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Preface

I would like to thank my supervisor and professor at the University of Stavanger, Tore Markeset, for giving me the opportunity to write for Aker Solutions.

I would like to thank Aker Solutions for giving me the master thesis proposal and the possibility to write for them.

I would like to thank Jan Dybdal and Rune Folstad at Aker Solutions for support and guidance.

I would like to thank my family for believing in me and my father, Gudmund Heggland, for always providing great input and support during my studies.

At last I would like to thank all the people who were willing to partake in the survey.

To explain all nature is too difficult a task for any one man or even for any one age. 'Tis much better to do a little with certainty, & leave the rest for others that come after you, than to explain all things by conjecture without making sure of any thing.

-Isaac Newton-

Abstract

The Oil and Gas industry's increasing demands within risk management, cost efficiency, plant availability and the technology development have led to an increased interest for monitoring of equipment for performance and maintenance purposes.

Today you have the possibility to monitor the condition and performance of almost every type of equipment. Characteristics of condition based maintenance are that many processes are involved, it includes many disciplines, it generates much information and it uses sophisticated computer and information technology. Increasing monitoring can therefore make maintenance operations and management more complex. Condition based maintenance has previously also suffered with implementation problems and conservatism towards it. Another challenge with monitoring is that it needs to be specified early in the project life cycle, limiting the time available for analysis.

This thesis focuses on instrumented monitoring for maintenance purposes and condition based maintenance. The issues mentioned above and the many factors to account for, as opposed to other maintenance strategies, makes the task of determining and justifying appropriate condition monitoring for effective maintenance purposes, challenging.

This thesis investigates, based on a survey targeting oil & gas companies, what challenges the companies experience and what their needs are in relation to condition based maintenance and condition monitoring. The objective is to see if increasing use of monitoring increases operational value and if increasing monitoring should be perused. The thesis also investigates a methodology used in an engineering contractor company as an example of how they treated the challenges on selecting CBM solutions. Standards on condition monitoring and condition based maintenance has been reviewed too see if they provide any useful information in solve the challenges.

The survey indicates that the companies encourage increased use of monitoring and that they are not experiencing any major challenges that will limit monitoring. The companies are aware of most challenges and are currently working to solve them in order to use the monitoring for its potential. There are mainly two challenges that the companies are experiencing which are that many condition monitoring products are incompatible. The other is integration of condition monitoring systems with computer maintenance management system. The standards cover most parts of condition monitoring especially technical areas, but lack solutions on practical challenges with condition monitoring e.g. implementation. The thesis also shows that there is some variation on practice within condition monitoring in the oil & gas industry and gaps between standard recommendations, practice and operator needs.

Contents

1. Introduction

1.1. Background

Maintenance is the set of activities that is done to assure the continued or satisfactory operation of mechanical and static equipment due to the fact that everything deteriorates with time. The maintenance discipline has developed into a scientific discipline in its own right with an enormous amount of literature and subjects. This development has been a natural one due to the increasing global competition and increased demands in Health, Safety and Environment (HES). It was realized that costs and risk could be minimized with the implementation of efficient maintenance strategies. The operational costs of a field development is often much higher than the investment cost and it is therefore the phase you have the greatest cost reduction opportunities hence the importance of efficient maintenance. In some industries maintenance is the second highest or even the highest element of operating costs (Moubray 1997). Many concepts, techniques and methodologies have therefore been developed in maintenance and reliability engineering in order to design, maintain and operate for increased safety and reduced costs. Still it is challenging to determine the most effective measures in order to achieve this.

Condition Based Maintenance (CBM), using Condition Monitoring (CM) to determine the need for maintenance, is one of the newest maintenance concepts with growing popularity and increasing application. The CM technology has had a rapid growth, enabled by the technological development of Information and Communication Technology (ICT). CBM has in theory many advantages as supposed to the more established techniques and practices. What the disadvantages are is not that clear. Predetermined Maintenance (PDM) is the dominating maintenance strategy, but the industry is slowly transitioning to CBM. One of the reasons for this is that PDM has not always shown to be efficient. Reliability stayed the same in aviation no matter how much they improved PDM and its maintenance intervals (Moubray 1997). Studies revealed that many failures were random and not age related, which is a problem for PDM. CBM has also shown to be more cost efficient than other maintenance strategies because it reduce much unnecessary maintenance. The implementation of CBM programs has nevertheless not always shown to be successful. One of the main reasons for CBM not being successful is that it has been applied in an unsystematic fashion as technology became available without any strategy or standard on how to effectively implement it.

Integrated Operations (IO) is a term coined by the Norwegian Oil & Gas (O&G) industry. The basic idea of the concept is to let all stakeholders of a project or asset to cooperate together across disciplines and organizations for increased operational performance. This concept has led to creating land based control centers which support the operation, makes decisions and process information. The concept increases the amount and speed of information that is processed, decisions are made in consensus, assets can be monitored continuously, the manpower offshore can be reduced etc. Effective maintenance management is an integral part of IO. IO, ICT and on line CM enables increased use of CBM which can make maintenance and operations more effective, which can explain the increased interests in CBM. As the oil fields mature and the production decreases, it becomes more difficult to stay profitable. Ageing installations in the North Sea is therefore growing more dependent on effective maintenance and increased process performance making the need for CBM and CM higher. Efficient operations further leads to the possibility of exploiting marginal oil fields.

1.2. Problem description

Almost all kinds of equipment have the possibility to be delivered with condition monitoring and smart systems if requested, due to the technological development. There is also already a lot of monitoring on installations in the North Sea, but very often not part of a CBM strategy. With focus on increasing condition monitoring, some questions arise. Will increasing monitoring solve future maintenance challenges and are the operator companies able to utilize these technical opportunities when transitioning from predetermined maintenance towards a CBM regime or is it becoming too complex? The monitoring of one machine is no problem, but when machines and equipment in the thousands is monitored and start generating data the picture is quite different. Besides making maintenance more complex it also makes it difficult to select and justify appropriate monitoring that will gain benefits. Many CBM implementation efforts fail, three (of many) reasons being inappropriate selection of condition monitoring, technology inappropriately applied, and no condition monitoring implementation strategy (Walker, 2005).

Established procedures recommend time consuming Reliability Centered Maintenance (RCM) analysis or Failure Modes and Effects Analysis (FMEA) to determine CBM applicability. This has shown to be unpractical during project execution. The reason is that various activities are performed at different stages in a project and that various departments have different responsibilities. The maintenance discipline has to specify instrumentation requirements before the group responsible for design and procurement of instrumentation can begin. Specification of instrumentation for CBM purposes therefore needs to be performed during FEED. At this early stage there is no time available for RCM or FMEA. When procurement and design is complete it is too late to determine instrumentation (Dybdal & Folstad, 2012).

The development of CBM solutions will in many cases include many organizations such as the equipment vendor, engineering contractor and the customer. This creates organizational challenges with integration, interplay, coordination and engineering between them. Their needs, practice, offers and responsibilities needs to be established through clear strategies covering implementation, operation, work processes, procurement, CM selection etc. Standards are intended to aid with these types of challenges. What standards on CBM and CM exist and do they provide recommendations or solutions to selection and implementation of CBM?

It has been proclaimed that the Oil & Gas companies and their employees are conservative towards CBM, which is a problem when transitioning to CBM. They still rely heavily on methods such as PDM. CBM, as a strategy, is only utilized in 10% of all maintenance activities in Swedish process industry, partly caused by conservatism (Bengtsson, 2007). Is conservatism an issue in Norwegian O&G and is it a limiting factor for the exploitation of CBM?

1.3. Scope and objectives

Main objectives:

- Investigate if current use of CBM solutions increases complexity leading to reduced benefits for users in Norwegian O&G

Sub objectives:

- Perform a survey to map O&G companies' overall experience in CBM.
- Introduce theory and concepts in maintenance engineering and CBM.
- Identify strengths and weaknesses of CBM
- Review standards and guidelines related to CBM and CM.
- Present a CBM selection methodology in an engineering company
- Find prerequisites for a successful CBM utilization based on input from the standards, operator experience and engineering practice.
- Identify current challenges on CBM in Norwegian O&G
- Investigate what methods exist on selecting appropriate and effective CM solutions

It is natural to investigate what needs, preferences and concerns the users of a CBM system have and what their current practice and goals towards CBM is. It is ultimately the users who decide what solutions to implement. This will be done by surveying companies in the O&G business. The survey is the main element of this thesis and will provide answers to the main objectives and the apparent challenges. The answers should be able to: indicate if increasing CM should be perused, influence how CBM solutions are selected and aid in further research.

1.4. Limitations

The objective of the thesis is not to find clear answers for every problem and technical issue in CM, but to evaluate CBM practice on a holistic level. The thesis will therefore not focus in detail on the different monitoring techniques, data analysis etc. The thesis will not present any quantitative data from operator companies because of policy and confidentiality reasons. The thesis will therefore limit itself to overall qualitative analysis due to unavailability and complexity of CM data.

1.5. Methodology

The work will be based on academic literature, journals, interviews, surveys, standards and company documentation. The thesis presents a literature study and a survey that validates or contradicts, discusses and connects relevant literature and paradigms that may exist. The thesis will not conduct or present any scientific results in its traditional sense, but will inquire experience and general thinking on the subject of CM and CBM through surveying experts within the field.

