Karsten Moholt AS (KMOAS) offer a wide range of condition monitoring and CBM solutions for the O&G industry, and it was the first DNV certified condition monitoring service provider in Norway (Karsten Moholt, 2015a). The OEM Wärtsilä do not offer any CBM solution for their thrusters, and as a result of this CDE have chosen to install the Vibroweb Wear Scanner Analysis System delivered by KMOAS for continuous condition monitoring of the thruster installation on COSL Innovator. The system comprise of 6 vibration monitoring devices for each of the 6 thrusters as described in Figure 37 below, obtained from the KMOAS Load Test Report Thrusters COSL Innovator (Karsten Moholt, 2013a). This application enables effective vibration monitoring of the bearings in the system which from experience are anticipated to give the first signs of system deterioration. In addition to this the RPM and active power consumption of the electric motor for the thruster is monitored in order to obtain useful operational data so that one can establish a picture of the actual technical state of the equipment. The condition monitoring is online, and the recorded data is automatically transferred to KMOAS condition monitoring department for treatment and analysis. In addition to this KMOAS are provided with information regarding any oil consumption in the thrusters, and they also have access to the latest oil sampling results from Invicta. Lastly they are provided with any relevant information regarding any CM that have been performed on the system that may have affected the operating conditions in any way. Dependent of their findings various actions will be taken, as explained in Figure 38 below, copied from the internal CDE document "Condition Monitoring" (COSL Drilling Europe, 2010). As the figure illustrate a report will be issued from KMOAS on a regular basis, but if there is detected any warning or alarm states CDE will be contacted directly so that the appropriate actions can be taken in a timely manner in order to avoid any unplanned downtime of the equipment. This will normally include the making of a CM WO for follow up of the findings.

As the thruster installation have a variable speed, and the running conditions varies continuously as a result of different sea, wind and weather conditions, there has been established a procedure for manual load testing of thrusters with a three month interval. In this way it is possible to obtain sensor readings from similar conditions on a regular basis, so that one can better assess and detect any developing deterioration.

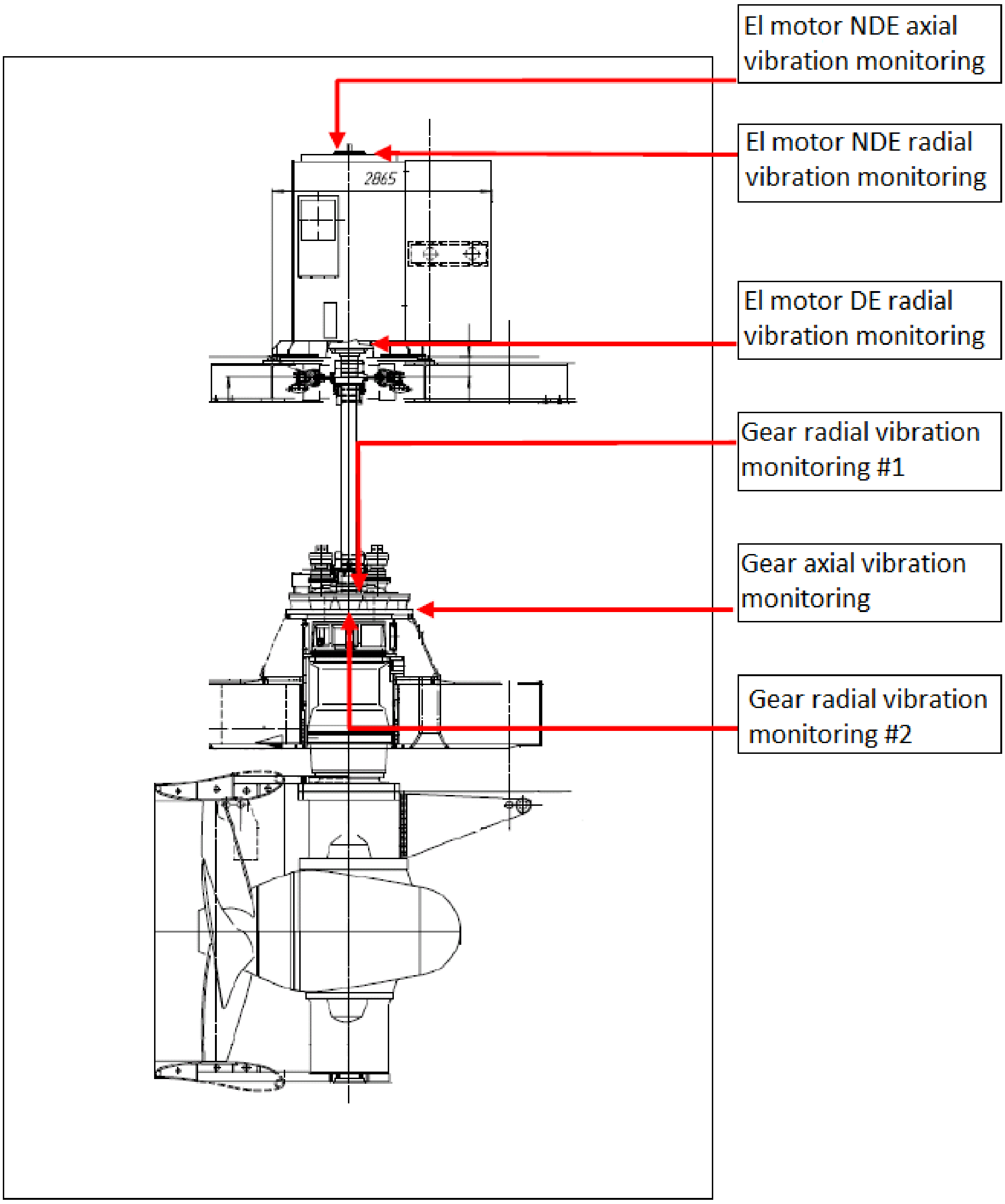
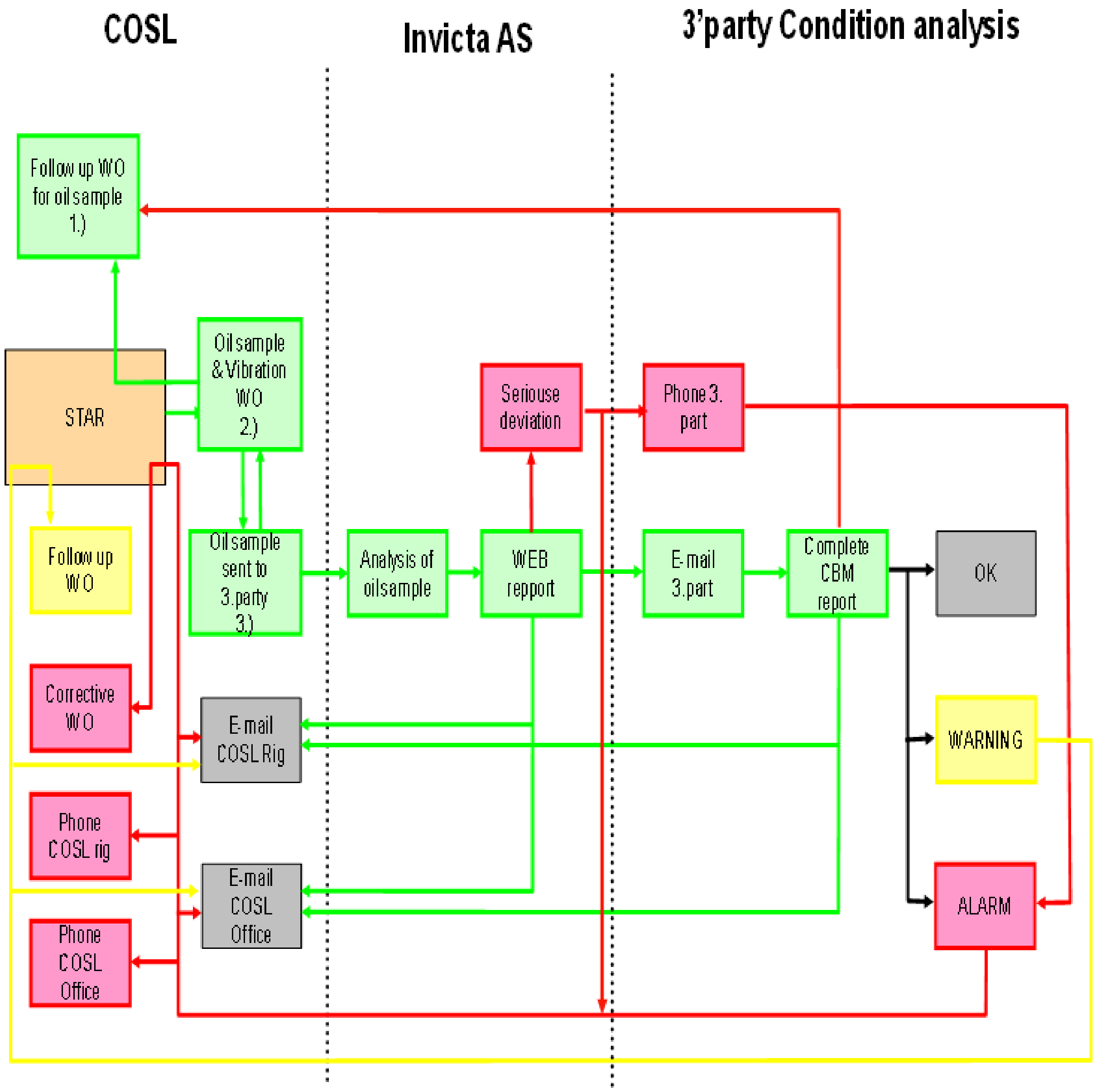


Figure 37 Sensor location for thruster vibration monitoring COSL Innovator (Karsten Moholt, 2013a)



1.) CBM report will close this WO
2.) After the Oil & Vibration WO is closed, the Follow up WO will open.
3.) Sending the samples will close this WO

Figure 38 The analysis and report process of Thruster CBM on COSL Innovator (COSL Drilling Europe, 2010)

KMOAS have developed the user friendly web-based reporting solution MY CBM REPORTS for effective exchange of information. This solution enables the collection of all relevant data and reports in one single place, where it is easily accessible for all relevant stakeholders. The current condition status of all thrusters are available here, together with the historic reports. It is possible to set up an automatic notification system for the users should this be desirable, and in this way one is enabled to perform appropriate actions in a timely manner (Karsten Moholt, 2015b).

The possible benefits gained by the CBM strategy for the thrusters are many. Firstly there is the opportunity of improved safety as the reliability of the plant is improved through the continuous online assessment of the technical state of the equipment. In addition to this the maintenance needs are reduced as the traditional PM strategy where the equipment is maintained according to a preset maintenance schedule is replaced by the CBM strategy where maintenance tasks are being performed based on the actual state of the equipment. The overall lifetime of components are also increased as one are enabled to intervene with deterioration trends at an early time.

The Cyberbase and eHAWK drilling remote support system

The complexity of the assets being operated on NCS have been dramatically increased during the last decade. This must be seen in relation to the implementation of advanced control and communication systems which have enabled a whole new way of performing operations compared to earlier times. An example of a this is the advanced drilling control system NOV Cyberbase Operator Station installed on COSL Innovator (National Oilwell Varco, 2015b). This unit enables the driller and roughnecks to control the entire drilling operation from their operator stations placed safely inside the drillers' cabin. The implementation of this system have significantly reduced the need for performing physically strenuous manual tasks on the drill floor, while at the same time bringing forth new demands for the workers when it comes to being able to assess large amounts of information provided by the HMI. The performing of simultaneous actions, while at the same time assessing large amounts of data, have placed new demands for the workers in the drilling department. One can say that the increased level of interdependabilities and multi-disciplinary actions have forced the workers to go from skill and rule based to knowledge based workers.

In order to mitigate the effect of any unplanned equipment failures in the computerized drilling system CDE have implemented the online support system eHAWK. This system enables specialist design engineers and subject matter experts placed in the continuously manned support center onshore to connect with the rig via an integrated network service. In this way they are enabled to perform advanced diagnostics and prognostics, and by this remotely resolve any issues or challenges with the system. This system significantly reduce the need for service personnel visits on the rig as most issues can be remotely resolved through effective cooperation with the offshore service technicians in CDE (National Oilwell Varco, 2015a).

5. Discussion of possible improvement potentials for CDE

Introduction

With the rapid development of available technology in the O&G industry it has become evident that the drilling contractors need to keep a strong focus on continuous improvement of existing processes, as well as being open-minded about the implementation of novel managerial and technological solutions in order to maintain a competitive advantage in the industry. In this section of the thesis a discussion of possible improvement potentials that can serve as facilitators for CDE to retain a top position in the drilling contractor market will be presented. The discussions and presented opportunities are mainly based on personal observations and considerations done by the author himself, but the study of CDE internal documents as well as discussions with key managerial personnel in the CDE organization have helped the forming of a clearer picture of the unreleased potentials of the organization. It is however underlined that proposed suggestions related to improvement potentials are based on the subjective opinion of the author only, and they do not in any way represent the given opinion of any other sources.

In relation to the presentation of the IAM Conceptual Model in section 2.5, some identified subject areas where asset management can be improved are discussed in section 5.1.

Section 5.2 is dedicated to a discussion of improvement potentials related to the current application of condition monitoring practices on the CDE asset COSL Innovator. These considerations are based on the presentation of the current application of condition monitoring techniques on COSL Innovator presented in section 4.

In section 5.3 a discussion of identified improvement potentials related to the existing application of CBM for the main engines and thrusters will be presented. Further some possibilities related to the implementation of novel CBM solutions for other equipment groups that can enable CDE to retain a top position in the drilling contractor market will be presented and discussed.

5.1 Identified subject areas where asset management can be improved

As aforementioned CDE have several advantages compared to other drilling contractors resulting from their asset portfolio consisting of three relatively new and near identical drilling rigs, in addition to the accommodation units and COSL Prospector. In addition to this the three drilling rigs are employed by the same client, namely Statoil. This enable CDE to standardize many tasks and processes by the employment of asset portfolio thinking, but it is in the author's opinion that the full potential of such processes not yet have been released.

Based on the 39 subjects groups of the IAM Conceptual Model some areas where improvement potentials have been identified by the author will be discussed in the following. In this context it important to point out that these are not the only areas where there may exist potential for improvement, but from the authors' point of view these however do stand out as some of the most relevant that can be looked into. The earlier described Figure 6 is recited below in Figure 39, with highlighting on the identified elements.

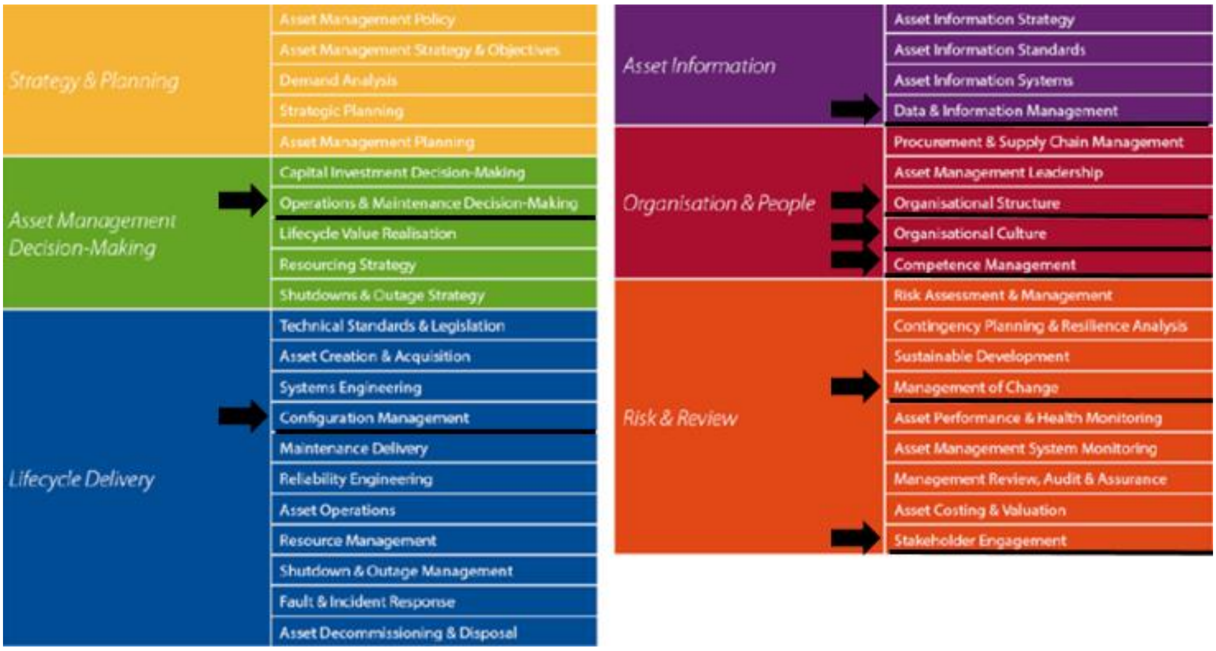


Figure 39 The 39 Subject groups of asset management with highlighting on the identified improvement areas in CDE (The Institute of Asset Management, 2014)

Organizational structure and organizational culture

From their operation of three near identical assets CDE have the opportunity of obtaining substantial benefits related to standardization of their operations. The organizational structure of CDE is to some degree compartmentalized, which means that it is organized by the structuring of the departments which serve as functional silos, performing tasks that relate to their specific area of operations. The current operational practice is that the rigs are operated by different operational teams. These teams are supported by other departments such as finance, technical department and so on when needed. The operational teams perform their work in close cooperation with the offshore management of the rigs. This is enabled by daily operational planning meetings between the on- and offshore organizations. These meetings are executed by the means of video conference systems, where all the participants can both hear and see each other in real time. This enable the teams to efficiently and effectively exchange relevant information and perform planning of the forthcoming operations on a daily basis. From this it can be concluded that even though there are physical boundaries between the on- and offshore organizations CDE have managed to mitigate the organizational boundaries between the two teams, through the establishment of a well-functioning virtual organization.