1.6. Abbreviations and definitions

API	American Petroleum Institute	
CAPEX	Capital Expenditures	
CBM	Condition Based Maintenance	Preventive maintenance which include a combination of condition monitoring and/or inspection and/or testing, analysis and the ensuing maintenance actions (BS EN 13306, 2010).
CM	Condition Monitoring	Activity performed either manually or automatically, intended to measure at predetermined intervals the characteristics and parameters of the actual state of an item (BS EN 13306, 2010).
CMMS	Computerized Maintenance Management System	Software used for maintenance purposes
	Dependability	Ability to perform as and when required (BS EN 13306, 2010).
Failure		Termination of the ability of an item to perform a required function (BS EN 13306, 2010).
Fault		State of an item characterized by inability to perform a required function, excluding the inability during preventive maintenance or other planned actions, or due to lack of external resources (BS EN 13306, 2010).
FEED	Front End Engineering and Design	A study used to analyze the various technical options for new developments with the objective to define the facilities required (Encyclo, 2012)
FMECA	Failure Mode, Effects and Criticality Analysis	Methodology used for the analysis of failure modes, it`s effects, it`s criticality and its consequences.
HSE	Health, Safety and Environment	
ICT	Information and Communication	

	Technology	
IEC	International Electrotechnical Commission	
	Implementation	The act of accomplishing some aim or executing some order (The Free Dictionary, 2012)
IO	Integrated Operations	An operational strategy for increased performance
ISO	International Organization for Standardization	
LCC	Life Cycle Cost	A method for estimating the cost of an item during its estimated life time
MTBF	Mean Time Before Failure	Average of the operating times between failures (BS EN 13306, 2010).
NDT	Non Destructive Testing	A method for assessing the condition of an item without destructing it
NORSOK	Norsk Sokkels Konkurranseposisjon	A Norwegian organization created to increase efficiency for petroleum installations
NPD	Norwegian Petroleum Directorate	
O&G	Oil and Gas	
OPEX	Operation Expenditures	
P&ID	Piping and Instrumentation Diagram	Diagram in the process industry which shows the piping of the process flow together with the installed equipment and instrumentation.
PDM	Predetermined Maintenance	Preventive maintenance carried out in accordance with established intervals of time or number of units of use but without previous condition investigation (BS EN 13306, 2010).
P-F	Potential Failure-Functional Failure	Interval between potential failure and functional failure
PM	Preventive maintenance	Maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item (BS EN 13306, 2010).
RAM	Reliability, Availability and Maintainability	Dependability analysis methods
RBI	Risk Based Inspection	A method for establishing inspection intervals and locations
RCM	Reliability Centered Maintenance	A systematic methodology for creating optimal maintenance programs
SAP		Administrative computer software

SPC	Statistical Process Control	Assessing condition of an item/system through statistical parameters

2. Theory and concepts on maintenance and condition based maintenance

Maintenance is defined as: *"a combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function*" (BS EN 13306, 2010).

This chapter presents a short review of the development of maintenance, what types of maintenance strategies and concepts exists, the responsibilities and activities of maintenance management and processes in maintenance engineering. The chapter will also describe a typical method on how the maintenance program for equipment and assets is constructed.

2.1. Maintenance development

During the industrial revolution around the shift to the 20^{th} century manpower were replaced by machine power. The introduction of machines also introduced maintenance to reduce breakdowns and to keep the machinery in a good working condition. The maintenance and operational costs of a facility is a major part of total costs and the initial approach towards this problem was that maintenance is a necessary evil and nothing can be done to reduce these costs (Mobley, 1990). In the beginning there were only basic maintenance like lubrication, simple adjustments and visual inspection and the machinery were often run until total brake down. The general view was that machines wear and will eventual brake down. Then it was simply replaced by a new machine or parts were replaced if possible – a reactive based maintenance solution and a costly one.

Later on as technology advanced, machine dependence grew and demands in quality, safety and cost increased as well as competition. Different approaches towards maintenance had to be developed. Preventive maintenance or PDM, which is time driven and utilizes statistical data, was introduced in the 1960s (Moubray, 1997). The mean time to failure probability and experience was used to plan repairs and overhauls before the machines broke down – a proactive approach. The general thought was to prevent machines from failing though timely adjustments, inspections, replacements etc. A subsequent development from this thought was RCM. This approach led to fewer breakdowns and better availability. A discovery of many failures not being age related meant that PDM were not effective for all failure modes and new methods were needed to detect and prevent them.

CM techniques were at the time being developed to monitor different parameters that were related to the machine condition so that repairs could be done when it was actually needed. This type of maintenance is what is known as CBM. One of the first techniques which were developed was vibration analysis on rotating machinery, as when machinery became bigger and increased in speed, more problems and breakdowns increased. The US Navy was also greatly interested in vibration analysis as lowered vibration gave superiority in submarines. The first monitoring equipment such as radiographs had to be used manually and results had to be written down on paper, which was a time consuming activity. Equipment was also very large and analysis needed much labor (Mitchell, 2007). Paper was later replaced by tape recorders. As the technological revolution advanced equipment became smaller and cheaper. The introduction of the microprocessor and the computer made it possible utilize CM`s full potential. The information technology enables you to connect monitoring equipment together and write powerful programs to aid the analysis of the machines or the whole plant all together. This has also led to development of CBM as powerful management tool to help management plan and schedule activities more efficiently and to make justified decisions.

Systems, reliability and risk engineering has also been developed in conjunction with maintenance as means to decreasing the cost of maintenance, increasing availability and improving safety. Common tools in systems, reliability and risk engineering are FMEA, criticality analysis, fault tree analysis and reliability block diagram analysis. The ICT development has also made it possible to create maintenance, logistics and analysis applications that improve the efficiency and accuracy of maintenance operations. Moubray (1997) has divided the development into 3 generations in figure 1:

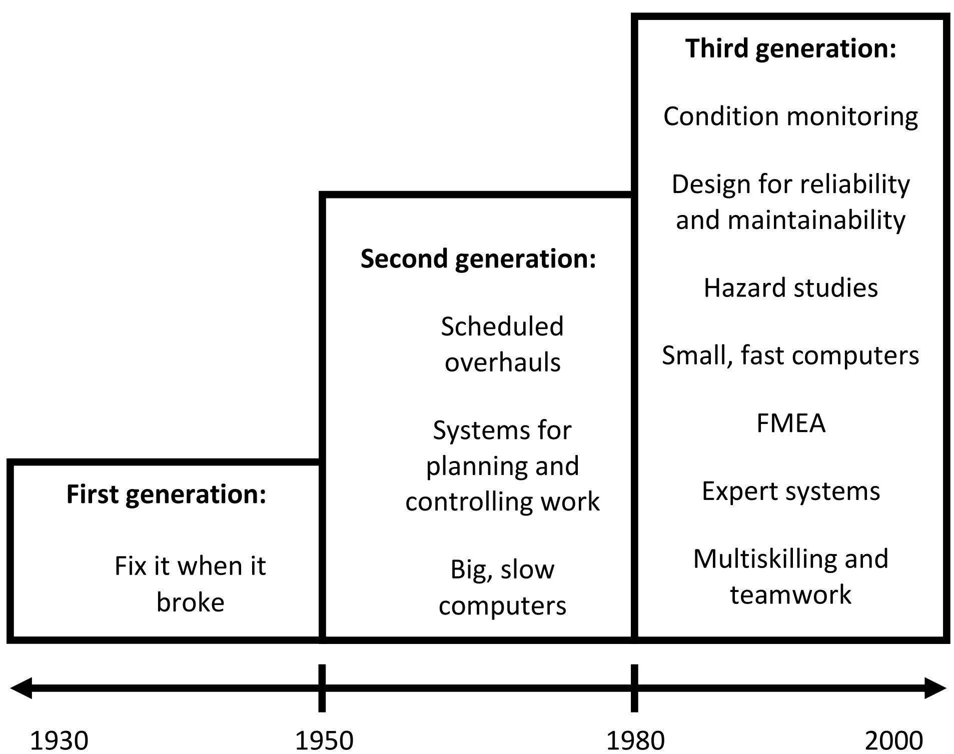

Figure 1 Changing maintenance regimes (Moubray, 1997)

2.2. Reliability Centered Maintenance

The definition of RCM is: "*a process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating context*" (Moubray, 1997). RCM has become one of the most popular and widely used maintenance analyses methods because of its success in increasing safety in the aviation industry and its overall effectiveness in handling failures and risk. It is a systematic method that involves an intensive analysis of the system, its failure modes, its consequences and how to select the best maintenance strategy to avoid them from occurring. This process includes most activities related to the development of the maintenance program which is explained further later. The RCM process contains the following activities:

- Define the functions and performance standards of the asset
- Seek out failures that can cause the asset to not fulfill its functions
- Seek out the causes of the functional failures
- Determine what happens with each functional failures
- Determine the consequences of the functional failures
- Find tasks to predict or prevent each failure
- Determine what should be done if a suitable proactive task cannot be found

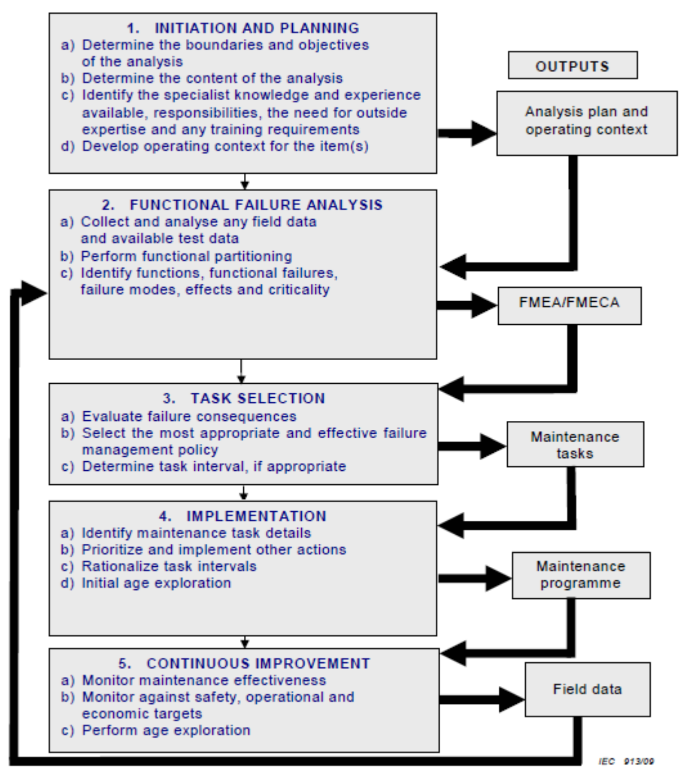

Figure 2 RCM process (IEC 60300-3-11, 2009)

The process and the various tasks in an RCM process is shown in figure 2. Central tools in RCM are FMEA, criticality analysis and decision gate diagrams. This analysis is often used on new and unfamiliar equipment as the main strategy for developing maintenance programs. It is a time demanding task and is normally applied for maintenance optimization in the operational phase rather than for developing initial maintenance programs during project phase (Dybdal & Folstad, 2012).

2.3. Maintenance strategies

The development of maintenance led to the creation or the division of various types of maintenance strategies. Figure 3 below divides maintenance into the elementary maintenance strategies that exists.