While there are daily meetings between the on- and offshore organizations of the rigs this does not seem to be the case for the collaboration between the operational teams of the different rigs. Both collaboration and non-formal talks exist, but it is the authors' opinion that there is room for extended collaboration both between the offshore operational teams of the different rigs, as well as between the onshore operational teams of the different rigs. One can claim that there to some degree exist organizational boundaries both between the offshore management of the different rigs, as well as between the different onshore operational teams of the rigs. Similarly this view can be advocated when it comes to the cooperation with other relevant stakeholders like third parties operating on the rigs, client communication, service supplier and vendor communication as well as for the communication with authorities. Even though the rigs are at different life stages and performing different tasks and operations there are several similarities between many tasks that are being performed, and thus the potential of performing parallel tasks exist. Examples of such duplicate tasks that may be better planned and performed on all assets is the execution of modification projects, purchasing, performing of improvement tasks on installed equipment and systems, as well as improvements to the way the daily offshore operations and maintenance are being performed. The challenge of effective coordination of such tasks have already been recognized and addressed by CDE in the forming of a procedure for the proposal and performing of technical modifications. This procedure entail the application of the modification flowchart as described in Figure 40below, established to ensure the quality of all parts of the processes involved. One example of the quality assurance enabled by this procedure is that if the proposed improvement for any reason is declined, it shall be clearly described and feedback be given to the originator of the proposal. The forming of such measures indicate that CDE is a learning organization which focus on continuous improvement of work processes related to the way their asset portfolio is being managed. An example of established routines for exchange of information regarding safety related issues is the application of the electronic system Synergi. Here safety observation cases are registered and experience is transferred to the other rigs' operational teams when this is relevant, in order to ensure the optimized exploitation of knowledge and improvement potentials across the asset portfolio.

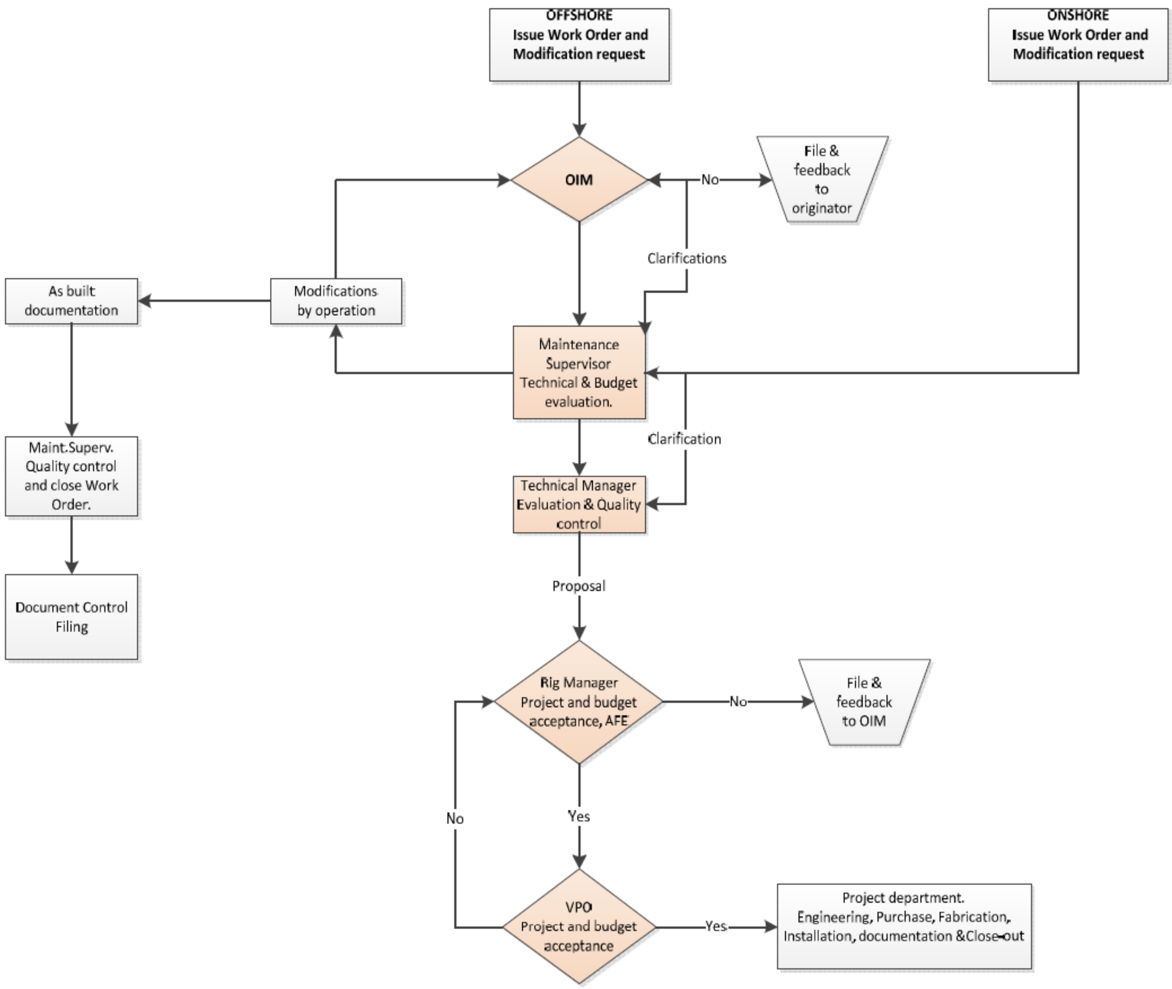


Figure 40 Modification procedure flowchart (COSL Drilling Europe, 2014b)

Still some challenges related to the performing of duplicate tasks remain and can be made subject to improvement measures. One specific suggestion for improvement related to this aspect would be the establishment of a forum for exchange of "lessons learned" between the different rig teams and departments of the CDE organization. Had a forum for experience transfer been established and followed up on a regular basis by key personnel in managerial positions one would have been able to form a more holistic approach to the management and operation of the asset portfolio, which in turn lends the opportunity of savings related to both CAPEX as well as OPEX. Another specific example that may reduce organizational boundaries between the different onshore operation teams of the rigs would be the collocation of these teams into an open office landscape structure. The forming of such an operations management room would eliminate the physical boundaries between the operational teams of the rigs, opening up for the possibility of improved collaboration and coordination and execution of simultaneous tasks. In other words one can say that the forming of such a multi-disciplinary cluster would further enable improved cooperation across traditional business sectors and departments, leading the way for establishing a more collaborative decision support platform entailing all related business processes. This could for instance include departments like purchasing and logistics, procurement and contracts, operation and maintenance as well as human relations. In the future also other functions related to improved cooperation with vendors and client could be implemented. One possible future scenario would be the ability to monitor and control some of the offshore operations by the application of IO solutions. Another possible benefit following such a restructuring of the organization into being more process oriented is the opportunity of reducing the number of administrative and managerial staff as more efficient asset management can be obtained.

The presented Figure 41 below is an attempt to illustrate current organizational boundaries of the operational organization in CDE. It is underlined that the figure is a coarse simplification of the reality, but it is the author’s opinion that it do however describe some relevant existing issues that are worth highlighting. Thin lines are used to illustrate some degree of organizational boundaries, thick lines illustrate more substantial organizational boundaries and double lines are applied where the organization is thought to have a larger degree of organizational boundaries. Blue arrows indicate the main flow of information and communications. It is however worth pointing out that other lines of communication do exist, like for instance between equipment vendors and the offshore organizations, between the onshore organizations of the rigs as well as between the offshore organizations of the rigs. These are however not formalized and established in the same way as for the main lines of communication.

The asset management of COSL Prospector is a special case, as it is managed and operated by the organization COSL China, while it as the same time is partially manned by Norwegian CDE employees. The asset is also owned by CDE. From this it can be concluded that organizational barriers between the two organizations, as well as cultural and language differences represent challenged that need special attention. As there exist plans for the possible future operation of this rig on the NCS it is important for CDE to maintain close communications with the management team of the rig located in China in order to follow it up from a technical integrity point of view.

There is also a double line indication between the accommodation units and the rest of the rigs as exchange of information between the operational teams of these assets and the others in the organization are not formalized. For some processes, especially those related to purchasing, logistics, human relations and execution of projects related to implementation of new equipment or modifications, it can prove to be beneficial with a higher degree of future collaboration with the operational teams of the accommodation units as well.

Client/ third party offshore representative	COSL Pioneer offshore organization	↔	COSL Pioneer onshore organization	↔	Equipment vendors , onshore third parties, client, authorities
Client/ third party offshore representative	COSL Innovator offshore organization	↔	COSL Innovator onshore organization	↔	Equipment vendors , onshore third parties, client, authorities
Client/ third party offshore representative	COSL Promoter offshore organization	↔	COSL Promoter onshore organization	↔	Equipment vendors , onshore third parties, client, authorities
Offshore client representative	COSL Rival offshore organization	↔	COSL Rival onshore organization	↔	Equipment vendors , onshore third parties, client, authorities
Offshore client representative	COSL Rigmar offshore organization	↔	COSL Rigmar onshore organization	↔	Equipment vendors , onshore third parties, client, authorities
Client/ third party offshore representative	COSL Prospector offshore organization	↔	COSL Prospector onshore organization located in China	↔	Equipment vendors , onshore third parties, client, authorities

Figure 41 Organizational boundaries in CDE

Operations and maintenance decision-making

According to the CDE maintenance management model an important and integral part of the managerial maintenance processes is the performing of analysis, improvement and implementation of measures in relation to these. CDE is a relatively young organization, which held little or no experience with the operation of its assets when the maintenance system for them was designed. In addition to this novel technological solutions now have emerged, rendering the opportunity for performing operations and tasks more efficiently. From this it can be claimed that there exist improvement potentials related to the implementation of systematic improvement measures related to established procedures, manuals and maintenance tasks. Such processes is stated to be the responsibility of the maintenance manager onshore by the aid of the MEG. The current practice in CDE is that if employees in the offshore organizations discover an improvement potential related to maintenance tasks, be it in relation to scheduling, work description, connected resources or others an improvement proposal it is presented to the offshore technical section leader. If he agrees with the view of the employee the improvement proposal is recommended for implementation to the onshore maintenance manager. The same process is applied for improvement proposals related to existing procedures, guidelines, checklists and manuals. This way of managing the improvement process hold both several benefits and drawbacks. The main benefits are related to the empowerment and engagement of all employees. This must be seen in relation to the philosophy of CDE which states "always do better". The employees that operate systems and perform operations and maintenance tasks on a daily basis are the best suited for detecting improvement areas. By encouraging them to contribute one is able to release the potential in the employees related to improvement of the organization, and by this maintain a satisfied and motivated organization with continuous improvement. On the other hand this approach for managing improvement to the operation and maintenance processes is unsystematic, as it is dependent on the voluntary contribution from the employees in the offshore organization, whose main tasks are related to the daily operations of the rig.

As Starr point out in his article "A structured approach to the selection of condition based maintenance" the performing of thorough maintenance audits will identify which maintenance activities are the major cost drivers, be they justified or not. In many cases new equipment comes with generic recommendations related to maintenance tasks, which are established to ensure the correct function of their delivered equipment under the most severe operating conditions (Starr, 1997). Customers are often forced to adhere to such maintenance programs in order to be able to maintain validity to warranty agreements and so on. Such issues have now become less relevant for CDE as most equipment no longer is dependent on such restrictions, and now the main focus is to maintain the safe and efficient operation of installed equipment in the most cost efficient manner in order to be able to maintain continuous operation of the assets. Obtained operational experience can be applied for changing the schedule for many maintenance tasks, and some can be considered eliminated. The consideration of implementation of other maintenance strategies for equipment like CBM could be an integral part of such a process. From this point of view the establishment of regular maintenance audits focusing on the validity of maintenance tasks and possibilities related to alterations to maintenance strategies could be carried out. Such audits could be for instance be performed by the MEG on a regular basis.

One specific example of an alternative approach to the implementation of improvement measures is the establishment of an annual revision program where key personnel from the different operational departments of the rigs evaluate the last years performed maintenance tasks with the goal of identifying tasks which can be better described, identifying major cost drivers and evaluate the possibilities or needs for changing the scheduling of tasks. Similar work groups can be established for the annual assessment of spare part needs, as the consumption of- and need of spare parts is an ever developing process which needs to be followed up systematically from time to time in order to keep track of inventory needs and requirements. The prevailing practice for such measures seems to be the performing of need based campaigns performed by key personnel on irregular basis initiated by the maintenance manager, and thus there seems to be room for formalization and improvement of such measures, which can be managed by the MEG.

Lastly it is worth mentioning that a more extensive and systematic approach to the application of opportunity based maintenance can lead to improved maintenance performance. Several maintenance tasks are for instance only performable when the rigs are not performing drilling operations, while others can only be performed when the rig is between wells. Improved planning of performing maintenance tasks within these limited time windows, including careful prioritizing of the planned tasks, can render CDE the opportunity of improved asset utilization as the overall operational time of systems can be optimized. This can be seen in relation to what is described as shutdown and outage strategy for improved asset management in section 2.

Configuration management and management of change

During the recent years CDE have performed several modification and installation projects on their rigs. The relatively large extent of such modifications and implementation of new equipment has followed as a natural part of the gradual obtaining of operational experience with the several newly acquired assets. These relate to the improvement of existing systems as well as the installation of new equipment. In addition to this some systems have been decommissioned. Even though CDE now have established the previously described procedure for the proposal and performing of technical modifications, there still seems to exist an unreleased improvement potential related to better end-to-end management and coordination of these processes. The opportunities related to the effective utilization of this procedure are many. Firstly CDE can obtain benefits from improved collaboration between the operational teams of the different rigs. If for instance a modification is planned on one rig, there is a potential for savings related to performing of the same modifications to the other assets as well. Through this one is given the opportunity to reduce engineering costs and the achievement of discounts related to several purchases at the same time. In addition to this one is given the opportunity of maintaining the similarity of the rigs, and thus the benefits this give in relation to standardization of operations, maintenance tasks and use of common fleet spare parts. From this it can be derived that the continued utilization of this procedure ensure a holistic approach to management of the entire asset portfolio, which is in line with prevailing asset management theories described in section 2.

When performing project based work it is important to be aware that the project is not complete until all the related tasks are complete. This include both design and implementation of drawings, operational procedures and maintenance tasks into the correct systems like CMS and CMMS. These are all tasks that require substantial efforts, both in relation to the performing of tasks as well as in relation to the quality, content and validity of the documentation that is being produced. The importance of documentation can be further illustrated by statutory demands which require that all relevant documentation is available prior to the equipment being put in operation. In can be claimed that the extent and importance of documentation tasks have not been given sufficient attention by the CDE organization during its first years of operations. This partially come as a result from the rapid development and expansion of the organization, and the fact that CDE operate several newly acquired and complex assets. As aforementioned CDE have however recently established a procedure for the performing of modification tasks to improve the processes related to this. In order to ensure the effective and efficient utilization of this procedure it needs to be prioritized as a focus area for all personnel involved in these processes, ranging from top management to ground floor workers. By managerial recognition and acknowledgement of the importance of good planning, adequate resources allocation and sufficient time to perform and implement modification tasks it is the authors' opinion that CDE have the opportunity to obtain substantial benefits in the future.

Stakeholder engagement

In todays' competitive market situation improved collaboration and forming of alliances with vendors and clients can lead the way for obtaining competitive advantages. Releasing the full potential from equipment and systems can be better achieved through continuous and reliable exchange of information and communication with vendors. Close communication and mutual trust with clients is also important when challenges are being met. Some recent developments related to this aspect have already been highlighted and discussed in section 2.6. It is the authors' point of view that the potential of forming such business-to-business relationships not have been fully released in the organization.

The current practice for communication and collaboration with vendors and service providers seems to be somehow limited to scheduled meetings with the related parties, where the main agenda is related to revision and evaluation of contractual framework agreements, and to some extent the evaluation of the quality of the services provided. Such meetings are mainly being performed by the financial department of the organization, with the assistance of key managerial personnel responsible for utilization of the specific services being provided. The future improvement of such communication and integration processes can take many forms, but from a general point of view one can promote a more aggressive implementation of vendors and clients in decision-making processes in the organization, as this can serve as an aid to obtain improved performance throughout the organization as well as improved utilization of the assets being operated. In other words, the effective integration of alliance partners into the decision-making processes of the organization can be an important step in the direction of achieving operational excellence.

One specific example how such a process can be initiated is the improvement or change of agenda in the meetings with key partners and vendors. The agenda for such meetings can be expanded to also include the presentation of the last years' operational data and experienced issues with equipment, with the goal of detecting improvement potentials together with operational and technical expertise from the vendors. In such meetings plans and opportunities related to future developments and implementation of novel available solutions can be discussed, and overall plans for the coming year in relation to these can be outlined. Another benefit with a new agenda for these meetings is improved budgeting as one is enabled better planning of future modifications and upgrades proposed by the vendors. By inviting technical personnel from the vendors to the meetings, they can be given a better impression of the specific needs of the organization, and thereby be able to present targeted solutions for improved value making. By involving technical personnel in meetings with service and equipment providers, specific technical challenges that CDE employees experience during their daily operations of equipment can be presented, and by the obtaining of this information the service providers are enabled to develop or present solutions to these challenges.

Based on the previous sections 4.4 and 4.6 the following list of key vendors and technical service providers have been identified, and some suggested topics for discussions in future meetings are also proposed. It is underlined that this list is not exhaustive, and the presented topics do not represent CDE in any way, even though their forming is based on conversations and discussions with personnel from the organization.

- Wärtsilä
    - Technical improvement potentials related to the existing CBM solution
    - Improvement potentials related to exchange of information and lines of communication regarding the CBM solution
    - Possibilities related to improved maintenance and utilization of equipment
    - Improvement potentials related to service bulletins
    - Possibilities related to provision of new services

- Karsten Moholt
    - Technical improvement potentials related to the current application of CBM
    - Improvement potentials related to exchange of information and communication regarding the CBM solution
    - Potentials related to improved maintenance and utilization of thrusters and related equipment
    - Potentials related to installation of new CBM services

- NOV
    - Improvement potentials related to maintenance and utilization of equipment
    - Improvement potentials related to upgrades of equipment
    - Improvement potentials related to implementation of new equipment
    - Improvement potentials related to use of e-Hawk online support solution

- Kongsberg
    - Improvement potentials related to the DP system
    - Improvement potentials related to the fire and gas system (VCS)
    - Improvement potentials related to the VCS
    - Improvement potentials related to exchange of information and lines of communication

To exemplify the importance of good communication with vendors and service providers a recent case regarding improvement of the operational availability of the CDE assets can be presented. Due to several factors like for instance limited operational experience with the rigs and improvement potentials related to the DP system CDE experienced challenges related to be able to perform continuous drilling operations independently of the prevailing weather conditions in the area of operations. Several meetings were held with Kongsberg Maritime, which is the vendor of the DP system. These meetings resulted in Kongsberg presenting a possibility for improvement to CDE, which was related to the installation of a dampening filter to the DP system. This led to the installation of the dampening filter on all CDE assets between the winters of 2013 and 2014. In addition to this several other actions in order to improve the situation were taken. Figure 42 below obtained from an internal CDE document present a comparison of the lost operational time in relation to waiting on weather in the winters of 2013 and 2014. From this graphical illustration one can conclude that the improvement measures taken have resulted in a significant reduction of the lost operational time related to waiting on weather, and thus provided a significantly improved utilization of the asset portfolio.

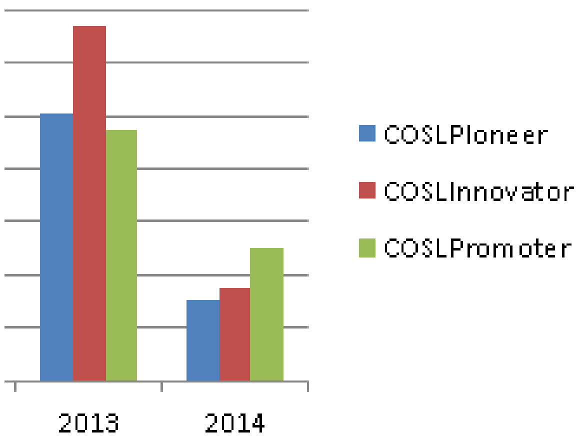


Figure 42 Comparison of lost operational time related to waiting of weather CDE assets 2013-2014 (COSL Drilling Europe, 2014f)

When performing meetings with key stakeholders it is important to have a clear definition of the responsibilities and expectancies of the different parties involved. It also follows that in order to release the potential that lies in forming collaborative alliances one is dependent of sharing extensive amounts of potential company sensitive information, and thus it can be concluded that a good relationship and high degree of mutual trust needs to be established between the involved stakeholders. In addition to this contractual agreements could be established for the handling of data and communication, in order to avoid exploitation of any involved parties.

Data and information management

In todays' highly information driven organizations which rely on complex interdepartmental and cross functional collaboration sharing and effective utilization of information seems to be an increasing challenge. As today's technological solutions enable generation, storing and sharing of vast amounts of information this challenge seems to be increasing even more. There exist many dissimilar sources and types of information within a number of different business areas, and being able to integrate them into a system so that it easily accessible for all relevant parties has now become an increasingly difficult task. There exist several reasons for this. Many OEM's and vendors provide customers with information like drawings, manuals, procedures, service bulletins and so on and so forth through their own in-house developed solutions. Clients often have their own systems for managing information, and so do third parties involved in the operations. Various organizational cultures related to the exchange of information makes standardization an issue. These are complicating factors as compatibility between different systems often do not exist.

Today CDE perform their business management processes based on the use of several computerized applications for managing data and information, of which none are fully integrated parts of the CMMS. In addition to this none of the applications are integrated or have compatible functions with each other, and this fact make the timely exchange and distribution of important information across the platforms a challenging task. Some examples of systems being used and their area of application are described in Figure 43 below. From this it can be seen that the management of data, and manual exchange of information between the different systems is both a strenuous and time consuming task. Such processes are further complicated by the different nature of the information, and in some cases the format that files are stored in. Strategic decisions on where to store data, information and communication and how to enable the employees easy and straightforward access to them are areas that need focus and attention in order to maintain CDE's position of being a well performing organization. Decisions related to this needs to be clearly communicated to all relevant parties so that one is able to access data and information in a timely manner.

It is the authors' opinion that this can be a future area of improvement for CDE. The way tasks are being managed today seem to lack a holistic approach for integration of work tasks into the CMMS. This can be exemplified by the current practice for management of the large number of certified equipment in the assets. Today the service providers that perform the recertification of such equipment provide the related certificates in their own systems as shown in Figure 43. In order to utilize this information for manual creation of WO's related to timely recertification of equipment, one is dependent on manually accessing the data from these systems in each specific case. Experience shows that failures in access to and sharing of the correct information in a timely manner in some cases have led to unfortunate events, like for instance damage to equipment causing operational downtime and thus loss of income. Effective access to and sharing of information is further complicated by the fact that not all employees have access to all the information stored in the different systems, as they require user specific usernames and passwords. All employees do however have access to the CMMS, and from this it can be derived that a more aggressive implementation of information here seems to be a suitable solution to the problem. On the other hand not all information is needed by all employees, and from this it can be seen that careful consideration must be taken in order to prevent employees being flooded with excessive amounts of information.

One specific measure that can be taken in order to mitigate the risk of the mentioned unwanted occurrences in the future would be the forming of a procedure for the sharing of information between the different systems, and the implementation of this throughout the organization. Here a system for sharing of information and processes related to quality assurance of the flow of information could be developed and clearly defined. This would enable the organization to form a holistic approach to the storing of data and sharing of information, so that retrieving it would become an intuitive process for all involved parties. Further the implementation of an integrating form of application which give access to all platforms for information can be considered.

Another specific alternative would be the strategic decision of choosing the implementation of a new platform with extended possibilities related to the seamless integration of information into one common system. Especially the CMMS which is in use today for managing a series of CDE's business areas have several user face limitations. These are related to lack of functionalities regarding integration between purchasing, spare parts administration, logistics, work planning, asset management module, project module and the reporting module. The system also have lack of functionality when it comes to the document management module. Lastly there is the aforementioned problem that third parties and vendors do not have any access to the CMMS, and they are thereby prevented the opportunity of sharing important information, like for instance service bulletins and alerts as well as analysis results and reports. They are also prevented access of historic maintenance data which could have been utilized in order to aid CDE in maintenance related decision-making processes.

An important aspect when considering the implementation of a new CMMS would be a thorough evaluation of the risks involved with pursuing such a complex task. Such a process could be initiated by performing an extensive analysis of the current and future needs of the application. In this way one can ensure that the maximum potential of the process is released, in terms of creating intuitive and well-designed interfaces which entail a large degree of integration of information and processes. If an implementation of a new system is to be commenced while the CDE assets are in continuous operation, this needs to be well planned in order to avoid any risks to personnel, equipment or the environment. One possible solution in this respect would be to implement the system in several phases, where a parallel operation of the existing and replacing system is maintained until the functions of the replacing system have been quality assured.

Service provider	Name of platform	Area of application
Axess	Axess Client Gateway	Surveys and documentation regarding lifting appliances, piping
DNV	DNV Exchange Server	Administration of surveys, statutory inspections, certificates and approvals
Invicta	ILA Web	Oil sampling and analysis reports
NOV	HED Bookshelf	Access to service bulletins, technical documentation, spare part lists etc.
Onix	Onix utstyrsportalen	Administration of control, service and certificates for fixed and portable lifting appliances
Sharecat	Sharecat	Spare parts evaluation
IKM	IKM Ekstranett	Calibration certificates of instruments and gauges
Wärtsilä	Eldocs, myWärtsilä, Wärtsilä CBM	Access to service bulletins, technical documentation, spare part lists, CBM reports, etc.
Karsten Moholt AS	KMOAS CBM	Access to information regarding technical state of thrusters
Onsoft Computer Systems	OCS HR and Employee Self Service	Payroll and crewing solution including the documentation of competence of employees
Kongsberg Group	Rig Manager	Reporting of daily operations and operational data related to KPI's such as daily drilling report etc.
DNV GL	Synergi	Reporting system for handling of safety observation cards and handling of non-conformities
OpenText	eDOCS DM	CMS document management system for management of procedures, guidelines, manuals, checklists etc.
SISMarine	IPS Star	CMMS

Figure 43 Platforms used by CDE and their area of application

Competence management

It is evident that the requirement for competence in the offshore workforce has been significantly increased during the last decade. The application of novel and advanced technology which require performing of complex, multi-disciplinary tasks have become an integral part of the daily offshore operations. In addition to this the application of IO and ever increasing interdependabilities of tasks, as well as a large extent in automation of processes places new demands to competence and requirements. An example of a complex control system that has been widely implemented on drilling rigs on the NCS is the previously mentioned NOV Cyberbase Operator Station (National Oilwell Varco, 2015b). This unit enables the driller and roughnecks to control the entire drilling operation from their operator stations inside the drillers' cabin. The design of the Cyberbase operator station is very much in line with emerging market trends in the industry related to human factors fields like systems thinking and anthropometry. This include a focus on physical design of system where strenuous and potentially dangerous tasks are designed out and made subject to automated processes, and ergonomically sound solutions are chosen for the performing of human tasks like control of complex operations. According to the skill-rule-knowledge framework presented by Rasmussen one can argue that the employees now have gone from skill- and rule based workers into being performing knowledge-based human interactions (Rasmussen, 1983). This he define as the highest level of complexity in performing of tasks, as it entail a certain degree of cognitive effort in order to decide on which action is the most appropriate. In order to ensure the safe and efficient operation of such complex systems a high degree of system understanding is required. On the other hand it can be argued that many of today's systems in fact now have become so advanced that it cannot be expected of the operators to fully understand them, and thus their roles have been reduced to operators that act upon a set of choices they are presented to by the HMI of the system. When problems occur one is to a large extent dependent on external expertise to solve complex technical issues related to both software and hardware. Similarly the tasks of maintenance personnel have been gradually evolving to become more related to condition monitoring and performing of less complex maintenance tasks, whereas special tools and expert knowledge is required for understanding problems and performing more extensive maintenance tasks. This general industrial development is also reflected in other business areas like the automotive industry, where cars now have become so advanced that the customer self-service and ability to perform maintenance is extremely limited (Hirsh et al., 2015).

These developments have led the way for new thinking when it comes to planning of complex and more extensive maintenance tasks. It has now become more usual to perform campaign-based maintenance executed by roving expert teams based on planned PM tasks. An example of this can be major overhauls of various equipment, which is normally performed or assisted by expert technicians from the OEM's. From this aspect the inclusion of CDE employees while performing such tasks can give the organization substantial benefits in terms of equipment understanding, which in turn can render the opportunity of improved operation and maintenance of equipment. In addition to this a deeper understanding of equipment functions and systems may serve as an aid in the early detection of errors and failure modes.

As previously described CDE use the CMMS Star IPS for all aspects related to maintenance of their asset. This system is both complex and extensive, and a number of different functionalities are available and expected used by the employees. From this it can be understood that adequate training in the use of the system serve as an important enabler when it comes to effective performing of tasks according to the given standards. It is the authors' opinion that CDE have a potential of better utilization of the CMMS through an improved focus on training and education of employees in correct utilization of the system and its functions. Current practices related to training and education seems to be related to ad hoc measures like man-to-man introduction to the system by colleagues, and thus it appears to be a lack of a systematic approach to training and education in the use of the system. CDE have however developed a set of guidelines to the application of the CMMS, which can be accessed by all employees at any time for self-training and retrieving information about the system functionalities. CDE have also established well-functioning computerized training programs for the effective utilization of other electronic application, like for instance the previously described CMS. CDE also seem to have a well-functioning system for maintaining the extensive statutory competence requirements of their employees by the application of the HR management system OCS.

Due to the new requirements to offshore workers related to the operation of novel and complex technology for drilling solutions CDE have partially financed the installation of a drilling simulator at Stavanger Offshore Tekniske Skole (SOTS). This advanced simulator, illustrated in Figure 44 below, is based on the same Cyberbase technology installed on the drilling rigs. The simulator can perform all activities in the same way as the actual drilling operations performed from the drillers' cabin offshore. The extended use of this simulator can serve as an aid to improve both safety and efficiency of operations offshore. This is especially valuable when new personnel are employed, but is also relevant in order to improve KPI's like consistency of drilling operations and so on. This has become more relevant during the last year resulting from a relatively high position turnover on personnel in the drilling department, as well as the forming of new teams resulting from the more extensive application of personnel rotation between the rigs following the suspension of COSL Pioneer. Similar practice with rotation of personnel have also been applied for the other departments in the offshore organization as well. While this practice give several operational challenges, it has also given the organization several advantages. With the arrival of new team members, holding substantial operational experience from the other rigs, one is enabled the exchange of information and effective first hand learning in the entire teams. From this point of view it can be suggested that the periodic rotation of personnel could be considered implemented as a part of the strategic asset portfolio management of CDE.

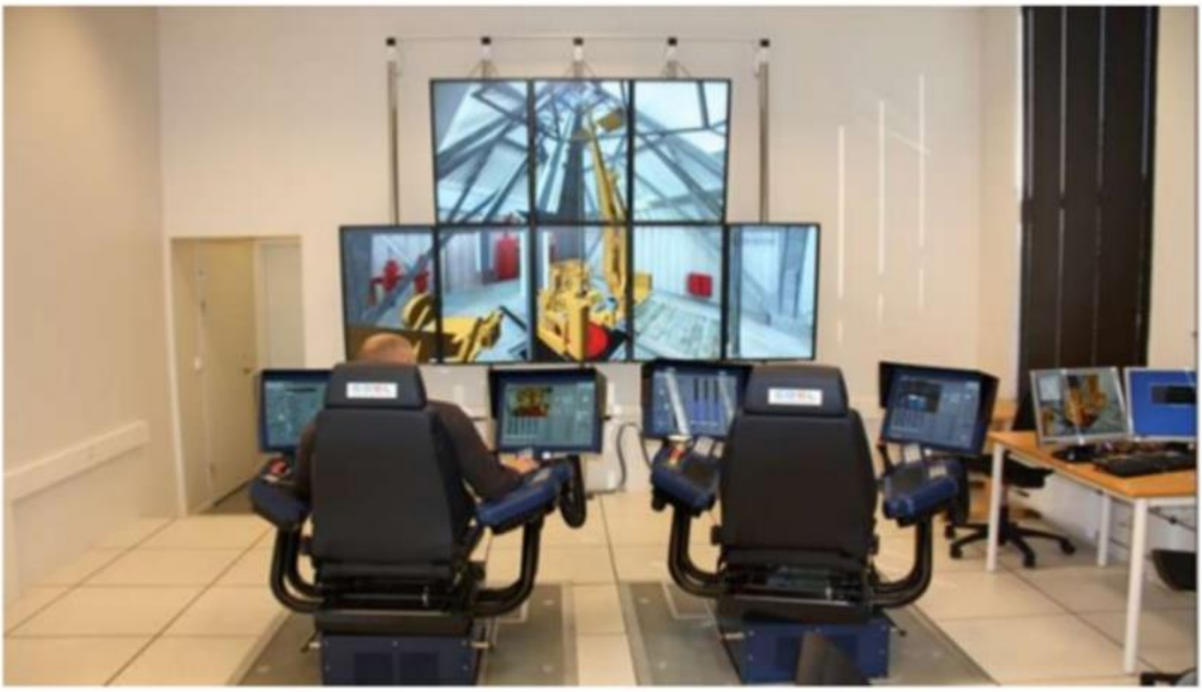


Figure 44 CDE Cyberbase Drilling Simulator installed at SOTS (COSL Drilling Europe, 2014c)

One current practice in CDE is to use personnel from the offshore organizations for assisting in some campaign based tasks in the onshore organization. Examples of such tasks is to assist in the revision of documentation, performing improvement measures related to maintenance tasks or project work related to implementing new equipment and so on. By doing this CDE is able to harvest on the human capital from the offshore organization in the onshore organization.

Other organizations, like for instance Statoil, practice a scheduled rotation system of key managerial personnel between their on- and offshore organizations. In doing this they are able to optimize the exploitation of the available human capital throughout the organization, independently of the organizational affiliation of the personnel. Personnel with recent offshore experience can serve as important attributes in relation to enabling improved decision making processes onshore. Similarly personnel with onshore organizational experience rotated to the offshore organization can serve as aids to breaking down organizational boundaries, as they have first-hand knowledge to the decision making processes being performed onshore. Such a practice can also be considered implemented for CDE in the future to enable optimized utilization of the human capital in the organization.

5.2 Possibilities related to current and future condition monitoring practices on COSL Innovator

One main challenge with the application of traditional condition monitoring practices is that the technique lack the ability to use the combination of several parameters to establish a picture of the technical state of equipment. The establishment of such a picture is dependent of the operator that assesses the data, and his analytical ability to compare and collocate the readings for doing so. All diagnostics and prognostics based on the acquired data from condition monitoring are in other words object to subjective analysis performed by different employees. This approach sets high demands to the workers in relation to having a systematic approach to be able to detect emerging problems over time. As the assets in CDE is operated by offshore personnel working 12 hour shifts, with a total working period of 14 days between each leave period of 31 days, while the assets are continuously operated, this approach to detecting emerging problems become a challenge. Different personnel with dissimilar experience and attitudes are performing the monitoring tasks, and they hold different levels of familiarity and knowledge in relation to the equipment they monitor. As aforementioned it can also be challenging to keep track of developing trends in specific equipment, as there are so many manually inspected parameters to keep track of throughout the asset. To remedy this situation CDE have established routines for noting relevant parameters into a data sheet on a weekly basis, so that incremental deterioration trends can be more easily detected. A more extensive exploitation of this data can in the future serve as an important aid in the detection of errors and failures.

The application of periodically performed condition monitoring tasks on COSL Innovator is both time consuming and complicated, at the same time as it has several inherent weaknesses in relation to effective diagnostics and prognostics. The technique can however give important system information to the assessor by limited means of effort, given that it is applied in a systematic manner and the given results can be apprehensible for the assessor. Training of personnel in the correct application of manual condition monitoring on COSL Innovator could therefore be made subject to continuous improvement measures as it is an important area for technical information gathering.

One specific example of a weakness with the continuous monitoring system on COSL Innovator is the ability to detect failures in the general service air compressors. The system operator manning the VCS can for instance be notified that the delivery pressure from the compressor is in an alarm state, as the air receiver pressure is subject to continuous monitoring, and will give an alarm to the VCS if the pressure falls below a preset value. As the only readings obtained on the VCS from the compressor itself is whether it is in an error state, operational state or shut down it will be impossible for the system operator manning the VCS to determine what the failure cause is. One possibility is that the air consumption at the given time is so high that the compressor fails to maintain the pressure above the alarm level, and that there in fact is no failure in the system at all. In any case technical personnel will have to be notified about the situation and perform a physical inspection of the compressor and the related equipment in order to establish a picture of what is wrong. This example is included as it effectively illustrate that in order to release the full potential of condition monitoring measures one is dependent of the continuous monitoring of an extensive number of parameters, which reality shows is not always the case. From this point of view one can consider the implementation of more continuously monitored parameters to the VCS, so that the assessment of error conditions and the ability to ferret out root causes for the problems can be made a more straightforward task.

On COSL Innovator continuous condition monitoring is, amongst other things, applied to tank levels on various tanks. In many cases irrelevant low level alarms present the VCS operator with unnecessary information that both steal attention from other important tasks and creates frustration. The systematic application of inhibitions of alarms could be applied to a larger extent in order to prevent such irrelevant alarms. Another possibility is to consider the extended application of altered alarm limits and time delays in order to improve the condition monitoring system.