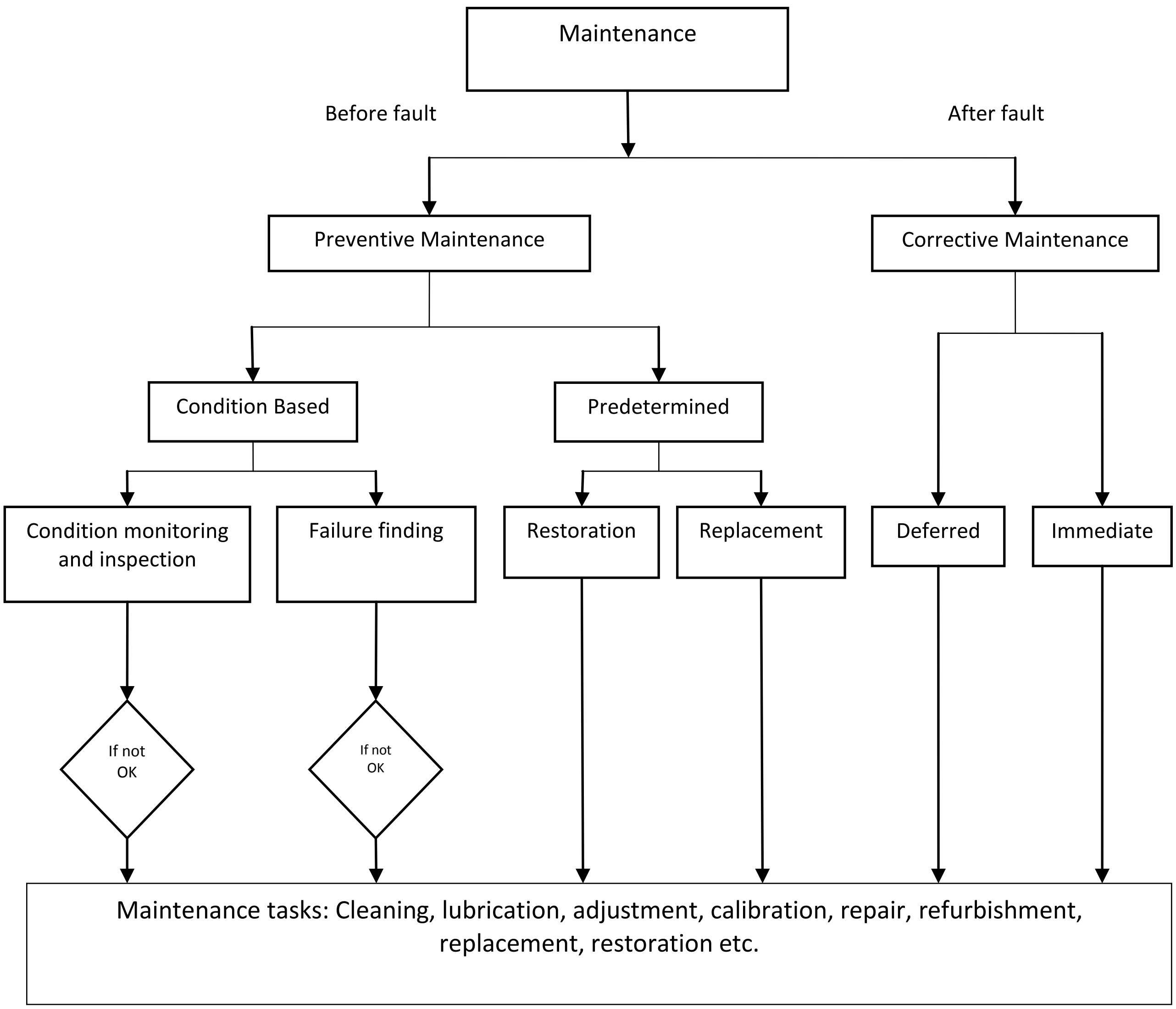

Figure 3 Maintenance types (IEC 60300-3-11, 2010)

The figure mainly divides between maintenance done before a fault occurs or after and is termed preventive maintenance and corrective maintenance, respectively. It is also common to divide between unforeseen maintenance and planned maintenance. Maintenance is in most cases triggered by a change in condition, performance or a predetermined interval where terms like error, failure and fault are central terms. It is therefore important to explain what is meant by fault before going into the various types of maintenance that figure 3 shows.

The error is when the machine condition parameters differ from normal or expected operating target. It is normal that there is variation due to various disturbances in the measurements. When the performance move outside these limits we then detect that the machine starts degrading either because of age related issues or internal/external direct/indirect problems with the machine. This is termed a failure (P) which is an event, but the machine still has capability of performing its required functions. It is commonly also called a potential failure. When the machine loses its ability to do its required function or it breaks down it's referred as a fault or functional failure which is a state (Rausand & Høyland, 2004). This description is illustrated in figure 4 below. The curve from failure to fault is also known as the P-F curve (Moubray, 1997).

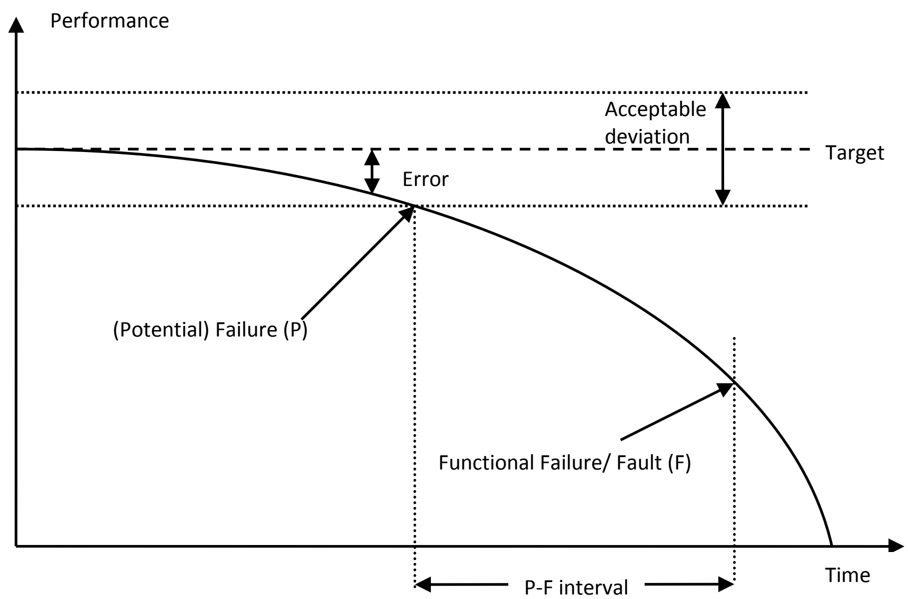

Figure 4 Development of a fault (Rausand, Høyland, 2004)

Corrective maintenance is triggered by fault and is done after it has occurred i.e. a reactive approach. The maintenance can either be deferred to a later time or performed immediately. This depends on the criticality of the fault. Faults that halt production are attended to immediately for example. Equipment that is no longer delivering its required function can be replaced, restored or repaired depending on cost, HSE and criticality.

Preventive maintenance is divided into condition based and predetermined. Condition based maintenance is triggered by an unsatisfactory performance or degraded condition whereas predetermined maintenance is triggered by fixed intervals, based upon statistical time to failure or experience. The objective of preventive maintenance is to prevent any faults from occurring, eliminating corrective maintenance. CBM is further explained in chapter 2.5.

Predetermined maintenance is a time driven strategy. Variables such as run time or fixed schedules define the intervals. PDM is predetermined using experience, statistics and vendor recommendations of the machine or component in question. The condition of the machine or component is in each interval supposedly returned to its original condition through the preventive maintenance tasks, but the actual condition before or after the maintenance is unknown. See figure 5. Equipment or components can also be replaced depending on what is most cost efficient.

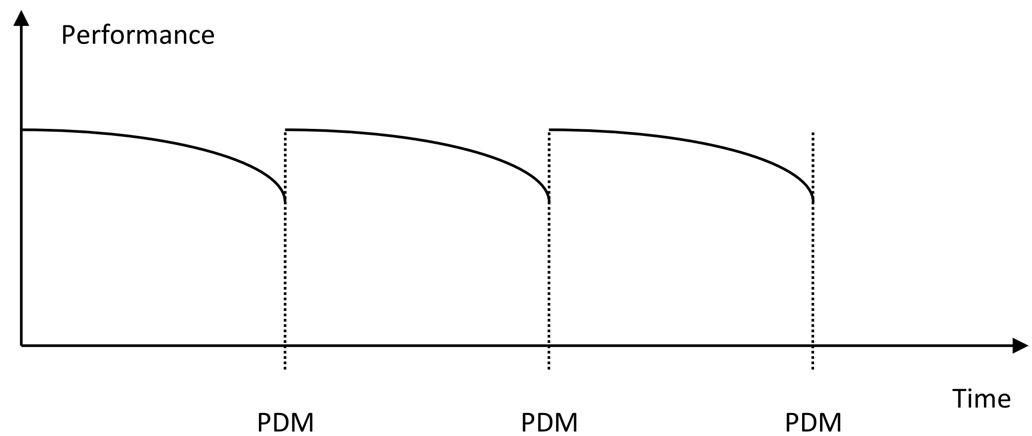

Figure 5 Predetermined maintenance

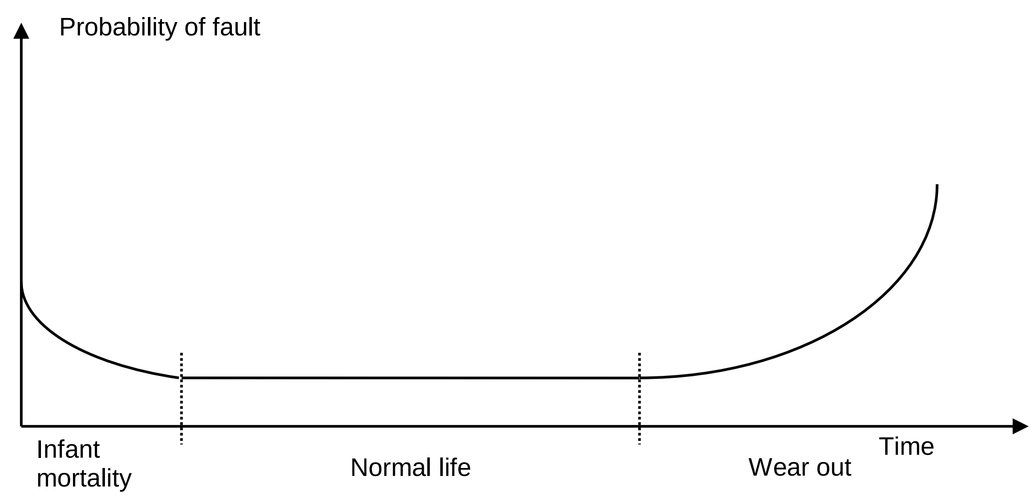

Figure 6 Bathtub hazard curve

The intervals are commonly determined from statistics such as mean time before fault (MTBF) where many machines and components follow a hazard curve in the shape of a bathtub curve. See Figure 6. PDM works best with components and machines that have age related failures as with the bathtub shape. There exist many other types of failure hazard curves for machines and components. The determination of the maintenance intervals will also be function of maintenance cost and the cost of fault for the specific item. Short intervals will increase maintenance cost while long intervals will increase fault costs.