When an anomaly is detected it is not always a straightforward task to decide on the suitable actions in order to assess or rectify the situation. In some cases the application of need-based condition monitoring would be the suitable action. In this way one can establish a better picture of what is wrong and thereby be able to ferret out the root cause of the failure. This will give the opportunity of performing CM on the exact part of the equipment that is need of it, instead of performing a series of unnecessary maintenance tasks in order to make the equipment functional again. In others cases the immediate shutdown of equipment in order to prevent the development of serious failures leading to faults in equipment would be the appropriate action. In order to enable improved decision-making processes related to this aspect the knowledge in use of need-based condition monitoring equipment needs to be held by the maintenance operators of the rig. In addition to this such equipment needs to be available and easily accessible for the maintenance operators when needed. It is the authors' point of view that this can be an area of improvement for CDE. In some cases the equipment is available, but the maintenance operators fail to recognize the applicability of equipment for effective detection of failures in equipment, or the do not have the knowledge in how to apply the equipment properly.

5.3 Possibilities related to current and future application of CBM on COSL Innovator

According to OLF the business trend for implementing a CBM strategy for assets involved in the O&G industry on the NCS is mainly evolving around heavy rotating equipment (Oljeindustriens Landsforening, 2005). This also seems to be the case for COSL Innovator, as its current application only regards the main engines and the thrusters. These are two of the largest and most cost driving systems installed on the rig, and in addition to this they can be argued to be the most important systems of the entire asset. This is because they are the lifeline of both the power and station keeping system. The reasons that the implementation of the CBM strategy so far is limited to these two systems are many. Firstly the rig was originally designed for another company, which was later procured by CDE. Therefore the rig was not designed according to the maintenance strategy applied by CDE. In addition to this the rig was designed more than a decade ago, and at that time novel solutions in relation to IO and CBM was just starting to being implemented on assets operating in the NCS. Experience shows that the installing of systems for condition monitoring and advanced communications solutions for implementing IO after rigs are both designed and built can be time consuming, complex and costly activities. Lastly there seems to be a reluctance towards implementing novel high technology solutions for CBM, as CDE experience that the existing systems are designed and operated according to the state of the art in the industry, and are functioning adequately both in relation to safety and the cost effective operation and maintenance of the asset. Through the implementation of a CMB strategy for the main engines and thrusters CDE have gained substantial benefits related to economies of scale, as the 6 identical main engines are hooked up to the same CBM solution, and similarly for the 6 thrusters.

Operational experience have proven that CDE have obtained substantial benefits by their implementation of a CMB strategy for the main engines and thrusters, and thus there exist a reason for raising the question whether CDE can obtain additional benefits from the application of this predictive maintenance strategy for other technical systems as well.

Based on the current trends in the market related to the implementation of CBM on mainly heavy, rotating machinery, as well as on the current available technical solutions some identified systems that can be eligible for consideration will be given a brief explanation and discussion in the following sections. It is important to point out that the possible implementation of CBM should not be limited to these identified systems, as other eligible systems may exist. The identified systems however seems to present themselves as the most obvious choices from the existing knowledge on the topic.

It is worth mentioning that it is important to comprehend the fact that the implementation of advanced condition monitoring techniques for monitoring and assessment of technical state of equipment is not always suitable, or even advisable, even if it is found to be a technically feasible solution. Deciding on whether or not the implementation of a CBM strategy for these systems is feasible will require more extensive studies, where one approach could be the application of cost-benefit analysis. Such extensive analysis is not included in the following as it lies outside of the scope of this thesis. Some presentation of quantifications will however be provided for the illustration of possible costs related to breakdown of equipment.

Improvement potentials related to current CBM practices

From what is described in section 4.6 it can be concluded that CDE have adopted some elements of 1st generation IO through its implementation of Wärtsilä and KMOAS CBM. This can be advocated as the boundaries of CDE's maintenance organization now have been extended to also include the aid provided by the expert knowledge of the Wärtsilä and KMOAS CBM centers. These experts are responsible for performing the advanced monitoring, diagnostics and prognostics of the equipment in a systematic way, while the system operators offshore are responsible for the safe and efficient operation of the equipment on a day to day basis. The decisions related to maintenance activities are however still being taken by the offshore organization in cooperation with the land organization of CDE. As the Wärtsilä and KMOAS CMB centers are only implemented as external aids for performing the decision-making processes, and are not fully integrated as contributors to these, it is further documented that only 1st generation IO processes are implemented.

Even though CDE have established well-functioning systems for CBM for the main engines and thrusters it is the authors opinion that the full potential of this strategy has not been released. This can be seen in relation to the previous section regarding the improved cooperation with service providers. The systemization of communication with the service providers regarding information about operations and maintenance actions that may have affect the monitored parameters could be established, for instance by the generation and implementation of a procedure describing roles and responsibilities of performing such communication tasks. In this way the service providers which assess the obtained data would be enabled to provide CDE with more relevant advice regarding upcoming challenges, and by this being able to partake in decision-making processes related to optimization of operations and the generation of maintenance tasks. In order to facilitate this a more aggressive integration of the CBM into the CMMS could be established. Real-time exchange of operational data and information could then be used for the automatic generation of maintenance tasks when needed. Furthermore all relevant parties should be granted user access to the CMMS. In this way the implementation of operational data to the CMMS would further improve the accessibility of this data for all related parties, and this integration could serve as a facilitator to improved quality and efficiency in processes. By doing this one would be moving in the direction of implementing elements of 2nd generation IO-processes. Currently there is no direct implementation of the CBM related data and information into the CMMS. Maintenance reports and other findings needs to be processed by supervisory maintenance personnel before the information can be applied for the generation of maintenance tasks in the CMMS. This manual processing present challenges both related to quality and regularity, in addition to being time consuming efforts. Similar practices exist for exchange of information between the service providers and CDE regarding performed maintenance tasks, which currently needs to be forwarded to the service providers manually by the maintenance manager, as they do not have access to any available technical information from the different functions of the CMMS.

It can be argued that the Wärtsilä CBM can be more aggressively utilized in the forming of PM tasks than the current practice demonstrate. Such an approach would entail a more extensive inclusion of the expertise in Wärtsilä in the revision of the current maintenance tasks based on experience and findings obtained by the application of the extensive condition monitoring and CBM. Such actions could lead to optimization of the asset utilization through improved quality of maintenance tasks and reduced spare part consumption.

Even though all condition monitoring parameters for the main engines are available for the offshore system operator through the VCS, this information is not applied for advanced diagnostics and prognostics presenting the system operator with possible emerging challenges. This current practice require substantial operator experience and knowledge in order to be able to utilize the available information for the correct and timely identification of emerging challenges. The obtained benefits given by integrating automated diagnostics and prognostics into the HMI in the VCS should however be made subject of a cost-benefit analysis before being considered implemented.

While all the condition monitoring parameters for the main engines are presented to the system operator through the HMI of the VCS this is not the case for the thruster monitoring system. These parameters are not implemented into the VCS at all, as they are being sent directly to the KMOAS CBM for assessment. From this it can be seen that the benefits of having this information available on the installation offshore is not obtained. Therefore one possible improvement potential would be the integration of the thruster condition monitoring system into the VCS. By doing this the system operator manning the VCS would be enabled real-time assessment of the monitored parameters so that the current technical condition, and monitoring of deterioration trends could be performed locally. In addition to this the obtained data could be made subject to advanced diagnostics and prognostics by the system similarly as the suggested solution for the obtained data from the main engines. In this way the system operator would be enabled the presentation of emerging challenges by the system, including the automatic identification of the root cause for the deteriorating trend.

Extended intervals for statutory surveys of thrusters

One of the main advantages that can be obtained by changing the maintenance strategy for the thrusters from PM to CBM is the possibility of extending the statutory maintenance intervals for the thrusters. This can be seen in relation to the already described benefits related to the possible postponing of the main overhaul of the main engines from 24000 running hours to 36000 running hours based on the CBM strategy applied. Based on the documented ability to continuously assess and verify the technical state of the thrusters CDE are now in the process of examining the opportunity of postponing the 5 year statutory class survey of the thrusters. If such a postponement can be achieved the significant costs related to the dismantling of the underwater parts of the thrusters, and thus the lost operational time following as a result of the extensive maintenance tasks, can be avoided. This will naturally depend on the ability to demonstrate that performing of the statutory maintenance tasks are not necessary from a technical integrity point of view.

Experience shows that the performing of a 5 year statutory class survey of 6 thrusters normally takes about 20 days of continuous work in a sheltered shipyard. In addition to the direct losses resulting from lost operational time come an extensive number of man-hours, costs related to considerable spare parts consumption and diving services, as well as expensive workshop overhaul of equipment.

From the above it can be derived that the postponing of a statutory 5 year class survey would enable CDE significantly improved asset utilization through the achievement of performing continuous drilling operations for the client for a prolonged period of time. In this aspect is relevant to mention that the maintenance needs of other types of equipment within the prolonged period of operations may still lead to the loss of ability to performing continuous operations, but the extent of such periods can be assumed to be significantly less extensive than the one related to the 5 year statutory class survey of the thrusters.

The above can be seen as an integral part of what is defined as *shutdown and outage strategy* and *shutdown and outage management* by the Institute of Asset Management, and they are two of the 39 subjects of asset management (The Institute of Asset Management, 2014).

Top drive

The top drive is the equipment used for pipe handling and rotating of the drill string during drilling operations. The top drive hangs from the travelling block and is also used for allowing flow of mud from the mud pumps into the drill string and eventually through the drill bit.
Some parameters in this system are already subject to continuous condition monitoring measures, which are integrated into the control system of the unit. These are however not applied for the forming of maintenance tasks, but used by the Cyberbase drilling system to ensure the safe and efficient operation of the equipment.

Figure 45 below present a graphical illustration of the assembly, retrieved from the technical description of the top drive. The drive system of the top drive, often referred to as “the train”, including its accessories comprise of the parts (National Oilwell Varco, 2007):

- Electric motor
- Gearbox
- Suspension system
- Thread compensation system
- Water course
- Drill stem subs

The other parts of the top drive are not described here as they are not deemed suitable for the installation of condition monitoring equipment, and thus further explanation is irrelevant.

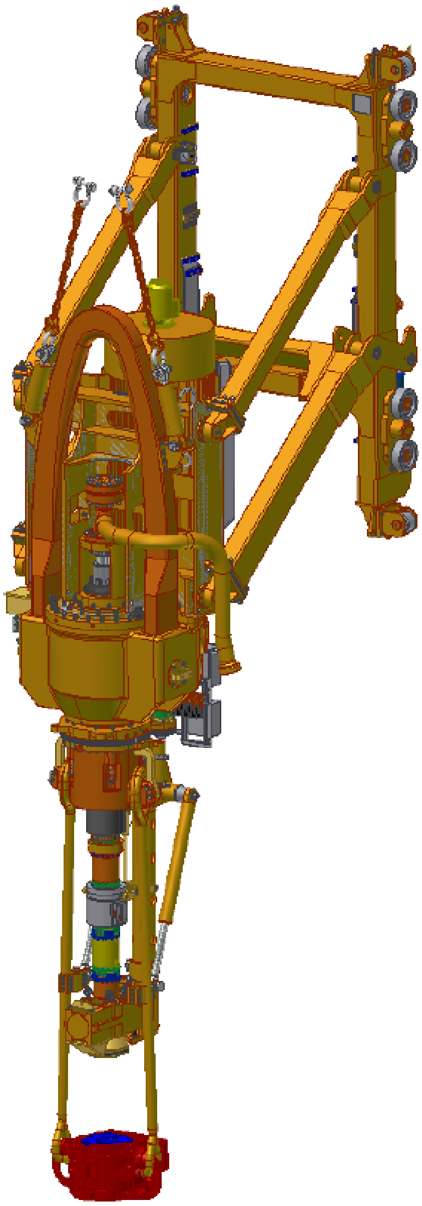


Figure 45 Top drive COSL Innovator (National Oilwell Varco, 2007)

The correct and effective function of the top drive lay the foundation for the performing of all drilling operations on COSL Innovator, and it is therefore suitable to refer to it as a main part of the backbone of the rig. With a daily operating rate of 335.000USD it is obvious that a breakdown in this type of machinery can be extremely costly for CDE, both in terms of lost income as a direct result of operational downtime, as well as the costs related to fault finding, spare part costs and repair of the equipment (Offshore.no, 2015b). As the top drive is a heavy suspended rotating machine safety issues related to a possible breakdown must also be treated seriously.

In September 2012 the top drive gear box installed on COSL Pioneer broke down. The installation on COSL Pioneer is identical as the one installed on COSL Innovator. In the CDE internal document "Karsten Moholt Top Drive Condition Monitoring Report" it is stated that inspection of the upper pinion bearing revealed inadequate lubrication of the bearing, resulting from oil pump problems. In addition to this improper alarm and emergency shutdown settings was reported to have occurred about the same time (Karsten Moholt, 2013c). Independently of what caused the fault in the system, it can be concluded that this fault caused CDE substantial losses.

A coarse estimate of the costs related to the breakdown is presented in Figure 46 below. It is underlined that even though this presentation is based on discussions with key personnel from CDE holding substantial experience from the O&G industry, it does not represent the actual costs involved in this specific case. Factors such as availability of spare parts and specialist expertize, the complexity of replacing the faulty parts and so on are factors that will vary from case to case. The estimate is however included to give an impression of the costs related to one single failure in equipment which have a high criticality to the operation of the rig.

Loss of income based on one week of downtime	16
CM on related equipment including spare parts	1,5
3rd party offshore man-hours	0,5
Total costs related to the incident	18

Figure 46 Costs related to breakdown of top drive gear box, numbers in MNOK

To further manifest the importance of avoiding breakdown in equipment with a high criticality on operations one need to consider that some spare parts have a long lead time, and are both costly to acquire and complex to replace. An example that illustrate this is the procurement cost of the electric motor for the top drive, which is approximately 200.000USD.

It is possible that this breakdown could have been avoided if condition monitoring of the equipment had been installed. It is a fair assumption that the installation and operation costs of condition monitoring equipment for the top drive would be significantly lower than the expenses resulting from the described breakdown. This can be argued because of the relatively low procurement and operation costs of novel condition monitoring technology available in the market today.

From a general review of state of the art condition monitoring techniques one can suggest that the monitoring of vibrations in the electrical motor and gearbox can be a feasible solution for effective continuous condition monitoring of the technical state of the most critical parts of this assembly. This view can be further supported by the fact that these two main components are the ones exposed to the highest levels of stress in the assembly, while they at the same time consist of the most complex and expensive parts by their nature of being heavy, rotating machinery. For this particular equipment it is reasonable to assume that any deterioration processes most likely will emit measurable vibrations at an early stage, and that continuous condition monitoring will enable the timely intervention of the root causes for the vibrations before an error can develop into a failure or fault, or project any secondary damage to related equipment. An illustration of suitable points for installing of vibration monitoring sensors is provided in Figure 47 below. This figure illustrate the sampling points used by KMOAS when they performed the vibration monitoring analysis on the identical top drive installed on COSL Pioneer in relation to the described breakdown in 2012. By further installing a multiplexer on the top drive and a triax cable between the top drive and the Signal Master in the local instrument room (LIR) via the existing service loop one can access the obtained vibration monitoring data from the control system of the unit. This data can be sent to an external service provider for signal processing and data assessment. One example of a service provider that can offer services related to diagnostics and prognostics of signals would be KMOAS.

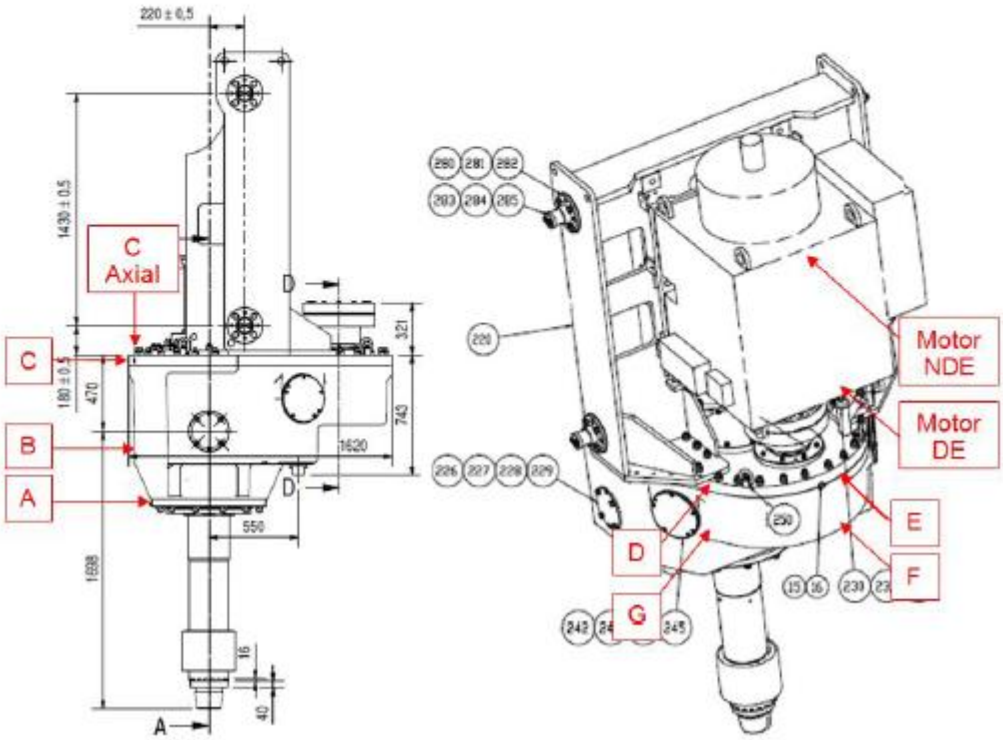


Figure 47 Suitable measurement points for vibration monitoring on top drive (Karsten Moholt, 2013c)

The future application of such a system would enable the introduction of a CBM strategy for the top drive, giving similar benefits as for the existing installation of CBM on the thrusters. If CDE find this a desirable solution they may also want to consider implementing this technology on their other drilling rigs which have the same top drive installed. If this is the case they can obtain positive synergies and reduced costs related to engineering, documentation, installation and operation as the installations on the rigs will be identical. Such an endeavor would be in line with the previously described strategy of improved asset portfolio management.

Active Heave Drawworks

The active heave drawworks (AHD) installed on COSL Innovator is a system applied for hoisting and lowering the top drive, and consist of the following main elements (National Oilwell Varco, 2006):

- Drawworks mechanical parts with AC-motors, disc brakes and emergency lowering system
- Cooling blowers for drawworks motors
- Drawworks control system
- Interface to operator stations and other PLCs

The main mechanical parts, which are of interest when it comes to the consideration of installation of condition monitoring equipment, comprise of:

- Wire drum
- Main drive electric motors
- Drive gear box
- Disc brake system including hydraulic HPU
- Lubrication oil system
- Blower unit

An illustration of the AHD mainframe and enclosure is presented in Figure 48 below.