2.4. Maintenance management and maintenance engineering

Maintenance management is defined as: "*all activities of the management that determine the maintenance objectives, strategies and responsibilities, and implementation of them by such means as maintenance planning, maintenance control, and the improvement of maintenance activities and economics''* (BS EN 13306, 2010).

Many organizations have now developed goals of having no unplanned maintenance that leads to lost production. To be able to reach aspirations like this you also need effective maintenance management both during operations and trough project development. The goal of maintenance management is to make sure the facility receive the optimal maintenance through various activities and analysis. The optimal maintenance strategy is the one that induces the lowest risk in HSE, the one that is the most cost efficient and gives the highest production availability. Other terms commonly used to describe the effectiveness and results of maintenance management are integrity and regularity. A well designed maintenance strategy will consist of a mix of the various forms of maintenance as a function of criticality in terms of a preventive or proactive company policy (De Groote, 1994).

The Norwegian Petroleum Directorate (NPD) developed a pilot study in 1996 in order to increase the quality of the maintenance management by addressing technical integrity and increasing safe operations (Norwegian Petroleum Directorate, 1997). The model presented in figure 7
Figure 7 Maintenance management loop (Norwegian Petroleum Directorate, 1998) describes the maintenance management function in general and its entire individual parts from design to operation. The model was developed for quality assurance of the operator companies' maintenance activities and is a fairly implemented and accepted model in many organizations. In order to reach the required results, which are developed during goal and requirements, you need resources. The resources are used in the various activities to generate the results. This is an ongoing process i.e. continuous improvement, which is why the model is constructed as a loop. The maintenance management loop is in accordance with the definition of maintenance management presented above.

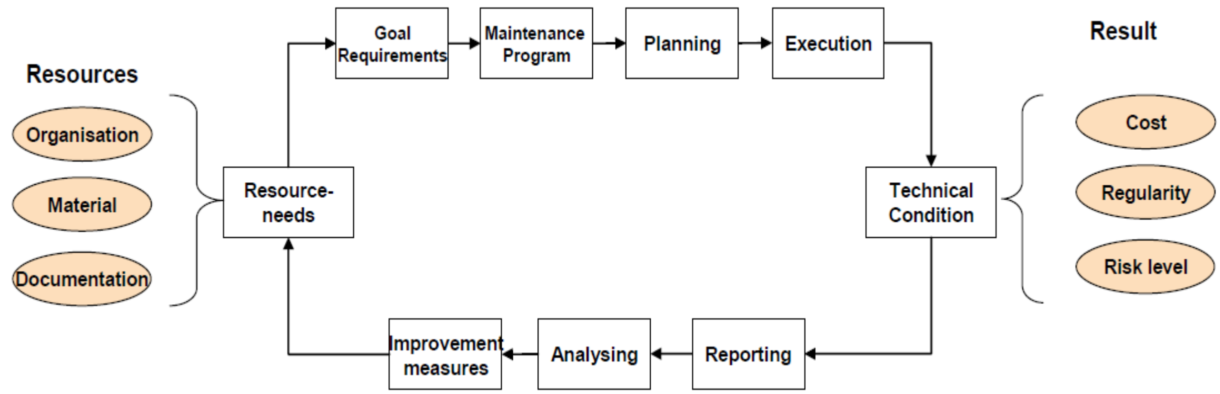

Figure 7 Maintenance management loop (Norwegian Petroleum Directorate, 1998)

Responsibilities of the maintenance management, not shown in the maintenance management loop, can be:

- Maintenance engineering
- Reliability engineering
- Manpower management
- Procurement
- Training
- Spare parts management
- Manage and develop Computerized Maintenance Management Systems (CMMS)
- Project and contract management
- Supervision and execution

Figure 8 shows an example of a typical maintenance engineering process. Maintenance engineering is tactical in nature ensuring that the assets within the plant meet the day to day demands for a reliable operation. They make sure that the right equipment receives the correct maintenance at the right time (Mobley, 2008). Maintenance engineering consists basically of assigning the most appropriate maintenance strategy to equipment and developing the maintenance program. The authority has some basic requirements on maintenance operation and developments that must be followed. Safety Integrity Level (SIL) is the level of risk reduction a safety instrumented function creates. This and risk analysis are characteristics of the systems and equipment and is important information which support the development of the maintenance program. Practice, experience, standards and vendor input are also very important in developing effective maintenance programs.

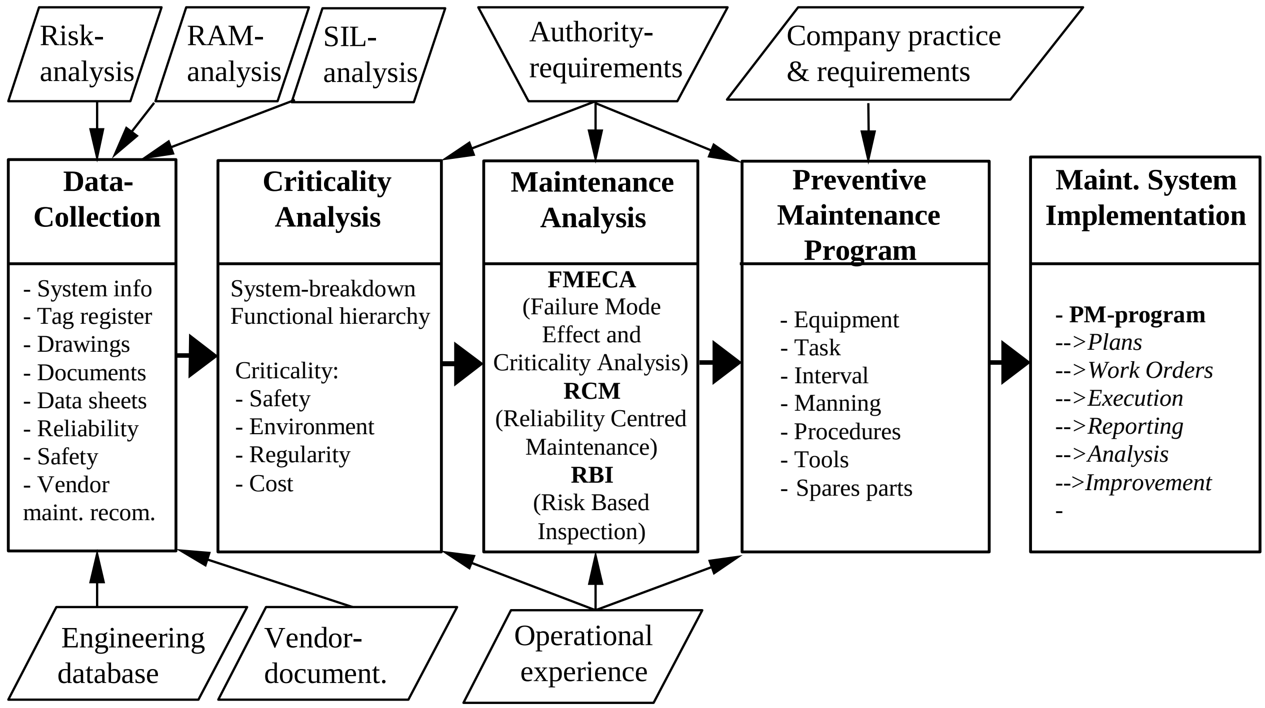

Figure 8 Maintenance engineering (Aker Solutions, 2010)

The output from the maintenance engineering process is the maintenance program as shown in the figure above. In this program all the work processes and resources needed in relation to maintenance is planned and allocated ahead in time for the lifetime of the assets. It tells us what needs to be done, who will do it and when it needs to be done for all systems and equipment. Maintenance intervals and inspection intervals, procedures for performing the maintenance or inspections, spare part needs, man hour needs and tools needed is specified in the program. This information is collected in what is called work packages. These packages are triggered either by schedules, runtime or state and generate a work order which is the actual maintenance that will be executed. When effective maintenance strategies do not exist, modifications or redesign must be done. Maintenance engineering also makes modification considerations in order to reduce or improve maintenance. Modifications are done if the design restricts maintainability or reduce reliability. Effective maintenance and modification tasks reduce the maintenance cost, increase maintenance support which is the ability to handle maintenance tasks upon demand, reduce risk, increase maintainability and availability.

Typical tasks in the maintenance engineering process are (Aker Solutions, 2010):

- Reliability, Availability and Maintainability (RAM) analysis
- Construction of equipment hierarchy
- Criticality analysis
- RCM analysis
- Maintenance program development
- Spare part evaluation
- Risk Based Inspection (RBI) analysis
- FMEA analysis
- Cost benefit analysis

The first step in developing the maintenance program consists of collecting all available and relevant data and technical documentation. The most important data is equipment and system specifications. Typical data required are (NORSOK, 2001):

Technical description of the plant systems containing:

- Detailed plant and system description.
- Capacity requirements.
- Operating conditions.
- Equipment description.

Technical drawings/diagrams containing process data, material and media codes:

- P&ID
- Flow diagrams.
- One line diagrams (electrical cables and equipment).
- Shut down logic.
- Fire and Gas cause and effect diagrams.
- Fire protection data sheets.

The next step is creating a hierarchy of the facility's system and subsystems in a logical systematic fashion. Tags, which are identification numbers, are assigned and basic information about the system such as operating conditions, operating limits and a description of the system is added.

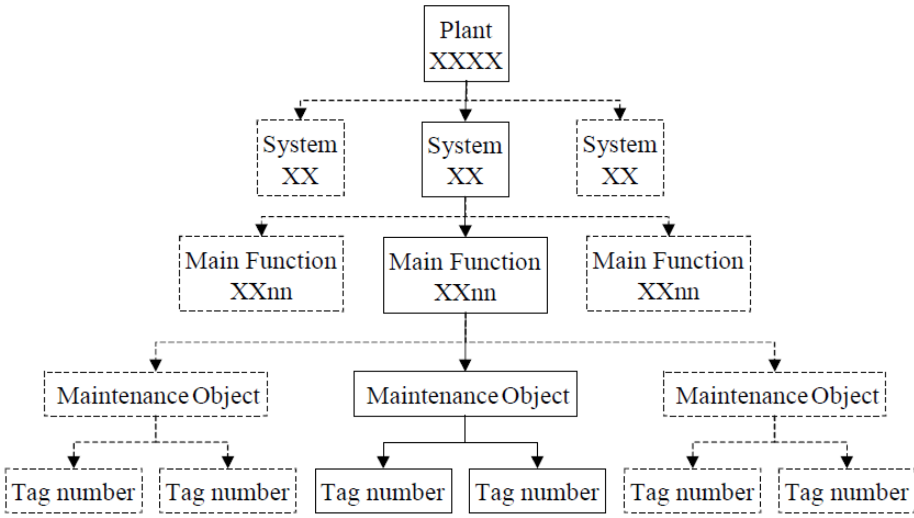

Figure 9 Illustration of a hierarchy (NORSOK, 2001)

The criticality analysis is used to rank systems, equipment and components events and faults in terms of how serious their consequences are. The consequences are based upon events related to HSE, production and costs. The event or fault frequency occurrence together with the consequence determines the criticality. Equipment with low criticality is usually assigned corrective maintenance. Equipment that has high or medium criticality needs further analysis to determine the most effective maintenance strategy. If the criticality is not acceptable or no task to minimize the risk exists a modification or redesign is required. The selection of the appropriate maintenance strategy for medium and high criticality is often put through cost benefit analysis and/or Life Cycle Cost (LCC) to find the most suitable strategy

FMECA or RBI analysis are the most common methods to find the most appropriate maintenance strategy for any given equipment The FMEA is a qualitative reliability tool that is used to systematically find and list all possible failure modes and the effects of such failures in a system. The main purpose of this analysis is to find strategies to avoid such failures from occurring assuring system operational success. This can be done with design alterations and creating barriers and activities that limit the occurrence of them. The FMEA also makes root causes analysis easier. A FMEA can contain information about the machine and system that is evaluated, its functions, operational modes, failure modes, failure cause, failure detection method, failure effect on system and sub system, failure rate, criticality ranking and risk reducing measures. RBI calculates the risk of system or component based on probability and consequences to determine inspection needs and intervals of the assets. It is very similar to a criticality analysis. RCM, FMECA and RBI are interrelated where RBI and FMECA are part of a RCM analysis, but they are in practice distinguished. RBI is mostly used for static equipment and components and FMECA for dynamic systems.

The last steps are implementation and construction of the maintenance program. This consists of planning activities, intervals, manpower, spare parts and documentation used to create the work packages that is what the maintenance program constitutes. Implementation consists of planning all other practical matters needed to assure an effective program, execution and improvement of it.

Detailed analysis such as FMECA is in many cases provided by the equipment vendor because it is a time consuming task. Some maintenance engineering models puts focus on creating and using generic maintenance strategies for systems or a set of equipment in order to reduce the amount of work required in the maintenance engineering. This is done on equipment where the maintenance previously has been effective and on equipment where much experience exists.

2.5. Condition Monitoring and Condition Based Maintenance

Condition based maintenance is defined as: *"preventive maintenance that include a combination of condition monitoring, inspection, testing and the ensuing maintenance actions"* (BS EN 13306, 2010). CBM is sometimes called predictive maintenance because it gives you the ability to predict degradation and faults, allowing you to plan the optimal time of maintenance. This is done by monitoring and inspecting equipment condition and process parameters that are linked to various failure modes. CBM and CM are sometimes used interchangeably. The main distinction is that CM is a method of acquiring information about the condition and CBM is the method of using that information to determine when and what maintenance needs to be executed. CM can be used in 5 different ways:

- Process monitoring (improving efficiency, verification, detect operational errors etc.)
- Safety monitoring systems (safeguard against catastrophic breakdown and consequential damage when operational errors occur. These are continuous and sensitive monitoring systems that shuts down the system immediately when serious abnormalities occur)
- CBM (for maintenance purposes using various tools to estimate the condition, degradation and to predict when maintenance is needed)
- Trouble shooting (give information when something has gone wrong and aid root cause analysis. Often used as an supplementary function when needed)
- Optimization of scheduled maintenance (the maintenance intervals are still determined by the PDM program, but these can be optimized on the basis of the actual condition)

CM can be on-line (continuous) or off-line (interval inspection). Most failures have a gradual development which gives you time to detect them and correcting them before they lead to faults. Random failure deterioration often accelerates whereas age failures have linearized deterioration. To be able to predict the maintenance interval you need to know the time from failure detection (P) to fault (F) for different failure modes. If the P-F interval (Figure 4) is shorter than the time to avoid a fault, then CBM is not feasible. The P-F interval can vary greatly between failure modes and also the

P-F interval itself varies. CM generates mainly three types of information which is the P-F interval, type of failure and the location of the failure. The P-F interval can also be predetermined if the failure mode is well known.

CM can account for machine load and thus enabling a dynamic trending of the condition. CM also has the ability to improve performance through performance measures. If an abnormality is detected the machine load can be reduced prolonging the life to the time when maintenance is most optimal. Failure finding is also a part of CBM where you test or inspect for hidden failures that cannot be detected during operation by monitoring means. The maintenance intervals in CBM are dynamic as supposed to static intervals in PDM.

The basic procedures of a CBM configuration for assessing machine condition are illustrated in figure 10. The three basic activities in CM are measuring to create a relevant data basis, analysis of the data and a decision based on the analysis. Sensor equipment, relevant to the failure modes it will monitor, is fitted to the equipment. The data that the sensors produce is either registered manually from readings or fed automatically into the computer for further analysis. The figure below and the explanation below describe the different steps from signal to usable information, needed in CBM.

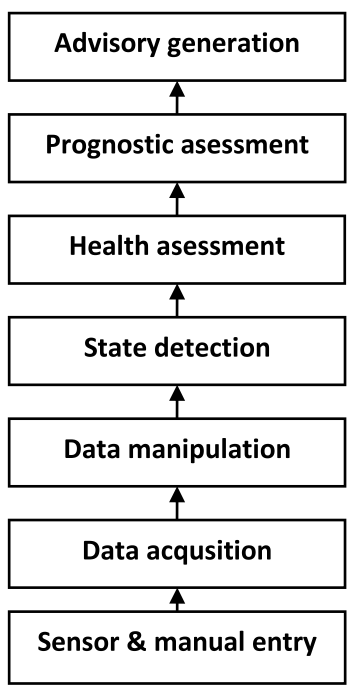

Figure 10 Machine condition assessment blocks in CBM (ISO 13374-1, 2003)

The first three blocks are of technological nature and consists of signal processing and data representation (ISO 13374-1, 2003):

1. **Data acquisition**: converts an output from the transducer to a digital parameter representing a physical quantity and related information (such as the time, calibration, data quality, data collector utilized and sensor configuration).

2. **Data Manipulation**: performs signal analysis, computes meaningful descriptors, and derives virtual sensor readings from the raw measurements.

3. **State Detection**: facilitates the creation and maintenance of normal baseline "profiles", searches for abnormalities whenever new data are acquired, and determines in which abnormality zone, if any, the data belong (e.g. "alert" or "alarm").

The three last functional blocks deals condition monitoring techniques to predict faults, detect failures, degradation rate and give corrective recommendations to management and personnel to help with the maintenance and planning (ISO 13374-1, 2003):

4. **Health Assessment**: diagnoses any faults and rates the current health of the equipment or process, considering all state information.

5. **Prognostic Assessment**: determines future health states and failure modes based on the current health assessment and projected usage loads on the equipment and/or process, as well as remaining useful life predictions.

6. **Advisory Generation**: provides actionable information regarding maintenance or operational changes required to optimize the life of the process and/or equipment. Information can be remaining life (P-F interval) and suggested actions.

The information that the CM system has constructed is used to plan and trigger work packages. There are in addition various levels of human/computer interaction when it comes to analysing and making decisions with regards to the output from the CM. At one end of the scale people perform all analysing, makes decisions and recommend actions. At the other end the computer handles everything and produces instructions or work orders that personnel perform without interaction.

CBM can be applied to at least 80% of maintenance according to International Foundation of Research in Maintenance (IFIRM) (Beebe, 2004). But CBM is not always been effective for every failure mode, machine and equipment. As part of an RCM process, condition monitoring will only be effective in 25-35% of all failure modes (Moubray, 1997). The challenge is therefore to determine what equipment should have CM and what monitoring techniques should be applied in relation to CBM.

The following has to be satisfied for CM to be applicable (IEC 60300-3-11, 2009):

- The condition has to be detectable
- The deterioration needs to be measurable
- The P-F interval has to be long enough for the condition monitoring task and actions taken to prevent functional failure to be possible
- The P-F interval needs to be consistent

A CBM decision process should be performed before you consider PDM activities when both types are technical feasible because CBM tasks are nearly always more cost efficient than scheduled tasks (Moubray, 1997). If you considered PDM tasks first, the benefits from CBM might be lost because a CBM evaluation process might not be performed. By not evaluating for both strategies each time saves time and cost.

2.5.1. Condition monitoring techniques

The monitoring types can be divided into 4 parts and the technical monitoring techniques into 6 parts (Moubray, 1997) and is given a short description below. This gives a huge amount of combinations that the monitoring of a machine can be done in. If you also consider all the products that exist from vendors and the amount of equipment at an O&G plant, the task of determining efficient monitoring systems can be challenging. The amount of equipment and techniques also require that people working with the task of selecting monitoring equipment has a thorough knowledge with the equipment and the monitoring techniques.