Figure 48 AHD mainframe and enclosure of main parts (National Oilwell Varco, 2006)

Similarly as for the top drive, the AHD can be said to be an important part of the backbone of the rig, as its correct operation is needed to be able to perform drilling operations. The AHD can be controlled and operated in a number of modes, depending on the operations being performed. In manual mode it can be controlled by a joystick on the Cyberbase operator station in the drillers' cabin. This mode is typically applied during tripping or other operations when the drill bit is off the bottom. In this mode the electric motors are applied to rotate the drum on which the drill line is fitted in order to change the position of the top drive. In active heave compensation mode the AHD automatically position the top drive, and eventually the connected drill bit at a set position. This is enabled through the AHD's automatic compensating for the heave of the rig. In this mode the electric motors are applied to rotate the drum on which the drill line is fitted, and in the need of braking the electric motors function as magnetic brakes, where the generated energy is either dumped by the application of a resistor system or fed into the power distribution system of the vessel. This mode is normally used during drilling operations. Through the application of various special AHD modes one is able to control the drilling operations in a very accurate manner (National Oilwell Varco, 2006).

The AHD It is connected to the other parts of the drilling systems by its integration to the SDI. A series of interfaces related to interlocks, power limitation, automatic anti-collision and shutdown system ensure the safe operation of the equipment at all times.

Similarly as for the top drive also the AHD have continuous condition monitoring of several parameters in order to ensure control and the safe operation of the equipment. Examples of these are pressure switches for low motor cooling flow alarms, temperature transmitters on the electric motors, encoders for monitoring and control of motor speed, tank level and temperature switches.

When it comes to the consideration of feasible continuous condition monitoring techniques, similar assumptions as the ones taken for the top drive can be applied. This follows as they are both heavy rotating machinery and entail the main components electric motors and a gear for transferring of energy. From this it can be derived that vibration monitoring of these components can give the required knowledge about any deterioration trends in the equipment, as it can be assumed that such trends will lead to the emission of measurable vibrations from the components at an early stage in the P-F interval. This render the possibility of intervention in the form of CM tasks well before an error develop into a failure or fault. From this it can be seen that the elements required for implementing a CBM strategy for the AHD is limited to the installation of vibration monitoring equipment on the main electrical motors and the gearbox. The already installed encoders for monitoring of the speed of the main electric motors can be applied for scaling purposes of the obtained vibration readings from the motor and gear bearings, as the magnitude of the readings will vary dependently on the speed of the main electric motors. In addition to this cabling for transferring of the data to the Signal Master in the LIR, as well as a network solution for transferring the data to an external service provider needs to be installed. Here one can either choose to use the network solution provided by NOV or the network available on the rig, dependent of the amount of data that is to be transferred. KMOAS is a service provider who can offer services related to the assessment of data and performing diagnostics and prognostics in relation to these.

If such a technical solution is chosen it lay the foundation for changing the maintenance strategy for the AHD to CBM. CDE will then have the possibility for obtaining similar benefits as for the existing CBM strategy for the thrusters. In the same way as for the top drive such an installation could also be considered implemented on the other rigs, as this would be in line with the previously described asset portfolio management strategy.

Part 4: Discussion, conclusion and recommendations for further studies

In this part of the thesis a discussion of the thesis is presented. This discussion is related to the identification of whether the scope of work and the defined objectives were met during the work. Further a presentation of findings, learning areas and finally a discussion of challenges encountered during the work is presented. This is followed by a short conclusion in section 7, which aims to sum up the work of thesis in a short but comprehensive way. Subsequently some recommendations for further studies are presented in section 8. Finally the bibliography is presented in section 9.

6. Discussion of the work with the thesis

6.1 Scope of work and objectives

The scope of this thesis involve several dissimilar objectives mainly related to three subjects, namely asset management, condition monitoring and CMB as well as the case study of CDE and the asset COSL Innovator. Even though one from a holistic perspective can see that the different objectives relate to each other, being able to present a "red thread" throughout the thesis by integrating the different subjects with each other have required a substantial effort. It is however the author's opinion that a presentation of how these subjects are interrelated with each other have been given.

By first performing an analysis of asset management theory and current asset management practices and challenges on the NCS it has been possible to identify some important areas that need attention and focus from the actors in the industry in order to maintain a positive development and increased value making from the O&G activities on the NCS.

Through the establishment of a picture of state of the art technology related to condition monitoring equipment, and its application for establishing CBM strategies one have reached the objective of identifying how organizations can implement this technology for improved utilization of assets. Also a presentation of novel technological solutions for advanced diagnostics and prognostics, and the advantages such technological solutions present, has been given.

Lastly the performing of a study of CDE and the asset COSL Innovator have enabled the author to fulfill the objective of providing some areas for improvement in relation to current asset management practices and application of condition monitoring and CBM, as well as identifying equipment types that may be considered for the future implementation of a CBM strategy.

From the above it is the authors' opinion that the defined scope of work and the objectives of this thesis have been fulfilled.

6.2 Main findings

As the work with this thesis has evolved it has become clear that the Norwegian O&G industry is a conservative business sector. Due to the vast complexity involved in the performing of offshore operations the actors seems to put their trust in well-proven solutions that fit their purpose adequately instead of being open minded when it comes to the implementation of novel approaches, both to asset management practices as well as technological solutions. More explicitly it can be advocated that due to a number of reasons there seems to be a reluctance throughout the industry when it comes to implementing substantial changes to organizational structures, as it can be hard to quantify the possible benefits gained in doing so. The same reluctance can be claimed to exist when it comes to implementing innovative solutions like for instance CBM, as the possible benefits gained will first be materialized after the changes have been made and the system has been in operation for some time.

With the rapid developing technological solutions in relation to advanced remote diagnostics and prognostics related to the determining health state of machines, it seems imperative for organizations to keep a strong focus on how these technologies can be utilized in organizations, in order for them to retain a top position in the market. Also novel solutions related to integration of operations enabled by the ICT-revolution one have seen during the last decade, as well as the removing of traditional organizational boundaries seems to present themselves as areas where substantial improvements can be achieved. A more extensive application of CBM strategies for equipment may lead to improved quality and regularity of operation, and thus give the possibility of improved asset utilization and increased value making in the organizations.

The case study of CDE and the asset COSL Innovator revealed several areas where improvements can be made, where several of these relate to the way the organization is structured and operated. It however also revealed that the organization already have addressed some of their main challenges by taking effective measures. This prove that the organization live by their “always do better” philosophy. They have already implemented novel technological solutions for the maintenance management of the main engines and thrusters throughout their asset portfolio of drilling rigs. In doing this they have proven that they focus on continuous improvement of the safety and efficiency in their organization, while at the same time optimizing the utilization of their assets.

6.3 Obtained learning

The work with this thesis have provided the author an overall learning and better understanding of the subject of asset management, and its related elements. A wider understanding of pressing issues that the operators on the NCS have to deal with in relation to how they can perform better asset management, and how they plan to do this, have been obtained by performing an extensive study of the subject.

The work with establishing a picture of state of the art technology related to condition monitoring and CBM have provided the author with a better understanding of available technology as well as their areas of application. Especially the contextualization of this technology towards novel technological solutions that can enable the performing of IO have been an interesting area of learning. The possibilities that present themselves by the effective implementation of the recently commercialized Watchdog Agent Technology seems to be formidable.

As a result of the extensive study of how CDE is organized, and furthermore how they have developed their maintenance strategy and maintenance program, a deeper understanding of the techniques applied have been obtained. The work with obtaining this understanding have been both interesting and challenging. By the study of the Wärtsilä CBM and KMOAS CBM solutions a more thorough understanding of how this technology is applied, and the benefits it has given to the organization has been obtained. This has also given the opportunity to identify improvement potentials related to the current application, which have been presented in this thesis.

During the study of possibilities related to future implementation of CBM strategies for equipment it soon became clear that an extensive review of the equipment types installed on COSL Innovator had to be performed in order to be able to present qualified recommended solutions. Even though these studies at an early point were narrowed down to focus on heavy rotating machinery with high criticality to operations many types of equipment still remained. In order to be able to present technical solutions a certain degree of technical knowledge and understanding of the equipment and system functions had to be established. Through the study of various operation and maintenance manuals, technical documentation and functional design specifications related to a number of equipment types the author have obtained a higher degree of knowledge and understanding of equipment and systems.

6.4 Encountered challenges

It became clear at an early point that fulfilling the defined objectives in the scope of work was an ambitious task. Firstly an extensive study of the subject asset management, as well as the challenges that the actors on the NCS have to overcome in relation to this, had to be performed. Secondly a study of condition monitoring equipment and techniques had to be executed in order to present how this can be applied for the forming of a CBM strategy. Lastly the performing of an extensive study of the CDE organization as well as the asset COSL Innovator had to be performed, in order to establish a picture of how asset management practices and the application of CBM technology could be improved. The contextualization of the three parts required a substantial effort. Even though the work with the thesis have been both very interesting and given the author a substantially improved insight in the studied topics, it is fair to say that the work involved with this master thesis has been both time consuming and required a great deal of effort. This represented a challenge in itself.

During the work with the study of CDE and COSL Innovator the obtaining of information like internal documents and technical documentation have been challenging. It soon became clear that external access to all the applications used by the organization had to be obtained in order to enable the progression with the work. The extensive number of different applications and databases that needed to be accessed in order to retrieve the required documentation can in itself be used to exemplify some of the challenges CDE face as an organization in relation to data and information management. It is however important to say that CDE have been very helpful in this aspect, and granted the author individual user access to the various applications when needed so that the progression with the work was enabled.

7. Conclusions

This thesis set out to describe state of the art theory on the subject of asset management. A contextualization of this theory have been made by looking into what current challenges the O&G industry on the NCS experience in relation to this aspect, and this have led to the identification of several areas. Firstly, challenges related to implementation of novel technological solutions for improved asset management and performance was identified, as the stakeholders report that they see existing workflows and processes as the largest barrier towards the realization of value from digital technologies. In addition, the forming of alliances and technological clusters seems to be a new approach taken by the stakeholders in order to improve asset management throughout the industry. The need for standardization of processes, applied technological solutions as well as standardization of documentation seems to be an important area for improvement in relation to asset management in the time to come.

It can be concluded that the extended application of condition monitoring equipment, and the utilization of the obtained data for implementing CBM strategies for equipment hold the potential for significant improvements to asset utilization in the future. By the implementation of novel technological solutions, which have the ability to perform advanced diagnostics and prognostics, the system owners can obtain benefits related to safer and more efficient operation of equipment, improved maintenance planning, reduced maintenance costs and so on. By taking on a holistic approach to the subject of IO the traditional organizational barriers can be removed, and thus the introduction of external expertize as well as the possibility of monitoring and operating equipment from remote locations can be achieved.

An extensive survey of the organization of CDE and the asset COSL Innovator has been performed, with the aim of identifying unreleased potentials related to both asset management practices as well as identifying equipment groups where a CBM strategy can be implemented. Based on the survey of state of the art asset management presented in section 2, improvement potentials related to 8 of the 39 subject groups of the IAM Conceptual Management Model were identified. These subjects are given a discussion including suggestions for how improvements can be made. Several of these improvement potentials relate to organization's culture and structure, operations and maintenance decision making as well as data and information management. The need for improved integration of processes and flow of information between the different stakeholders seems to stand out as one of the most important areas for improvement. Such an integration of processes may be enabled by implementing a new CMMS system, and the possibilities and potential pitfalls of performing such a process have been discussed.

The survey of the asset COSL Innovator enabled the highlighting of how CDE have achieved substantial benefits by their implementation of a CBM strategy for the main engines and thrusters. As this strategy has proven to be beneficial for the organization by improving the utilization of the asset COSL Innovator, it seemed suitable to investigate whether an extension of this strategy could give additional benefits in the future. Two equipment types, namely the top drive and the AHD, were identified as eligible for consideration of a future implementation of a CBM strategy, and a suggestion for how this can be done has been presented in the thesis.

8. Recommendations for further studies

As earlier described in this thesis the topic of asset management have become very relevant during the last few years, and several large organizations have now embraced the new ISO55000 standard regarding this topic. It is anticipated that this new standard will impose a large impact to the organizations involved in the O&G industry on the NCS in the future. An interesting topic for further studies could therefore be the identification of which processes that needs to be initiated by a drilling contractor that wants to be certified according to this standard.

The vast amount of data we are producing in the world today have now become so extensive that it is hard to comprehend. If we take all the data the human kind have produced from the beginning of time until 2008, the same amount of data will in the near future be generated every minute. It is the author's opinion that those organizations that can develop and manage systems for the effective exploitation of this unprecedented amount of data to improve business performance and processes in the future are the ones that will prevail and achieve excellence. How actors in the O&G industry can achieve this can prove to be an equally interesting and important topic for further studies. Subjects like stock optimization based on predictive models for spare part consumption, improved planning of operations based on integration of weather forecasting or related activities of other assets in the portfolio and so on can prove to be especially interesting topics.

In this thesis only two specific equipment types are highlighted in relation to the possible future implementation of a CBM strategy. It is however clear that several other equipment types may also prove to be both eligible and suitable for such an implementation. One example of this can be the three identical mud pumps installed on COSL Innovator, whose functions can be said to be a part of the backbone of the drilling operations performed by the asset. By implementing a CBM strategy for these three pumps one can further continue to benefit from the economies of scale, similarly as for the already implemented CBM strategy for the main engines and thrusters. The mud pumps have however not been subject to detailed studies in this thesis, as such a task would be too extensive in relation to the scope of work. The performing of a detailed study of the entire asset COSL Innovator with the aim of identifying all systems that could and should be made subject to the application of a CBM strategy could however prove to be an interesting topic for further studies, as the work with this thesis have demonstrated that implementing CBM strategies for equipment may give substantial benefits to the organizations operating the assets.

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Appendix 1: Overview of standards related to condition monitoring and PHM

Org.	Standard	Title	Overview	Dependability analysis	Measurement techniques	Diagnostics and prognostics	Data management	Training
ISO	13372	Condition monitoring and diagnostics of machines – Vocabulary	X		X			
ISO	13380	Condition monitoring and diagnostics of machines – Vibration condition monitoring – Part 1: General procedures				X	X	
ISO	16587	Condition monitoring and diagnostics of machines – Vibration condition monitoring – Part 2: Processing, analysis and presentation of vibration data					X	
WD	17359	Condition monitoring and diagnostics of machines – Vibration condition monitoring – Part 3: Diagnostic techniques				X		
ISO	19860	Condition monitoring and diagnostics of machines – Data processing, communication and presentation – Part 1: General guidelines	X					
ISO	22096	Condition monitoring and diagnostics of machines – Data processing, communication and presentation – Part 2: Data processing					X	
ISO/DIS	13373–1	Condition monitoring and diagnostics of machines – Data processing, communication and presentation – Part 3: Communication					X	
ISO	13373–2	Condition monitoring and diagnostics of machines – Data interpretation and diagnostic techniques – Part 1: General guidelines				X		
ISO	13373–3	Condition monitoring and diagnostics of machines – General guidelines on using performance parameters	X					
ISO	13374–1	Condition monitoring and diagnostics of machines – Prognostics – Part 1: General guidelines				X		
ISO/PWI	13374–2	Condition monitoring and diagnostics of machines – Tribology based monitoring and diagnostics – General guidelines	X		X			
ISO	13374–3	Mechanical vibration and shock – Performance parameters for condition monitoring of structures				X		
ISO	13379–2	Condition monitoring and diagnostics of machines – General guidelines	X		X			
ISO	13381–1	Condition monitoring and diagnostics of machines – Thermography – Part 1: General procedures			X			
ISO	14830–1	Condition monitoring and diagnostics of machines – Requirements for qualifi cation and assessment of personnel – Part 1: Requirements for certifying bodies and the certifi cation process						X
ISO	15909-3*	Condition monitoring and diagnostics of machines – Requirements for qualifi cation and assessment of personnel – Part 2: Vibration condition monitoring and diagnostics						X
ISO	18129*	Condition monitoring and diagnostics of machines – Requirements for qualifi cation and assessment of personnel – Part 3: Requirements for training bodies and the training process						X
ISO	18434–1	Condition monitoring and diagnostics of machines – Requirements for qualifi cation and assessment of personnel – Part 4: Field lubricant analysis						X
ISO/DIS	18435-3*	Condition monitoring and diagnostics of machines – Requirements for qualifi cation and assessment of personnel – Part 5: Lubricant laboratory technician/analyst						X
ISO	18436–1	Condition monitoring and diagnostics of machines – Requirements for qualifi cation and assessment of personnel – Part 6: Acoustic emission						X
ISO	18436–2	Condition monitoring and diagnostics of machines – Requirements for qualifi cation and assessment of personnel – Part 7: Thermography						X
ISO	18436–3	Gas turbines – Data acquisition and trend monitoring system requirements for gas turbine installations			X	X	X	
ISO	18436–4	Condition monitoring and diagnostics of machines – Acoustic emission			X			
ISO	18436–5	Condition monitoring and diagnostics of machines – Ultrasound – Part 1: General guidelines			X			
SAE	18436–6	Condition Based Maintenance (CBM) Recommended Practices	X					
IEEE	18436–7	Standard Framework for Prognostics and Health Management of Electronic Systems				X		
ISO/IEC	22400-1*	Software and system engineering – High-level Petri nets – Part 3: Petri Net Extensions		X				
ISO	22400-2*	Condition monitoring and diagnostics of machines – Approaches for performance diagnosis				X		
ISO	29821–1	Manufacturing operations management – Key performance indicators – Part 1: Overview, concepts and terminology				X		
ISO	ARP6204*	Manufacturing operations management – Key performance indicators – Part 2: Definitons and descriptions of KPIs	X					
ISO	P1856*	Industrial automation systems and integration – Diagnostics, capability assessment and maintenance applications integration – Part 3: Applications integration description method	X					

ANALYSIS REPORT

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Appendix 2 :Oil analysis report Thruster 2 HPU COSL Innovator

COSL OFFSHORE MGMT -COSL INNOVATOR
PO BOX 34

4064 STAVANGER

TEKNISK

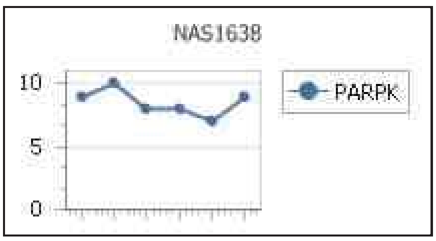
D/R COSL INNOVATOR
COSL
THRUSTER STEERING HPU #2 — 3 MND/UTTAK 2
SYSTEM — onlinesupport@kmoas.no
IN635CT202
CASTROL HYSPIN AWH M46