Technical monitoring

All machinery that moves gives off vibration. Sources of vibration can be ball bearing defects, misalignment, gear deterioration, imbalance etc. The amplitude of the specific frequency will rise with the severity of the failure. Machines that start vibrating at the natural frequency affect the performance and deterioration to a serious degree. Vibration monitoring is the most used monitoring technique and is especially effective on rotating equipment. Accelerometers, velocity and amplitude transducers are used, depending on frequency, to measure the vibration frequency and amplitude.

Another characteristic of machines that wear is that they generate particles that are analyzed to determine what is wearing and the severity. It also gives indications upon when oil, hydraulic fluids or filters should be changed because of particle contamination. The particles themselves also generate wear and are often a problem in hydraulic systems. Particle analysis can be done manually or automatically and there exist a range of products such as particle counters.

Chemical analysis is used to detect traceable amounts of contaminants in the operating fluid that is caused by wear or problems somewhere in the system. These are techniques used to assess the deterioration of the fluid itself, detect wear metals, leaks and corrosion. Most methods have to be done manually with samples taken from the system.

Physical monitoring encompasses various non-destructive techniques (NDT) to physically analyze equipment for cracks, fractures, fatigue and visible effects for wear and dimensional changes. These are effects that are a result from corrosion, fatigue, high load, poor design/ quality and temperature changes.

Many machines that start to degrade increase in temperature at the location of the failure. This can be detected by thermography techniques.

Monitoring techniques to detect wear and corrosion in electrical systems, insulation, electrical motors and batteries also exists.

Product quality variation

Another characteristic that can indirectly measure machine effectiveness and give indications about machine condition is the quality of the product that is produced. This is especially important in the manufacturing industry, not only for condition monitoring purposes, but quality too. A defect in a product can be directed to the machine or process producing the defect. Many defects develop gradually allowing you to plan for the restoration of the potential failures. A method called Statistical Process Control (SPC) uses product attributes such as dimensions, weight, functionality and other measurements to draw conclusions about the stability of the process (Moubray, 1997). This method tracks these attributes in relation to what is statistically expected to show that a process or machine is failing.

Process monitoring

Process monitoring uses parameters of the actual process in a machine or system to provide information about the efficiency of the process. Examples can be thermodynamic, fluid dynamics, power usage etc. The deviation from the theoretical calculated process properties gives the efficiency. This type of monitoring will inform about the performance that indirectly indicate incipient machine failures. These measures are also used for performance optimization.

Human senses

The human senses (look, listen, feel and smell) have been the most used method to detect problems with machinery and is still used today. A survey discovered that human senses are used by 10.75% across the industry (Higgs, 2004).The main problem with the human enquiry of condition information is that it is not sensitive and not objective. But humans can detect a wide range of problems with little and fast evaluation, but from experienced and trained personnel.

2.5.2. Implementation of condition based maintenance

There exists several propositions on how to implement CBM, but this thesis will present one of them. The lack of an implementation strategy has been one of the reasons why many CBM efforts have not been successful. When organizations acquire new technology, create new operational procedures, produce new products or services or rearrange the business plan it needs to be implemented into to all affected parts of the organization. The implementation describes how to put the relevant functions that belongs to CBM into practice in order to make it work as intended. Change management is an important part of implementation when organizations experience large changes. The implementation strategy describes all planned activities and factors that the organization needs to do and account for when acquiring CBM. These are e.g. technical aspects, work processes, management aspects, training, responsibilities etc. The model below will describe important aspects when implementing CBM. Research shows that a successful implementation depends upon a number of reasons (Higgs, 2004):

- Support from top management
- Reassess the organizations entire maintenance strategy. Full integration of CBM into overall maintenance strategy
- Select a system matching your organizations capabilities, resources and employee expertise
- Document financial gains
- Integrate test technology and experience from other locations
- Assessment of the implementation
- Staff selection and training

Bengtsson (2007) provides an example on an overall implementation model of CBM based on Swedish manufacturing industry. The implementation model includes four parts and can be seen in figure 11:

- Feasibility test
- Analysis
- Implementation
- Assessment

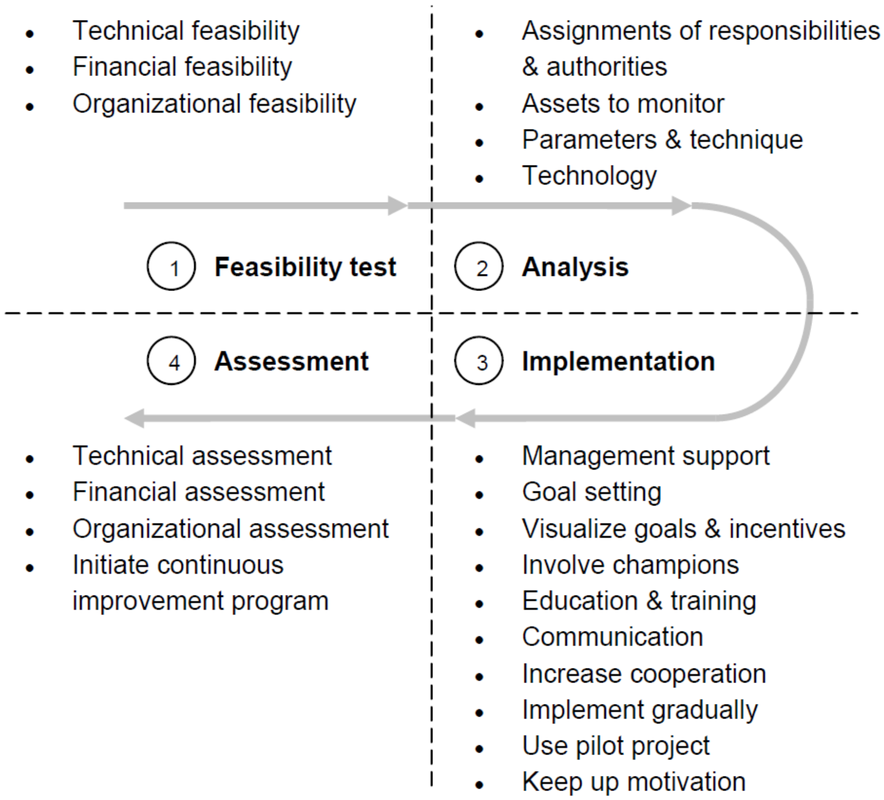

Figure 11 Implementation Strategy (Bengtsson, 2007)

The model tries to capture all aspects and activities related to a full CBM implementation. The implementation phase is of most interest to this thesis, but the other steps are also relevant. The feasibility step (1) includes technical, organizational and financial feasibility criteria. As the implementation matures the more detailed the implementation becomes. Organizational maturity is an important criterion in this model. This determines how advanced CBM implementation the organization can handle. The transitional gap should not be too large. He also mentions that a too detailed CBM evaluation is not suggested in this step. The analysis step (2) is more detailed and includes many of the typical maintenance engineering processes. The model states that quantifying possible gains/losses and developing decision support is important in the feasibility (1) and analysis (2) step. The last phase assesses the effectiveness of the implementation which is a feature also included in the maintenance management loop that were mentioned earlier.

In the implementation step (3) it is important to focus on the interplay between the technological, organizational and human aspects. This phase describes enabling factors for a successful CBM implementation in the organization shown outside the circle in figure 12 below. The enabling factors are divided in two as to where they apply; management and introduction in the organization.

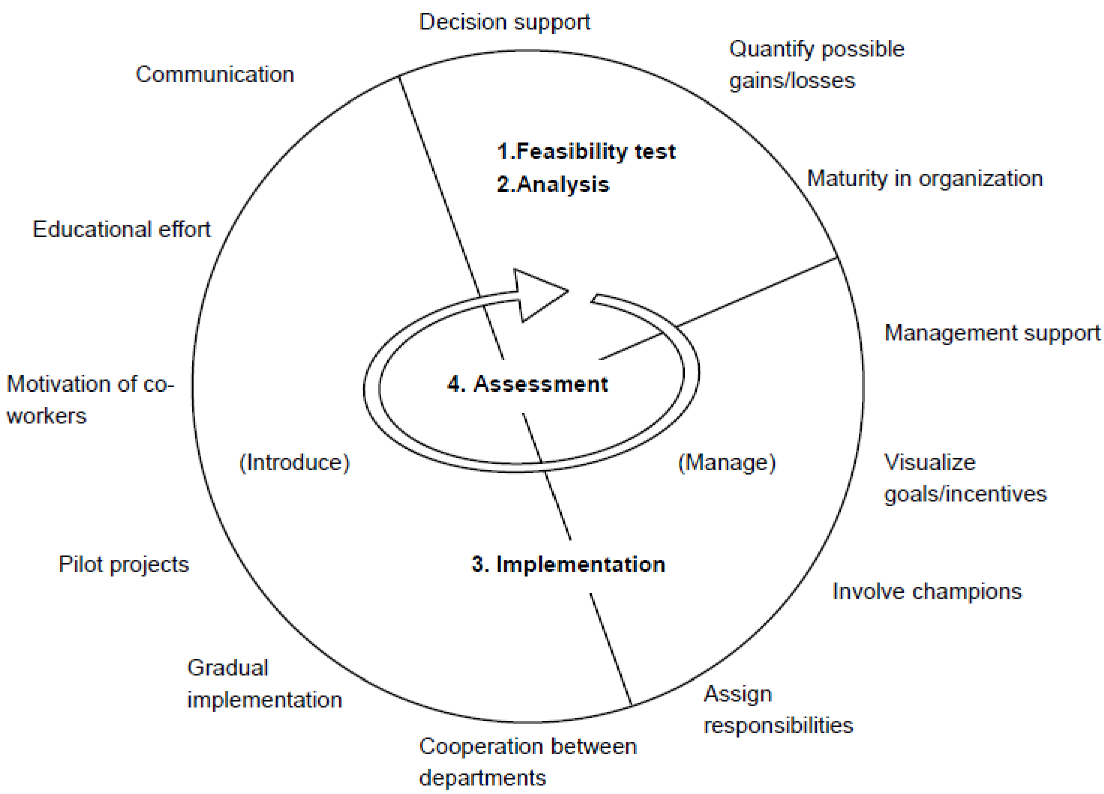

Figure 12 Implementation Phase (Bengtsson, 2007)

Besides knowing what important factors should be accounted for when implementing CBM, a more specific implementation plan should be created for the organization adopting to or increasing the use of CM for maintenance and performance purposes. This plan should include things like what monitoring methods should be used and on what equipment, work processes, CMMS integration, acceptance criteria, supportive documentation and standards. There is large amount of useful information this plan should contain. An example of important things to include in such a strategy is shown below (Markeset, 2008). The sub points are examples of what this could be.

1. Purpose with CBM:
    - Avoid shut down
    - Better planning of the maintenance
    - Analysis of failure causes and creation of preventive measures
2. Criteria for applying CBM:
    - On what equipment should CBM be used?
    - What CM methods should be used?
3. Conducting measurements:
    - Create baselines after installation of equipment and maintenance of equipment
    - Continuous measurements or inspections

- Measurements before and after maintenance
- Special measurements

4. Diagnosis of condition:
    - What information is needed to evaluate the condition?
    - What methods should be used to evaluate the condition?
    - What computer software/hardware is needed to evaluate the condition?
    - Should condition analysis be performed by 3rd party experts?
5. Reporting to maintenance management:
    - Who should be notified when abnormalities occur?
    - Generating work orders in the CMMS
    - How the CBM work orders should be planned
6. Reviewing maintenance performed.
    - Reporting the history/experience in CMMS
    - Analysis of failure causes and consequences
    - Reviewing selected maintenance strategy and see if changes should be made
7. Benefits and adaption of a CBM program:
    - Perform cost benefit analysis
    - Evaluate the scope of the CBM program
8. Organization, competency and training:
    - Maintenance personnel competency requirements
    - Engineering competency requirements
    - 3rd party experts competency requirements

2.5.3. Advantages and disadvantages of CBM

Much focus has previously been put on the advantages associated with CBM and less focus exists on its challenges and disadvantages. Table 1 below shows a summary of advantages and disadvantages associated with CBM compared with PDM as the alternative. The claims in the table are loosely based on literature, informal interviews and the authors own assertions which are why they should be considered as potential and not absolute.

	Advantages	**Disadvantages**
Condition based maintenance	Enables opportunity maintenance which is maintenance performed at opportunistic windows in time giving the least impact on production. This is made possible by the occurrence of other activities which affects production and the prediction and awareness of maintenance needs.	Increased instrumentation can decrease reliability. Instrumentation can fail. False alarms and incorrect analysis can lead to unnecessary maintenance activities and shut downs.
	Can detect and avoid random failure progression leading to less downtime	Less application and less experience which can introduce management and operational challenges.
	Only actual needed maintenance is performed, given that analysis is correct, which leads to less maintenance activity, workload and downtime.	Generates much information and data management which can increase work load. Failures can go unnoticed or be incorrectly deferred.
	Accounts for changing operating conditions	Increased procurement, installation and training costs which increases CAPEX
	Increased reliability because of less interference with machinery. Many maintenance activities create failures not previously present.	People’s conservative or skeptical view towards new solutions and concepts.
	Inspections are done while machinery is in service. Machinery does not need to be shut down to be able to evaluate the condition.	Dynamic planning of maintenance tasks can increase work load and make it challenging to predict resource needs.
	Decreased spare parts inventory and costs due to less maintenance activity.	Complex computer technology and analysis methods
	More information available about asset condition which increase experience.	Increased number of work processes
	Creates reliability data that can be used to assess equipment performance since maintenance intervals are not static.	Increased need of competence
	Increased verification of repairs because of available monitoring	
	Can detect infant failures because of available monitoring	
	Can reduce operational costs because of less and more effective maintenance tasks and less downtime.	
	Aids in root cause analysis because of available information from the monitoring	
	Can increase maintenance intervals, as opposed to scheduled intervals, leading to less maintenance activity	

	Advantages	**Disadvantages**
Predetermined maintenance	Maintenance tasks are scheduled which make it easier to predict resource needs during operation.	Potential failures/incipient failures are unknown
	Applied practice with much experience which makes it easier to manage, implement and design.	Many maintenance tasks are performed needlessly
	Less information that is more comprehendible which makes follow up easier with this maintenance strategy	Does not prevent random failures
	Does not affect reliability negatively	Shorter maintenance intervals which increase maintenance activity
	No additional CAPEX associated with installation and implementation.	Changing operating conditions is challenging to account for.
	Less operational analysis needed which reduce work load.	Decreased reliability because of unnecessary tasks that may interfere with machinery.
		Inspections must be done on shut down machinery.
		The spare parts inventory can be larger than actually needed.
		MTBF is static intervals. No reliability data to determine equipment performance.
		Limited verification of repair
		Can not detect infant failures.
		Can be cost inefficient. Many resources are spent needlessly.
		Does not aid in a root cause analysis
		Does not provide data to allow opportunity maintenance.

Table 1 Advantages and disadvantages

It is important to note that many of the disadvantages of CBM can occur with increasing monitoring and instrumentation. Monitoring of a limited set of equipment is not very challenging, but monitoring of equipment in the thousands can be, as mentioned in the introduction. The disadvantages lie within human factors, reliability factors and costs. If the disadvantages and challenges are apparent in current operations has been investigated through the survey presented in chapter 5.

3. Standards related to condition monitoring and condition based maintenance

Industrial standards that cover CM and CBM are presented in this chapter. A short summary of the standards, its purpose and area of use will be given. There exist a large amount of standards that cover maintenance in general, but only the most relevant standards are presented. The standards provides in many cases guidelines, knowledge and how to apply this knowledge in specific technological areas. Standards ensure compliance between organizations working methods that result in cost efficiency, increased quality, ease of transition between operation, safety, increased inter-operability, compatibility and they eliminate trade barriers. A complete and accepted standard that enables effective CM and CBM programs can save time and costs for all parties involved in designing and developing CM systems for assets. Much time is spent on, not only developing the programs, but also planning and discussing how the CM solutions shall be selected and constructed. This is exemplified in chapter 4 which presents a company methodology on how the CM systems were selected and developed.

The purpose of examining standards is to:

- See if there exist standards that can aid in the development of the maintenance program in relation to CBM
- If they have any methodology for equipment selection based on CBM needs, selection of CM equipment and implementation of CBM.

The following standards have been reviewed:

- International organization for standardization:
    - Condition monitoring and diagnostics of machines:
        - ISO 17359: General guidelines
        - ISO 13380: General guidelines on using performance parameters
        - ISO 13373: Vibration condition monitoring
        - ISO 13381: Prognostics
        - ISO 13374: Data, communication and presentation
        - ISO 13379: General guidelines on data interpretation and diagnostics techniques
        - ISO 18434: Thermography
        - ISO 18436: Requirements for training and certification of personnel
        - ISO 22096: Acoustic emission
        - ISO 29821: Ultrasound

        - ISO 14830: Tribology
        - ISO 10438: Lubrication, shaft-sealing and control-oil systems and auxiliaries
- American petroleum institute:
    - API 610: Centrifugal Pumps for Petroleum, Petrochemical and Natural Gas Industries
    - API 670: Machinery protection systems
- International electrotechnical commission:
    - IEC 60812: Procedure for failure mode and effects analysis (FMEA)
    - IEC 60300: Dependability management
- NORSOK:
    - Z-008: Criticality analysis for maintenance purposes

3.1. International organization for standardization

ISO 17359: General guidelines

This is a central standard on CM which gives an overview and recommendations, through various steps, on setting up and operating a CM program for all machines. An extract from this process can be seen in figure 13 below.

There are two steps in this model that can be used as decision support which is the FMECA and if the failure mode is measurable. In the flow chart it seems as if only the measurable factor is included in the decision process, but this is not true. In the explanation of each step the standard recommends that a criticality analysis on the basis of cost, down time, redundancy, safety and environmental impact etc. should be performed to prioritize machines to be included. It also recommends that the feasibility of the monitoring options should be evaluated. This standard supports the other more specific standards on CM. An example of a recommendation is that accuracy in monitoring for maintenance reasons is not important to account for as measures are relative and that they are trended.

The model starts with a cost benefit analysis including factors such as life cycle cost, cost of lost production, consequential damage, warranty and damage. This step is not meant to act as decision support when planning and selecting the CM system. The purpose for this analysis is establishing accurate key performance indicators and benchmarks for the CM program in order to assess its effectiveness when reviewing it in order to improve it. It could also be used for setting goals and strategies that will serve as a guideline for other activities.

The next step is the equipment audit. This step identifies and classifies all equipment and sets it up into a hierarchy. It also identifies its functions, interdependencies and operating conditions.