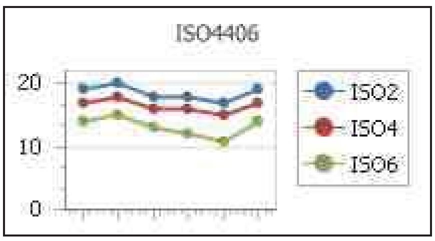
Sample number 121268 Sample comment

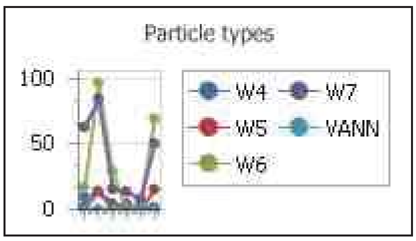
Comments

Particle contamination exceeds ISO4406 class 19/16/13. Particles detected appear to be potential fatigue wear shaped. Recommend new sample for verification.
Sign. Kevin Hughes

Results			This Sample	Previous samples				
SAMPLE NUMBER			121268	120186	118000	117185	116594	115969
CUSTOMER SAMPLE NUMBER								
DATE			31.03.2014	28.12.2013	03.07.2013	05.06.2013	25.04.2013	03.04.2013
TOT. HOURS/KILOMETER			0	0	0	0	8250	0
HOURS/KM. OIL			0	0	0	0	0	0
MAKE UP OIL / LITER			0	0	0	0	0	0
APPROVED.			✗	✓	✓	✓	✗	✗
Qty.5-15µm (6-14µm(c))	PARA1	Qty	78 188	23 712	36 250	44 543	194 416	91 544
Class 5-15µm	PARK1	NAS	9	7	7	8	10	9
Qty.16-25µm (14-21µm(c))	PARA2	Qty	8 924	615	1 539	3 078	14 466	5 879
Class 16-25µm	PARK2	NAS	8	5	6	7	9	8
Qty 26-50µm (21-38µm(c))	PARA3	Qty	3 231	462	462	1 385	5 386	2 785
Class 26-50µm	PARK3	NAS	9	6	6	8	10	9
Qty 51-100µm (38-70µm(c))	PARA4	Qty	0	0	0	0	154	0
Class 51-100µm	PARK4	NAS	0	0	0	0	7	0
Qty > 100µm (>70µm(c))	PARA5	Qty	0	0	0	0	0	0
Class > 100µm	PARK5	NAS	0	0	0	0	0	0
NAS1638 Sample Class:	PARPK	NAS	9	7	8	8	10	9
AS4059(A-F) Sample class	AS7	AS	10	7	8	8	11	9
Part > 4µm	ISO1	/ml	4 213	797	1 351	1 733	8 067	3 591
ISO 4406:99 Class >4µm	ISO2	ISO	19	17	18	18	20	19
Part > 6µm	ISO3	/ml	903	248	383	490	2 144	1 002
ISO 4406:99 Class > 6µm	ISO4	ISO	17	15	16	16	18	17
Part > 14µm	ISO5	/ml	122	11	20	45	200	87
ISO 4406:99 Class > 14µm	ISO6	ISO	14	11	12	13	15	14
ISO 4406:99 Sample Class:	ISO7	ISO	19/17/14	17/15/11	18/16/12	18/16/13	20/18/15	19/17/14
Total Particles per ml	W1	/ml	4212,6	796,6	1351,1	1732,7	8067,1	3591,4
Avg. Diameter	W2	µm	6,3	6,0	6,0	6,2	6,3	6,4
Max. Diameter	W3	µm	62,0	40,0	66,0	41,0	59,0	63,0
Cutting Particles >20µm	W4	/ml	1,9	1,9	1,9	3,9	13,5	9,6
Severe Sliding Particles >20µm	W5	/ml	15,4	0,0	3,9	1,9	13,5	1,9
Fatigue Particles >20µm	W6	/ml	69,3	3,9	0,0	28,9	96,2	17,3
NonMetalic Particles >20µm	W7	/ml	50,0	7,7	13,5	15,4	84,7	63,5
Unclassified	W8	/ml	1,9	0,0	3,9	0,0	3,9	3,9
Fibers	W9	/ml	10	0	0	0	2	0
Water (ppm/mg/kg) ASTM6304(/c)	VANN	ppm	0	0	0	0	0	0







Sample reported: 11.04.2014 This report generated: 11.04.2014

ANALYSIS REPORT

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Appendix 3: Oil analysis report Main Engine 1 COSL Innovator

COSL OFFSHORE MGMT -COSL INNOVATOR
PO BOX 34

4064 STAVANGER

TEKNISK

D/R COSL INNOVATOR
COSL
MAIN ENGINE
NO.: 1
IN651DD001
CASTROL MHP 154 (13.5/132/TBN15)

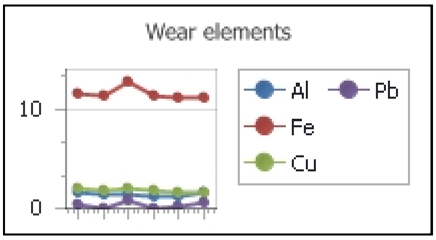
500 Timer/UTTAK 14
tobias.mandell@wartsila.com

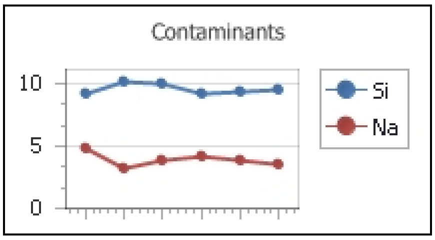
Sample number 390685 | Sample comment CC: WARTSILA

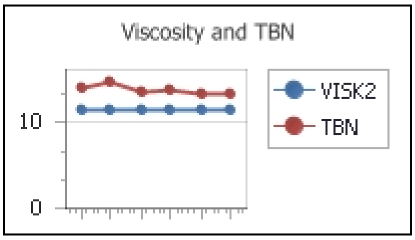
Comments

Analysis results as specified show satisfactory condition of the oil and a satisfactory wear trend. Viscosity @40°C (max +25%/-45% - minimum 82,6cSt), Viscosity @100°C (max +20%/-25% - minimum 10,35cSt), Water content max 3000 ppm, TBN within 50% (min 7,5) of new oil value. Flashpoint within 190°C. Oil parameters within specification for given oil type. No indication of contaminants like dust/dirt, coolant or abnormal fuel dilution.If continued use of the oil is planned, please be sure to follow filter change intervals and other planned maintenance procedures. Condemning limits according to Wärtsilä Data & Specifications Technical bulletin 3202N045

Results			This Sample	Previous samples				
SAMPLE NUMBER			390685	389226	388197	387906	387030	385383
CUSTOMER SAMPLE NUMBER								
DATE			15.03.2015	25.02.2015	28.01.2015	30.01.2015	25.12.2014	18.11.2014
TOT. HOURS/KILOMETER			0	17395	17142	17019	0	0
HOURS/KM. OIL			0	0	0	500	0	0
MAKE UP OIL / LITER			0	0	0	0	0	0
APPROVED.			✓	✓	✓	✓	✓	✓
Aluminium	Al	ppm	2	1	1	2	1	2
Iron	Fe	ppm	11	11	11	13	11	12
Chromium	Cr	ppm	0,5	0,3	0,0	0,7	0,0	0,4
Copper	Cu	ppm	2	2	2	2	2	2
Nickel	Ni	ppm	0,0	0,2	0,0	0,0	0,0	0,0
Lead	Pb	ppm	0,6	0,1	0,0	0,8	0,0	0,4
Tin	Sn	ppm	0	0	0	0	0	0
Molybdenum	Mo	ppm	0	0	0	0	0	0
Vanadium	V	ppm	0	0	0	0	0	0
Silicon	Si	ppm	9	9	9	10	10	9
Barium	Ba	ppm	0	0	0	1	0	0
Magnesium	Mg	ppm	20	19	20	21	19	19
Zinc	Zn	ppm	999	957	1 009	979	1 089	1 067
Phosphorus	P	ppm	712	816	754	890	675	631
Calcium	Cahi	ppm	3 925	4 016	4 159	4 289	4 332	4 532
Sodium	Na	ppm	4	4	4	4	3	5
Potassium	K	ppm	1	1	2	2	1	2
Visc. cSt/ 40°C- ASTM D445	VISKO	cSt	98,7	99,4	99,6	98,8	99,5	100,4
Visc. cSt/100°C- ASTM D445	VISK2	cSt	11,43	11,43	11,49	11,43	11,47	11,56
Viscosity Index (VI)	VI	VI	103	102	102	102	102	103
TBN ASTM D-2896	TBN	KOH	13,5	13,5	13,9	13,8	14,8	14,1
Water (ppm/mg/kg) ASTM6304(/c)	VANN	ppm	256	239	215	243	294	336
FT-IR#1 SOOT %	FTIR1	%	0,3	0,3	0,3	0,3	0,3	0,3
FT-IR#2 COOLANT	FTIR2	I.R	NO	NO	NO	NO	NO	NO
Flash point	FLPKT	°C	199	202	200	202	202	200
Div. See Comments.	DIV	***						







Sample reported: 26.03.2015 | This report generated: 27.05.2015

WÄRTSILÄ

THE ENGINE OF INDUSTRY

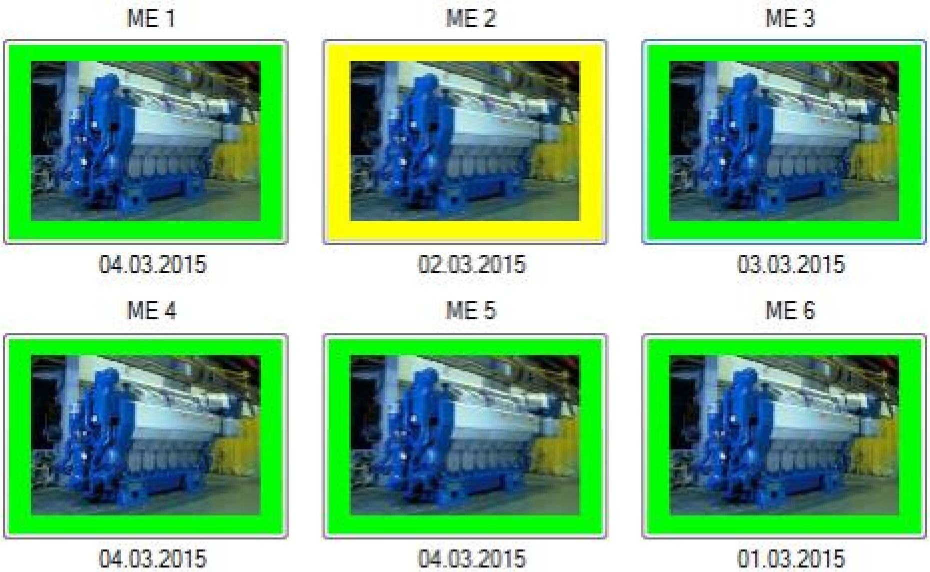
Appendix 4: Monthly Wärtsilä CBM Report COSL Innovator February 2015

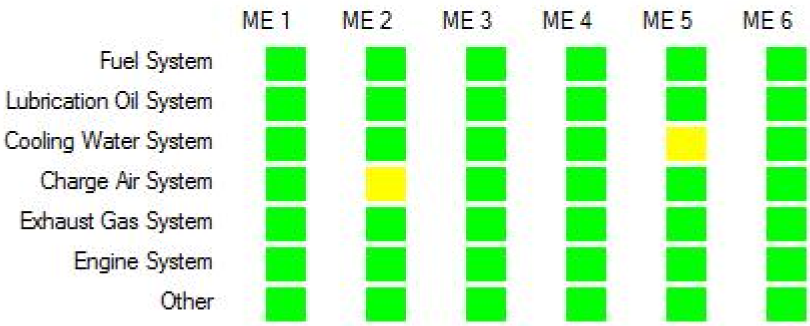
CBM MONTHLY REPORT

COSLInnovator

February 2015

Engine condition





Reported by: Tobias Mandell

tobias.mandell@wartsila.com

Date: 06.03.2015

Contents

1 General

The Wärtsilä **Condition Based Maintenance** concept has been developed by engine and installation experts to support the owners and users in their daily work, while at the same time reducing the operating costs for the owners.

The CBM system calculates the ideal operation parameters based on the engine type design. Correction factors based on ambient conditions, load levels, as well as installation specific settings are used to calculate reference values for actual conditions.

- The reference values have high- and low-spread limits that have been developed through years of experience, and have a much narrower gap than the alarm limits on the installation.
- This makes it possible to spot a deviation long before an engine parameter reaches a critical level and ensures the ability to perform proactive maintenance.
- The data which is gathered is presented as a daily average rather than instant values. This gives a much broader picture of the engine condition.

The measured operation data is automatically compared with the calculated reference values and are presented in the report colored as yellow or red depending on how large the deviation is from the calculated ideal value.

The Traffic Light

The traffic light system used in the report gives a clear overview of the installation condition. The large traffic light picture presents the overall condition of the engine while the smaller lights present the condition of specific areas on the engine.

- "Green" engine means that all measured important and critical engine parameters are within the normal operation window.
- "Yellow" engine means that one or more of the measured important or critical engine parameters are slightly outside the normal operation data window.
- "Red" engine means that one or more of the measured important or critical engine parameters are outside both the "Green and Yellow" operation data window.
- "Blue" engine means that the engine is stopped, or that the pre-set load limit has not been exceeded.

The purpose of the CBM is to have a daily follow up of the installation condition, and to give early notifications about engine running parameters deviating from the optimal levels.

2 Comments and recommendations

2.1 Installation general information

There are some indications present and some of them may need attention. For further recommendations, see the engine specific comments.

2.2 ME 1

Date/time:	04.03.2015			Installation:	COSLInnovator
				Engine no.	ME 1 (PAAE082777)
Load (%):	27			Run hrs.	17978
				Air int. temp.	5,7

Operation data	Unit	Site values	High-spread	Low-spread	Comment(s)

Table 1. Operation data out of limits, ME 1

The engine operation parameters were inside the optimal range.

2.3 ME 2

Date/time:	02.03.2015			Installation:	COSLInnovator
				Engine no.	ME 2 (PAAE082778)
Load (%):	28			Run hrs.	17973
				Air int. temp.	6,7

Operation data	Unit	Site values	High-spread	Low-spread	Comment(s)
Turbocharger speed B	rpm	12507	12418	10918	

Table 2. Operation data out of limits, ME 2

Turbocharger speed B is indicated slightly high. This is not critical at this stage since the engine is running on low load but turbocharger washing could be performed if it hasn’t been done recently.

2.4 ME 3

Date/time:	03.03.2015			Installation:	COSL Innovator
				Engine no.	ME 3 (PAAE082779)
Load (%):	27			Run hrs.	17235
				Air int. temp.	11,9

Operation data	Unit	Site values	High-spread	Low-spread	Comment(s)

Table 3. Operation data out of limits, ME 3

The engine operation parameters were inside the optimal range.

2.5 ME 4

Date/time:	04.03.2015			Installation:	COSL Innovator
				Engine no.	ME 4 (PAAE082780)
Load (%):	26			Run hrs.	16190
				Air int. temp.	14,8

Operation data	Unit	Site values	High-spread	Low-spread	Comment(s)

Table 4. Operation data out of limits, ME 4

The engine operation parameters were inside the optimal range.

2.6 ME 5

Date/time:	04.03.2015			Installation:	COSLInnovator
				Engine no.	ME 5 (PAAE082781)
Load (%):	27			Run hrs.	17778
				Air int. temp.	14,1

Operation data	Unit	Site values	High-spread	Low-spread	Comment(s)
HT w ater temperature, engine inlet	°C	91	90	83	
HT w ater temperature, B-bank outlet	°C	85	92	86	

Table 5. Operation data out of limits, ME 5

HT water temperature, engine inlet is slightly high. The HT water temperature is slightly higher than compared with the other engines. This is not critical at this stage as long as the temperature is following a normal trend when running on higher load.

2.7 ME 6

Date/time:	01.03.2015			Installation:	COSLInnovator
				Engine no.	ME 6 (PAAE082782)
Load (%):	30			Run hrs.	16060
				Air int. temp.	14,5

Operation data	Unit	Site values	High-spread	Low-spread	Comment(s)

Table 6. Operation data out of limits, ME 6

The engine operation parameters were inside the optimal range.

3 Predicted running hours

Based on the previous 6 months operation profile, the running hours is predicted to be:

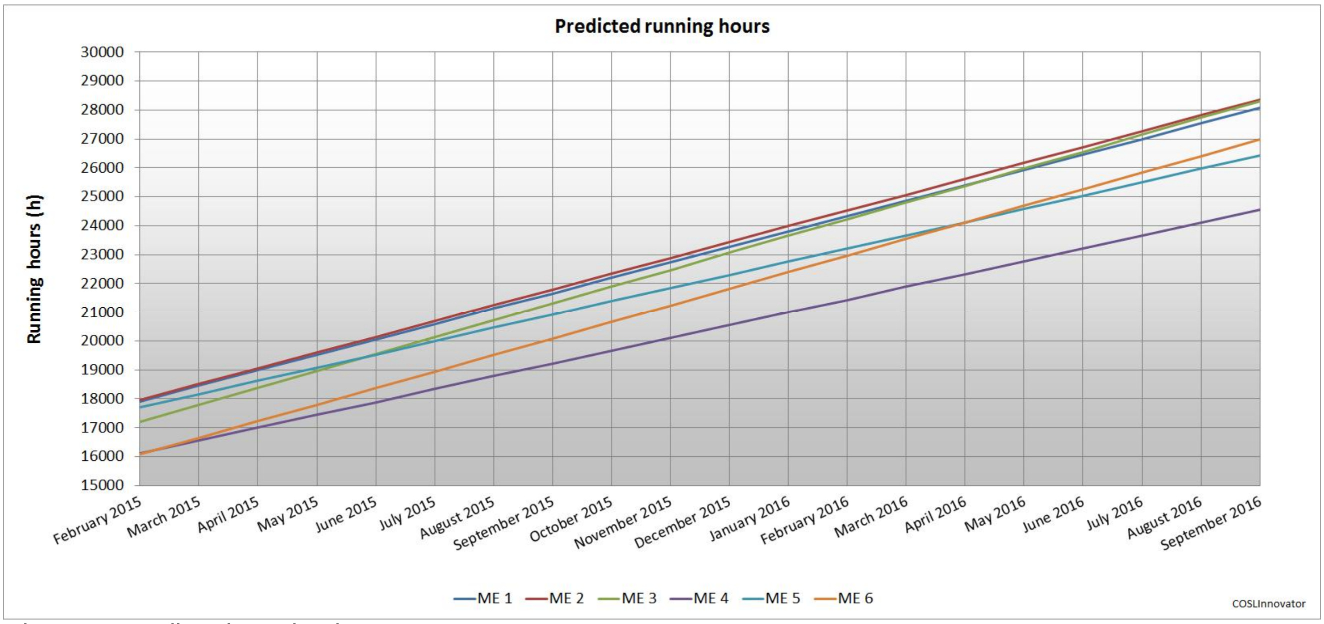


Figure 1. Predicted running hours

4 Statistics

4.1 Engine running hours

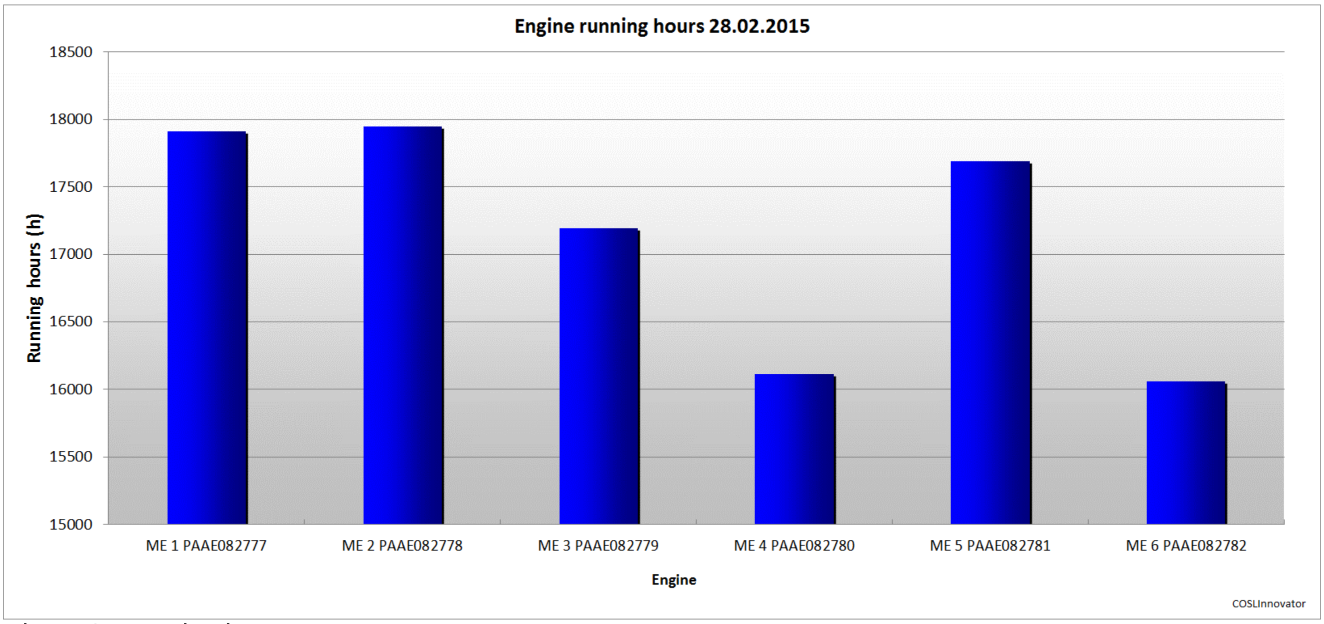


Figure 2. Running hours

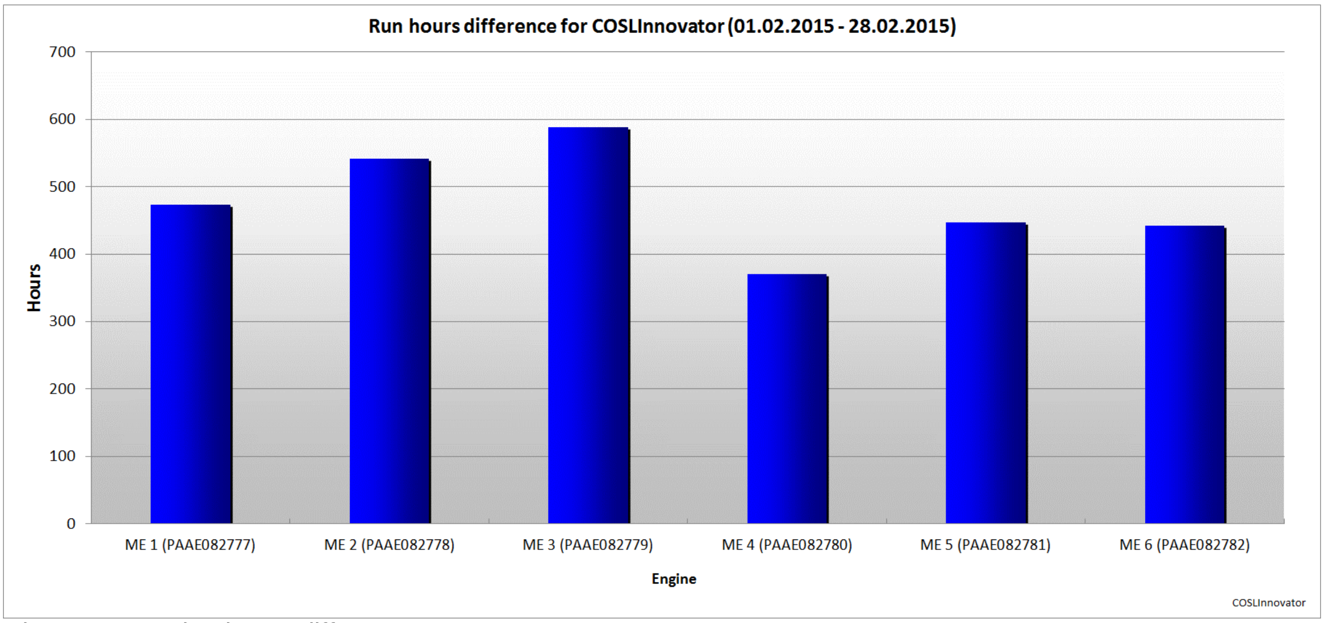


Figure 3. Running hours difference

4.2 Average load and load while running

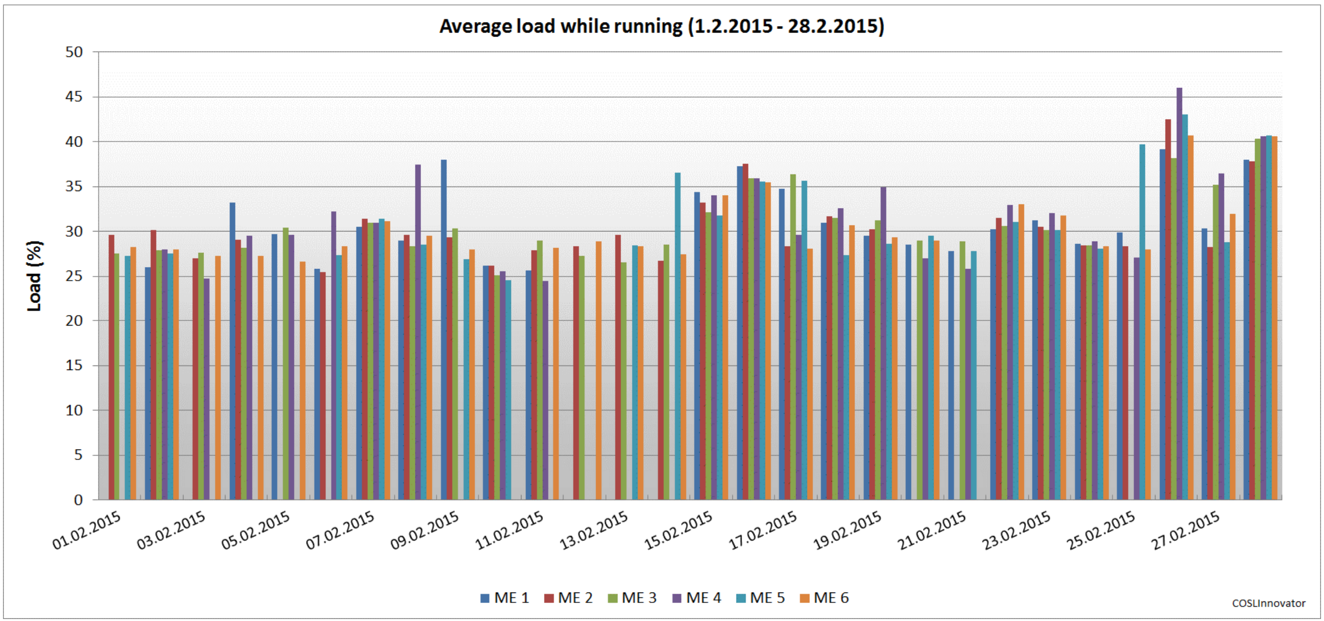


Figure 4. Average load while running over the load limit / day (%)

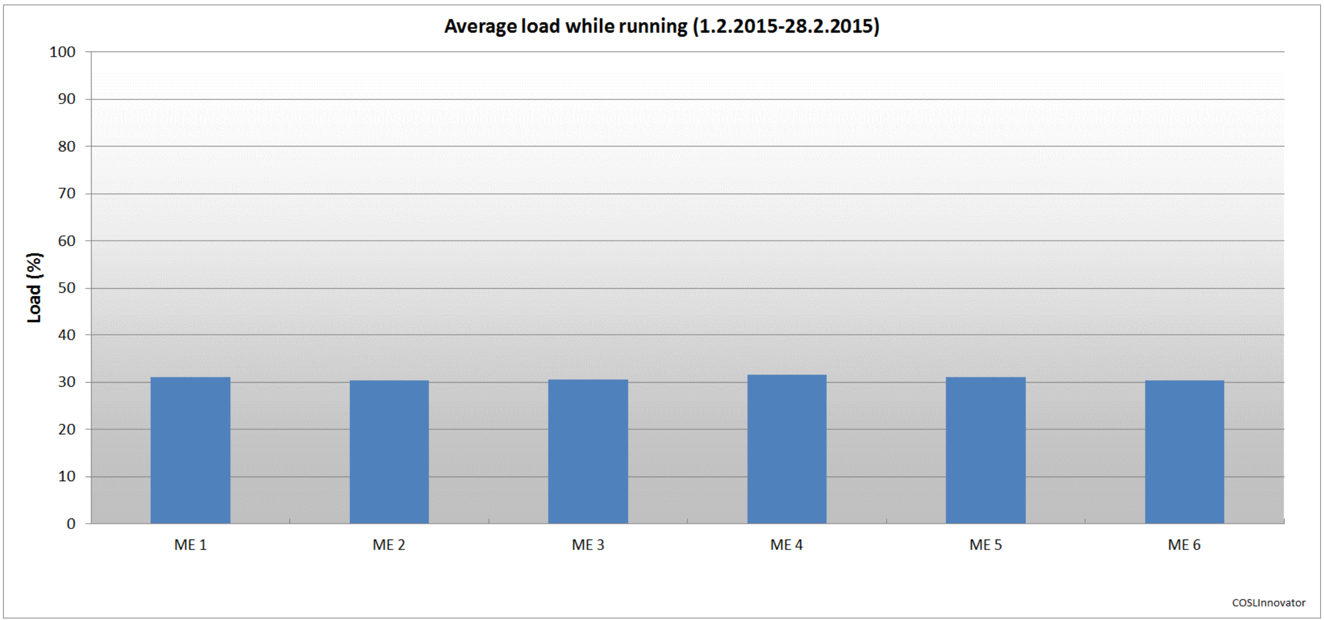


Figure 5. Average load while running over the load limit / month (%)

4.3 Production profile

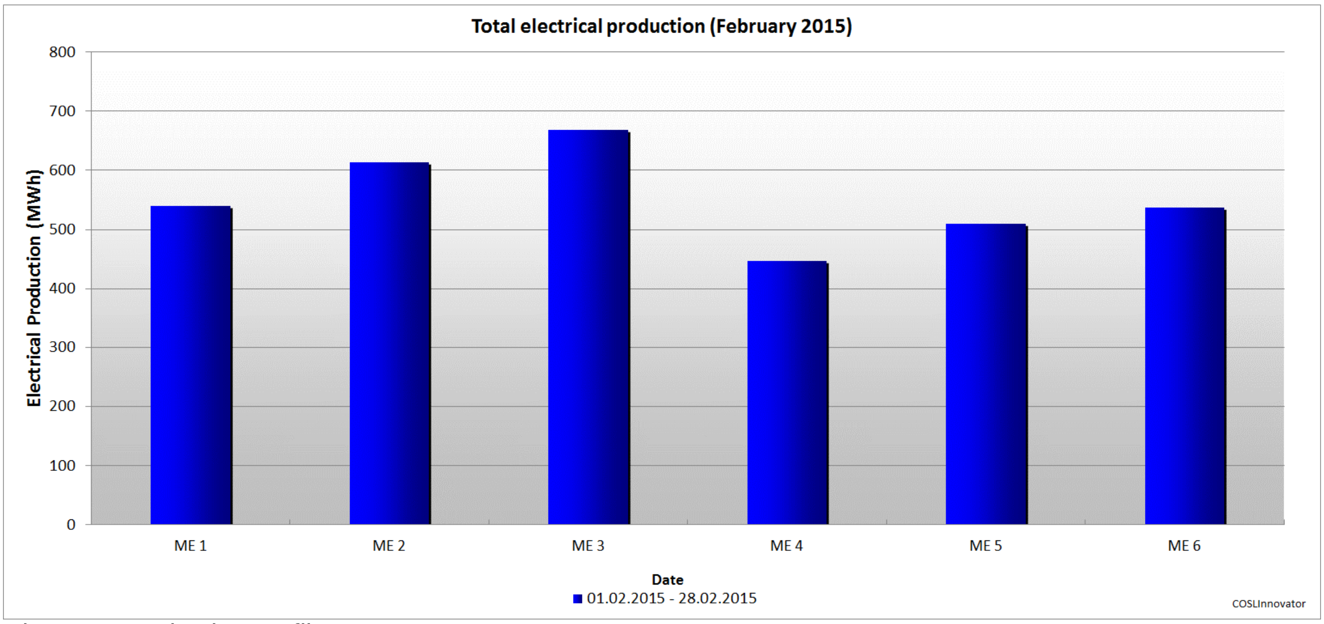


Figure 6. Production profile

4.4 Start statistics

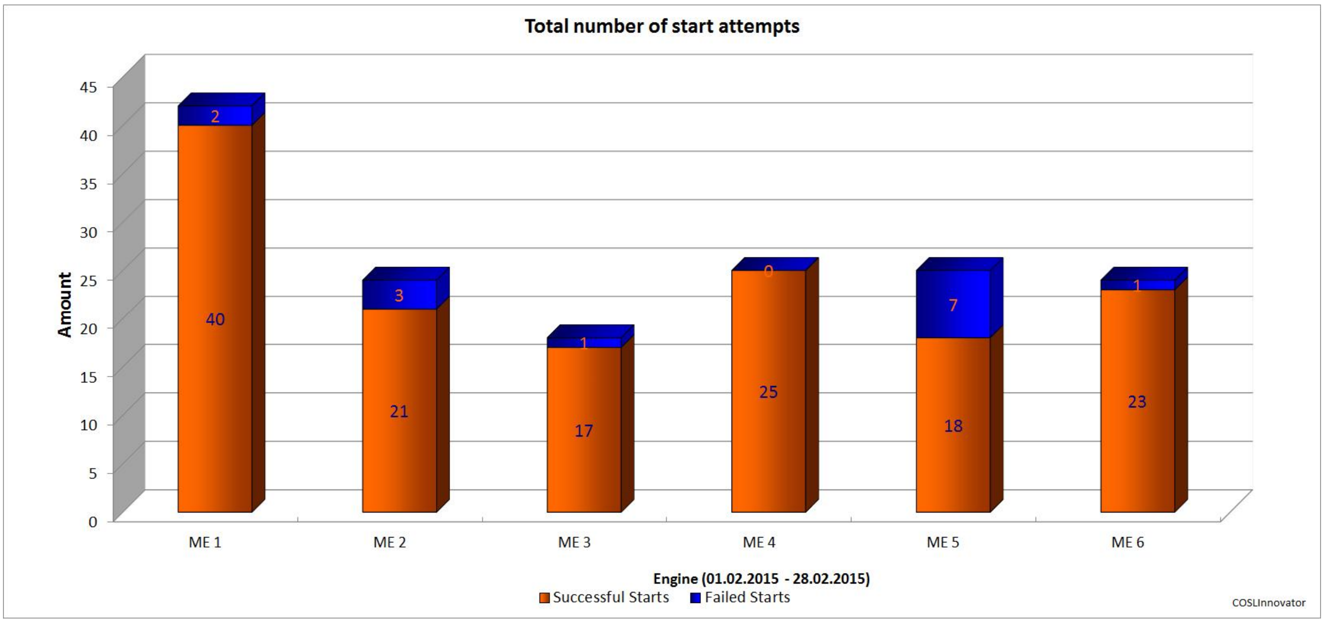


Figure 7. Total number of start attempts

Note:

If the engine is stopped within 3 minutes after the start signal, the start is considered as a failed start in the statistic.

5 Attachments

5.1 Complete operation data analysis, ME 1

Date/time:	04.03.2015	Installation:	COSLInnovator
		Engine no.	ME 1 (PAAE082777)
Load (%):	27	Run hrs.	17978
		Air int. temp.	5,7

Operation data	Unit	Site values	High-spread	Low-spread	Comment(s)
Air intake temperature, common	°C	6	45	-20	
Fuel oil pressure, engine inlet	bar	6,6	9,5	5,0	
Fuel oil temperature, engine inlet	°C	25	50	5	
Lubrication oil pressure, engine inlet	bar	5,1	6,0	4,0	
Lubrication oil pressure drop over filter	bar	0,300	1,100	0,010	
Lubrication oil temperature, engine inlet	°C	57	65	56	
Lubrication oil pressure, turbocharger A inlet	bar	4,5	5,1	3,9	
Lubrication oil pressure, turbocharger B inlet	bar	4,5	5,1	3,9	
Lubrication oil temperature, turbocharger A outlet	°C	61	76	51	
Lubrication oil temperature, turbocharger B outlet	°C	62	76	51	
Charge air pressure	bar	0,334	0,600	0,200	
Charge air temperature	°C	40	49	40	
Engine Speed	rpm	721	736	500	
Turbocharger speed A	rpm	11636	12146	10646	
Turbocharger speed B	rpm	11857	12146	10646	
HT water pressure, engine inlet	bar	3,4	4,0	3,0	
HT water temperature, engine inlet	°C	86	90	83	
HT water temperature, A-bank outlet	°C	91	92	86	
HT water temperature, B-bank outlet	°C	89	92	86	
LT water pressure, engine inlet	bar	2,6	3,0	2,2	
LT water temperature, engine inlet	°C	32	38	30	
LT water temperature, lube oil cooler outlet	°C	37	45	37	
Exhaust gas temperature, after cylinder A1	°C	303	344	234	
Exhaust gas temperature, after cylinder A2	°C	299	344	234	
Exhaust gas temperature, after cylinder A3	°C	301	344	234	
Exhaust gas temperature, after cylinder A4	°C	298	344	234	
Exhaust gas temperature, after cylinder A5	°C	297	344	234	
Exhaust gas temperature, after cylinder A6	°C	315	344	234	
Exhaust gas temperature, after cylinder B1	°C	306	344	234	
Exhaust gas temperature, after cylinder B2	°C	306	344	234	
Exhaust gas temperature, after cylinder B3	°C	319	344	234	
Exhaust gas temperature, after cylinder B4	°C	308	344	234	
Exhaust gas temperature, after cylinder B5	°C	312	344	234	
Exhaust gas temperature, after cylinder B6	°C	311	344	234	
Exhaust gas temperature, before turbocharger A	°C	353	413	303	
Exhaust gas temperature, before turbocharger B	°C	370	413	303	
Exhaust gas temperature, after turbocharger A	°C	316	355	255	
Crankcase pressure	mbar	0,730	1,533	0,010	
Main bearing temperature, thrust bearing	°C	71	100	65	
Main bearing temperature, bearing 1	°C	76	100	65	
Main bearing temperature, bearing 2	°C	78	100	65	
Main bearing temperature, bearing 3	°C	81	100	65	
Main bearing temperature, bearing 4	°C	81	100	65	
Main bearing temperature, bearing 5	°C	78	100	65	
Main bearing temperature, bearing 6	°C	79	100	65	
Main bearing temperature, bearing 7	°C	78	100	65	
Starting air pressure, engine inlet	bar	20	30	0	

5.2 Complete operation data analysis, ME 2

Date/time:	02.03.2015	Installation:	COSLInnovator
		Engine no.	ME 2 (PAAE082778)
Load (%):	28	Run hrs.	17973
		Air int. temp.	6,7

Operation data	Unit	Site values	High-spread	Low-spread	Comment(s)
Air intake temperature, common	°C	7	45	-20	
Fuel oil pressure, engine inlet	bar	6,2	9,5	5,0	
Fuel oil temperature, engine inlet	°C	27	50	5	
Lubrication oil pressure, engine inlet	bar	5,4	6,0	4,0	
Lubrication oil pressure drop over filter	bar	0,300	1,100	0,010	
Lubrication oil temperature, engine inlet	°C	57	65	56	
Lubrication oil pressure, turbocharger A inlet	bar	4,8	5,1	3,9	
Lubrication oil pressure, turbocharger B inlet	bar	4,8	5,1	3,9	
Lubrication oil temperature, turbocharger A outlet	°C	64	77	52	
Lubrication oil temperature, turbocharger B outlet	°C	64	77	52	
Charge air pressure	bar	0,328	0,623	0,223	
Charge air temperature	°C	45	50	40	
Engine Speed	rpm	729	744	500	
Turbocharger speed A	rpm	12399	12418	10918	
Turbocharger speed B	rpm	12507	12418	10918	
HT water pressure, engine inlet	bar	3,4	4,0	3,0	
HT water temperature, engine inlet	°C	87	90	83	
HT water temperature, A-bank outlet	°C	90	92	86	
HT water temperature, B-bank outlet	°C	90	92	86	
LT water pressure, engine inlet	bar	2,5	3,0	2,2	
LT water temperature, engine inlet	°C	32	38	30	
LT water temperature, lube oil cooler outlet	°C	38	45	37	
Exhaust gas temperature, after cylinder A1	°C	318	345	235	
Exhaust gas temperature, after cylinder A2	°C	330	345	235	
Exhaust gas temperature, after cylinder A3	°C	323	345	235	
Exhaust gas temperature, after cylinder A4	°C	303	345	235	
Exhaust gas temperature, after cylinder A5	°C	314	345	235	
Exhaust gas temperature, after cylinder A6	°C	333	345	235	
Exhaust gas temperature, after cylinder B1	°C	327	345	235	
Exhaust gas temperature, after cylinder B2	°C	329	345	235	
Exhaust gas temperature, after cylinder B3	°C	320	345	235	
Exhaust gas temperature, after cylinder B4	°C	310	345	235	
Exhaust gas temperature, after cylinder B5	°C	304	345	235	
Exhaust gas temperature, after cylinder B6	°C	316	345	235	
Exhaust gas temperature, before turbocharger A	°C	400	418	308	
Exhaust gas temperature, before turbocharger B	°C	395	418	308	
Exhaust gas temperature, after turbocharger A	°C	346	358	258	
Crankcase pressure	mbar	0,946	1,556	0,010	
Main bearing temperature, thrust bearing	°C	69	100	65	
Main bearing temperature, bearing 1	°C	76	100	65	
Main bearing temperature, bearing 2	°C	77	100	65	
Main bearing temperature, bearing 3	°C	78	100	65	
Main bearing temperature, bearing 4	°C	79	100	65	
Main bearing temperature, bearing 5	°C	79	100	65	
Main bearing temperature, bearing 6	°C	80	100	65	
Main bearing temperature, bearing 7	°C	82	100	65	
Starting air pressure, engine inlet	bar	24	30	0	

5.3 Complete operation data analysis, ME 3

Date/time:	03.03.2015	Installation:	COSLInnovator
		Engine no.	ME 3 (PAAE082779)
Load (%):	27	Run hrs.	17235
		Air int. temp.	11,9

Operation data	Unit	Site values	High-spread	Low-spread	Comment(s)
Air intake temperature, common	°C	12	45	-20	
Fuel oil pressure, engine inlet	bar	6,8	9,5	5,0	
Fuel oil temperature, engine inlet	°C	29	50	5	
Lubrication oil pressure, engine inlet	bar	5,1	6,0	4,0	
Lubrication oil pressure drop over filter	bar	0,300	1,100	0,010	
Lubrication oil temperature, engine inlet	°C	57	65	56	
Lubrication oil pressure, turbocharger A inlet	bar	4,5	5,1	3,9	
Lubrication oil pressure, turbocharger B inlet	bar	4,4	5,1	3,9	
Lubrication oil temperature, turbocharger A outlet	°C	63	76	51	
Lubrication oil temperature, turbocharger B outlet	°C	62	76	51	
Charge air pressure	bar	0,318	0,586	0,186	
Charge air temperature	°C	42	49	40	
Engine Speed	rpm	722	737	500	
Turbocharger speed A	rpm	11794	12200	10700	
Turbocharger speed B	rpm	12037	12200	10700	
HT water pressure, engine inlet	bar	3,5	4,0	3,0	
HT water temperature, engine inlet	°C	87	90	83	
HT water temperature, A-bank outlet	°C	90	92	86	
HT water temperature, B-bank outlet	°C	90	92	86	
LT water pressure, engine inlet	bar	2,5	3,0	2,2	
LT water temperature, engine inlet	°C	33	38	30	
LT water temperature, lube oil cooler outlet	°C	38	45	37	
Exhaust gas temperature, after cylinder A1	°C	297	346	236	
Exhaust gas temperature, after cylinder A2	°C	319	346	236	
Exhaust gas temperature, after cylinder A3	°C	318	346	236	
Exhaust gas temperature, after cylinder A4	°C	300	346	236	
Exhaust gas temperature, after cylinder A5	°C	307	346	236	
Exhaust gas temperature, after cylinder A6	°C	318	346	236	
Exhaust gas temperature, after cylinder B1	°C	293	346	236	
Exhaust gas temperature, after cylinder B2	°C	320	346	236	
Exhaust gas temperature, after cylinder B3	°C	338	346	236	
Exhaust gas temperature, after cylinder B4	°C	292	346	236	
Exhaust gas temperature, after cylinder B5	°C	316	346	236	
Exhaust gas temperature, after cylinder B6	°C	305	346	236	
Exhaust gas temperature, before turbocharger A	°C	375	413	303	
Exhaust gas temperature, before turbocharger B	°C	385	413	303	
Exhaust gas temperature, after turbocharger A	°C	331	355	255	
Crankcase pressure	mbar	0,0	1,5	0,0	
Main bearing temperature, thrust bearing	°C	69	100	65	
Main bearing temperature, bearing 1	°C	74	100	65	
Main bearing temperature, bearing 2	°C	79	100	65	
Main bearing temperature, bearing 3	°C	79	100	65	
Main bearing temperature, bearing 4	°C	80	100	65	
Main bearing temperature, bearing 5	°C	83	100	65	
Main bearing temperature, bearing 6	°C	76	100	65	
Main bearing temperature, bearing 7	°C	82	100	65	
Starting air pressure, engine inlet	bar	23	30	0	

5.4 Complete operation data analysis, ME 4

Date/time:	04.03.2015	Installation:	COSLInnovator
		Engine no.	ME 4 (PAAE082780)
Load (%):	26	Run hrs.	16190
		Air int. temp.	14,8

Operation data	Unit	Site values	High-spread	Low-spread	Comment(s)
Air intake temperature, common	°C	15	45	-20	
Fuel oil pressure, engine inlet	bar	6,4	9,5	5,0	
Fuel oil temperature, engine inlet	°C	28	50	5	
Lubrication oil pressure, engine inlet	bar	4,9	6,0	4,0	
Lubrication oil pressure drop over filter	bar	0,201	1,100	0,010	
Lubrication oil temperature, engine inlet	°C	56	65	56	
Lubrication oil pressure, turbocharger A inlet	bar	4,3	5,1	3,9	
Lubrication oil pressure, turbocharger B inlet	bar	4,3	5,1	3,9	
Lubrication oil temperature, turbocharger A outlet	°C	62	76	51	
Lubrication oil temperature, turbocharger B outlet	°C	63	76	51	
Charge air pressure	bar	0,251	0,571	0,171	
Charge air temperature	°C	44	49	40	
Engine Speed	rpm	720	735	500	
Turbocharger speed A	rpm	11334	12120	10620	
Turbocharger speed B	rpm	11136	12120	10620	
HT water pressure, engine inlet	bar	3,4	4,0	3,0	
HT water temperature, engine inlet	°C	88	90	83	
HT water temperature, A-bank outlet	°C	90	92	86	
HT water temperature, B-bank outlet	°C	90	92	86	
LT water pressure, engine inlet	bar	2,4	3,0	2,2	
LT water temperature, engine inlet	°C	33	38	30	
LT water temperature, lube oil cooler outlet	°C	37	45	37	
Exhaust gas temperature, after cylinder A1	°C	327	347	237	
Exhaust gas temperature, after cylinder A2	°C	346	347	237	
Exhaust gas temperature, after cylinder A3	°C	331	347	237	
Exhaust gas temperature, after cylinder A4	°C	312	347	237	
Exhaust gas temperature, after cylinder A5	°C	312	347	237	
Exhaust gas temperature, after cylinder A6	°C	325	347	237	
Exhaust gas temperature, after cylinder B1	°C	317	347	237	
Exhaust gas temperature, after cylinder B2	°C	306	347	237	
Exhaust gas temperature, after cylinder B3	°C	306	347	237	
Exhaust gas temperature, after cylinder B4	°C	286	347	237	
Exhaust gas temperature, after cylinder B5	°C	306	347	237	
Exhaust gas temperature, after cylinder B6	°C	312	347	237	
Exhaust gas temperature, before turbocharger A	°C	396	410	300	
Exhaust gas temperature, before turbocharger B	°C	359	410	300	
Exhaust gas temperature, after turbocharger A	°C	339	354	254	
Crankcase pressure	mbar	-0,8	1,5	0,0	
Main bearing temperature, thrust bearing	°C	67	100	65	
Main bearing temperature, bearing 1	°C	74	100	65	
Main bearing temperature, bearing 2	°C	80	100	65	
Main bearing temperature, bearing 3	°C	77	100	65	
Main bearing temperature, bearing 4	°C	82	100	65	
Main bearing temperature, bearing 5	°C	80	100	65	
Main bearing temperature, bearing 6	°C	80	100	65	
Main bearing temperature, bearing 7	°C	78	100	65	
Starting air pressure, engine inlet	bar	22	30	0	

5.5 Complete operation data analysis, ME 5

Date/time:	04.03.2015	Installation:	COSLInnovator
		Engine no.	ME 5 (PAAE082781)
Load (%):	27	Run hrs.	17778
		Air int. temp.	14,1

Operation data	Unit	Site values	High-spread	Low-spread	Comment(s)
Air intake temperature, common	°C	14	45	-20	
Fuel oil pressure, engine inlet	bar	6,4	9,5	5,0	
Fuel oil temperature, engine inlet	°C	29	50	5	
Lubrication oil pressure, engine inlet	bar	4,8	6,0	4,0	
Lubrication oil pressure drop over filter	bar	0,202	1,100	0,010	
Lubrication oil temperature, engine inlet	°C	58	65	56	
Lubrication oil pressure, turbocharger A inlet	bar	4,2	5,1	3,9	
Lubrication oil pressure, turbocharger B inlet	bar	4,2	5,1	3,9	
Lubrication oil temperature, turbocharger A outlet	°C	64	78	53	
Lubrication oil temperature, turbocharger B outlet	°C	65	78	53	
Charge air pressure	bar	0,303	0,586	0,186	
Charge air temperature	°C	44	49	40	
Engine Speed	rpm	722	737	500	
Turbocharger speed A	rpm	11758	12268	10768	
Turbocharger speed B	rpm	12015	12268	10768	
HT water pressure, engine inlet	bar	3,5	4,0	3,0	
HT water temperature, engine inlet	°C	91	90	83	
HT water temperature, A-bank outlet	°C	90	92	86	
HT water temperature, B-bank outlet	°C	85	92	86	
LT water pressure, engine inlet	bar	2,7	3,0	2,2	
LT water temperature, engine inlet	°C	34	38	30	
LT water temperature, lube oil cooler outlet	°C	38	45	37	
Exhaust gas temperature, after cylinder A1	°C	291	347	237	
Exhaust gas temperature, after cylinder A2	°C	309	347	237	
Exhaust gas temperature, after cylinder A3	°C	305	347	237	
Exhaust gas temperature, after cylinder A4	°C	303	347	237	
Exhaust gas temperature, after cylinder A5	°C	310	347	237	
Exhaust gas temperature, after cylinder A6	°C	321	347	237	
Exhaust gas temperature, after cylinder B1	°C	321	347	237	
Exhaust gas temperature, after cylinder B2	°C	323	347	237	
Exhaust gas temperature, after cylinder B3	°C	314	347	237	
Exhaust gas temperature, after cylinder B4	°C	297	347	237	
Exhaust gas temperature, after cylinder B5	°C	308	347	237	
Exhaust gas temperature, after cylinder B6	°C	312	347	237	
Exhaust gas temperature, before turbocharger A	°C	360	414	304	
Exhaust gas temperature, before turbocharger B	°C	383	414	304	
Exhaust gas temperature, after turbocharger A	°C	325	356	256	
Crankcase pressure	mbar	0,287	1,537	0,010	
Main bearing temperature, thrust bearing	°C	66	100	65	
Main bearing temperature, bearing 1	°C	74	100	65	
Main bearing temperature, bearing 2	°C	79	100	65	
Main bearing temperature, bearing 3	°C	79	100	65	
Main bearing temperature, bearing 4	°C	80	100	65	
Main bearing temperature, bearing 5	°C	81	100	65	
Main bearing temperature, bearing 6	°C	79	100	65	
Main bearing temperature, bearing 7	°C	76	100	65	
Starting air pressure, engine inlet	bar	24	30	0	

5.6 Complete operation data analysis, ME 6

Date/time:	01.03.2015	Installation:	COSLInnovator
		Engine no.	ME 6 (PAAE082782)
Load (%):	30	Run hrs.	16060
		Air int. temp.	14,5

Operation data	Unit	Site values	High-spread	Low-spread	Comment(s)
Air intake temperature, common	°C	14	45	-20	
Fuel oil pressure, engine inlet	bar	6,9	9,5	5,0	
Fuel oil temperature, engine inlet	°C	29	50	5	
Lubrication oil pressure, engine inlet	bar	5,2	6,0	4,0	
Lubrication oil pressure drop over filter	bar	0,300	1,100	0,010	
Lubrication oil temperature, engine inlet	°C	56	65	56	
Lubrication oil pressure, turbocharger A inlet	bar	4,6	5,1	3,9	
Lubrication oil pressure, turbocharger B inlet	bar	4,6	5,1	3,9	
Lubrication oil temperature, turbocharger A outlet	°C	63	77	52	
Lubrication oil temperature, turbocharger B outlet	°C	63	77	52	
Charge air pressure	bar	0,400	0,645	0,245	
Charge air temperature	°C	42	50	40	
Engine Speed	rpm	717	732	500	
Turbocharger speed A	rpm	12915	12916	11416	
Turbocharger speed B	rpm	12902	12916	11416	
HT water pressure, engine inlet	bar	3,3	4,0	3,0	
HT water temperature, engine inlet	°C	88	89	82	
HT water temperature, A-bank outlet	°C	89	91	85	
HT water temperature, B-bank outlet	°C	90	91	85	
LT water pressure, engine inlet	bar	2,4	3,0	2,2	
LT water temperature, engine inlet	°C	31	38	30	
LT water temperature, lube oil cooler outlet	°C	37	45	37	
Exhaust gas temperature, after cylinder A1	°C	291	350	240	
Exhaust gas temperature, after cylinder A2	°C	309	350	240	
Exhaust gas temperature, after cylinder A3	°C	318	350	240	
Exhaust gas temperature, after cylinder A4	°C	313	350	240	
Exhaust gas temperature, after cylinder A5	°C	316	350	240	
Exhaust gas temperature, after cylinder A6	°C	325	350	240	
Exhaust gas temperature, after cylinder B1	°C	296	350	240	
Exhaust gas temperature, after cylinder B2	°C	300	350	240	
Exhaust gas temperature, after cylinder B3	°C	304	350	240	
Exhaust gas temperature, after cylinder B4	°C	285	350	240	
Exhaust gas temperature, after cylinder B5	°C	294	350	240	
Exhaust gas temperature, after cylinder B6	°C	301	350	240	
Exhaust gas temperature, before turbocharger A	°C	380	426	316	
Exhaust gas temperature, before turbocharger B	°C	365	426	316	
Exhaust gas temperature, after turbocharger A	°C	335	362	262	
Crankcase pressure	mbar	-0,2	1,6	0,0	
Main bearing temperature, thrust bearing	°C	71	100	65	
Main bearing temperature, bearing 1	°C	77	100	65	
Main bearing temperature, bearing 2	°C	79	100	65	
Main bearing temperature, bearing 3	°C	82	100	65	
Main bearing temperature, bearing 4	°C	86	100	65	
Main bearing temperature, bearing 5	°C	79	100	65	
Main bearing temperature, bearing 6	°C	78	100	65	
Main bearing temperature, bearing 7	°C	77	100	65	
Starting air pressure, engine inlet	bar	24	30	0	