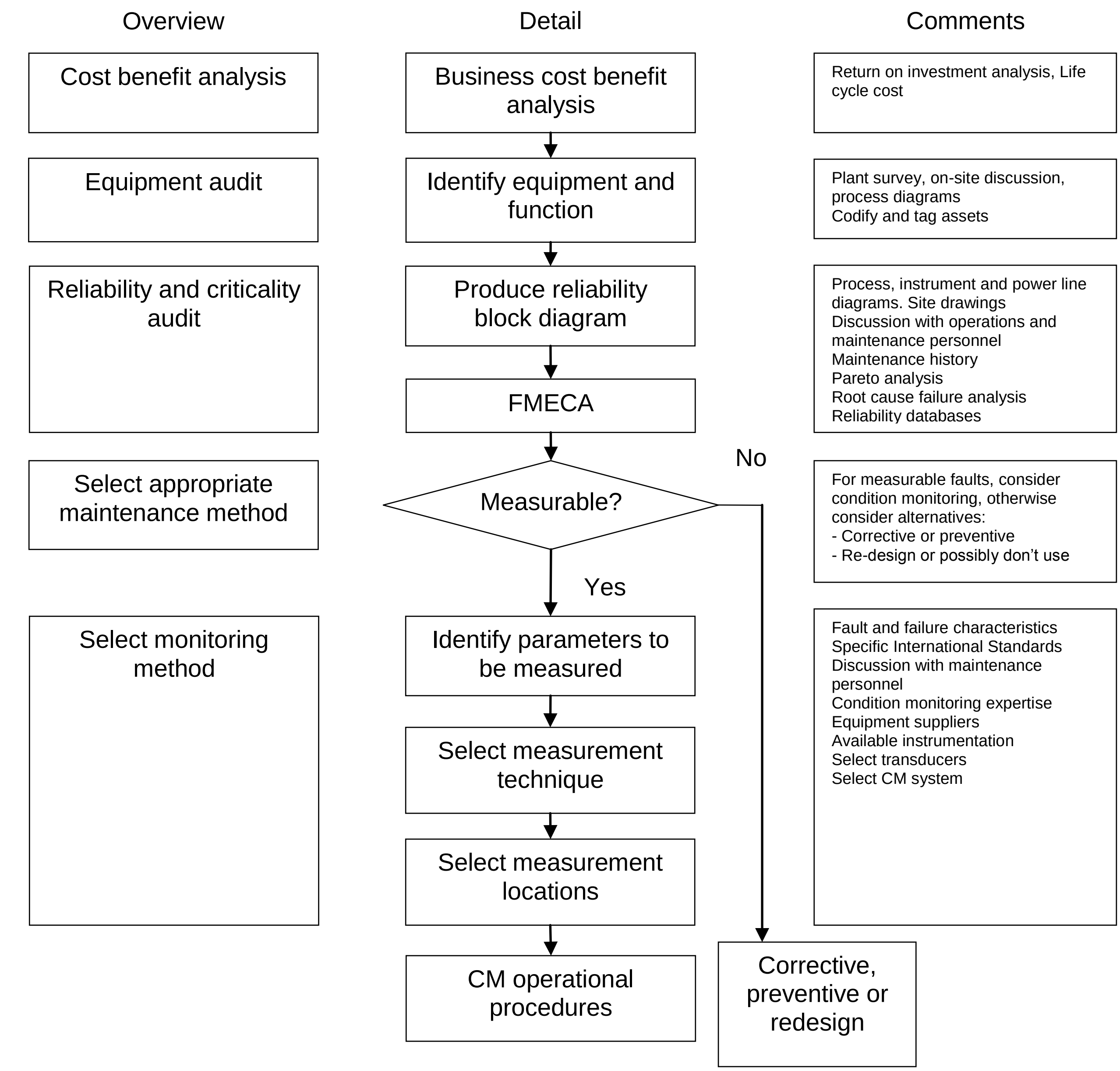

Figure 13 Flow chart for setting up CM (ISO 17359, 2011)

In the reliability and criticality audit step it is recommended to set the systems into a high level reliability block diagram to evaluate where CM is most effective and to reveal series and parallel reliability effects. A criticality ranking is also used to prioritize the equipment to determine where CM should be installed, based upon various factors. The commonly used FMECA is then recommended to detect possible faults, symptoms and other potential parameters that can occur on a deeper level.

Selection of the appropriate maintenance strategy is the next step and depends upon whether the failure mode is measurable or not. If a symptom or failure mode is not measurable another maintenance strategy should be applied. The standard does not give any recommendation on whether to choose between corrective or scheduled maintenance, but this is can be determined by a criticality and cost benefit analysis. The standard does not mention any of the more specific selection criteria for CBM e.g. the P-F interval.

The succeeding steps within this standard define operational procedures and are useful for those who will set up and use the CM system. The standard also provides tables to determine applicable monitoring methods for various machines, to determine failure modes from various symptoms and examples of relevant data recording. Most of the content in the standard is clear, concise and easily comprehendible. Parts of this standard can be regarded as an implementation strategy as describes how various tasks should be performed in practice. The standard also provides a table linking all of their standards on CM.

ISO 13380: General guidelines on using performance parameters

This standard gives guidance for condition monitoring and diagnostics of machines using parameters such as temperatures, flow rates, contamination, power and speed, typically associated with performance, condition, safety and quality criteria. It also provides tables on applicable parameters to monitor on various machines and symptoms related to various faults.

ISO 13373: Vibration condition monitoring

This standard gives general guidelines on vibration monitoring, factors for selecting vibration monitoring, transducer selection, transducer location, measurement types and quantities, data presentation, trending etc. It also provides tables that determine applicable set up for various machine types and vibration characteristics for various causes. This series also provide standards on signal analysis and data processing on machine vibration. A part of this series is also being developed for diagnostics. Refer to ISO 7919 and ISO 10816.

ISO 18434: Thermography

This standard provides guidance on the use of infrared thermography (IRT) as part of a programme for condition monitoring and diagnostics of machines. IRT can be used to identify and document anomalies for the purposes of condition monitoring of machines. These anomalies are usually caused by such mechanisms as operation, improper lubrication, misalignment, worn components or mechanical loading anomalies. The standard does not provide any guidelines as to where and when IRT is applicable, but this is given in other standards. It also provides case examples.

ISO 14830: Tribology

This standard is under development and has not yet been published. This standard covers lubrication and oil analysis.

ISO 22096: Acoustic emission

This standard specifies the general principles required for the application of acoustic emission (AE) to condition monitoring and diagnostics of machinery operating under a range of conditions and environments. It is applicable to all machinery and associated components and covers structure-borne measurements only. It provides tables determining on what equipment AE is applicable.

ISO 29821: Ultrasound

This part of ISO 29821 outlines methods and requirements for carrying out condition monitoring and diagnostics of machines using airborne and structure-borne ultrasound. It provides measurement, data interpretation, and assessment criteria. This technique is typically carried out on operating machinery under a range of conditions and environments. This is a passive technique that detects acoustic anomalies produced by machines. It gives examples of application areas and fault assessment.

ISO 13381: Prognostics

This standard gives guidelines on how to make prognosis on machine future fault progression.

ISO 13374: Data, communication and presentation

The intent of this standard is to provide the basic requirements for open software specifications which will allow machine condition monitoring data and information to be processed, communicated and displayed by various software packages without platform-specific or hardware-specific protocols. It consists of three parts: General guideline, data processing and communication.

ISO 13379: Data interpretation and diagnostics techniques

This standard contains general procedures that can be used to determine the condition of a machine relative to a set of baseline parameters. Changes from the baseline values and comparison to alarm criteria are used to indicate anomalous behaviour and to generate alarms: this is usually designated as condition monitoring. Additionally, procedures that identify the cause(s) of the anomalous behaviour are given in order to assist in the determination of the proper corrective action: this is usually designated as diagnostics.

ISO 18436: Requirements for training and certification of personnel

Condition monitoring and diagnostics of machines are integral parts of an effective maintenance programme. Non-intrusive technologies used in condition monitoring and fault diagnosis include vibration, infrared thermography, lubrication, oil analysis, acoustic and ultrasonic analysis, and electric current analysis. In many instances these technologies act as complimentary condition-analysis tools. The skills and expertise of the practitioners performing the measurements and analysing the data are critical to the effective application of these technologies.

3.2. American petroleum institute

API develops many well recognized international standards and guidelines applicable in the petroleum industry. They have standards on operation, maintenance, design and construction. They also have machine specific standards on common machinery such as API 610: Centrifugal Pumps. These standards are extensive standards for specification and classification of equipment types and are more detailed than the ISO standards above. What differs is that the ISO standards on CM are recommendations. The machine specific standards also specify procedures and activities that vendor and customer are responsible for. On instrumentation the standards specifies instrumentation on vibration and temperature and refers to API 670: Machinery protection systems and ISO 10438: Lubrication, shaft-sealing and control-oil systems and auxiliaries. The standards also have requirements on material inspection. The standards mentions many procedures and requirements related to maintenance, but non on maintenance relative to CM or on selection of appropriate maintenance strategy.

The ISO 10438 addresses lubrication, shaft-sealing and control-oil systems and auxiliaries. The primary purpose of API 670 is to establish minimum electromechanical requirements. This limitation in scope is one of charter as opposed to interest and concern. This standard covers the minimum requirements for a machinery protection system measuring radial shaft vibration, casing vibration, shaft axial position, shaft rotational speed, piston rod drop, phase reference, over speed, and critical machinery temperatures (such as bearing metal and motor windings). It covers requirements for hardware (transducer and monitor systems), installation, documentation, and testing. This standard specifies monitoring systems and transducers for the purpose of machinery protection and not for maintenance.

3.3. International Electrotechnical Commission

IEC 60812: Procedure for failure mode and effects analysis

This standard describes Failure Mode and Effects Analysis (FMEA) and Failure Mode, Effects and Criticality Analysis (FMECA), and gives guidance as to how they may be applied. The standard states that one of the purposes of the FMEA is determining preventive maintenance actions and design alterations. The standard does not give any recommendations as to what criticality or which machines should have condition monitoring. It appears that this is only determined through analysis.

IEC 60300: Dependability management

This is a large series of standards covering dependability management. Dependability is the collective term describing the availability performance of any simple to complex product. The factors influencing the availability performance of a product are the reliability and maintainability design characteristics and the maintenance support performance. Dependability testing and measurement relies on the accuracy of instrumentation and measuring devices. These standards give recommendations on how to select maintenance tasks (PDM, CBM or corrective) through analysis i.e. RCM, but they do not give any specific recommendations or requirements for instrumentation of various equipment. These standards give a complete presentation of maintenance management and engineering.

3.4. NORSOK

Z-008: Criticality analysis for maintenance purposes

This standard covers requirements and guidelines for establishing a basis for preparation and optimisation of maintenance programs for new and in service facilities offshore and onshore taking into account risks. The standard recommends that if a generic maintenance concept is not available and system has a high/medium criticality, a RCM/FMECA process should be undertaken. This is illustrated in a flow chart for establishing the maintenance program. It also presents some factors that should be accounted for when analyzing and allocating maintenance activities. The standard is a bit unclear on the selection process and no specifics on instrumentation are given for different equipment.

4. CBM selection methodology at an engineering company

This chapter presents a methodology developed and used by Aker Solutions. The methodology, called the "IO review" methodology, was developed in conjunction with a specific project at Aker Solutions and was continued with a more detailed "P&ID review" methodology at a later stage. Their strategic documentation containing the methodology defines specifications on how projects shall design for IO. Specification on IO solutions covers monitoring, automation, ICT infrastructure, information management systems, onshore operations centre and collaborative functions, to support CM. Recommended solutions are justified through added value on operations and maintenance. The results generated by the methodologies serve as a precursor to detailed engineering.

The IO review methodology is applied during concept phase (FEED) to prioritize and select equipment and systems where it will be beneficial to add monitoring instrumentation and automation devices. Figure 14 below shows the different activities and phases of the IO review methodology.

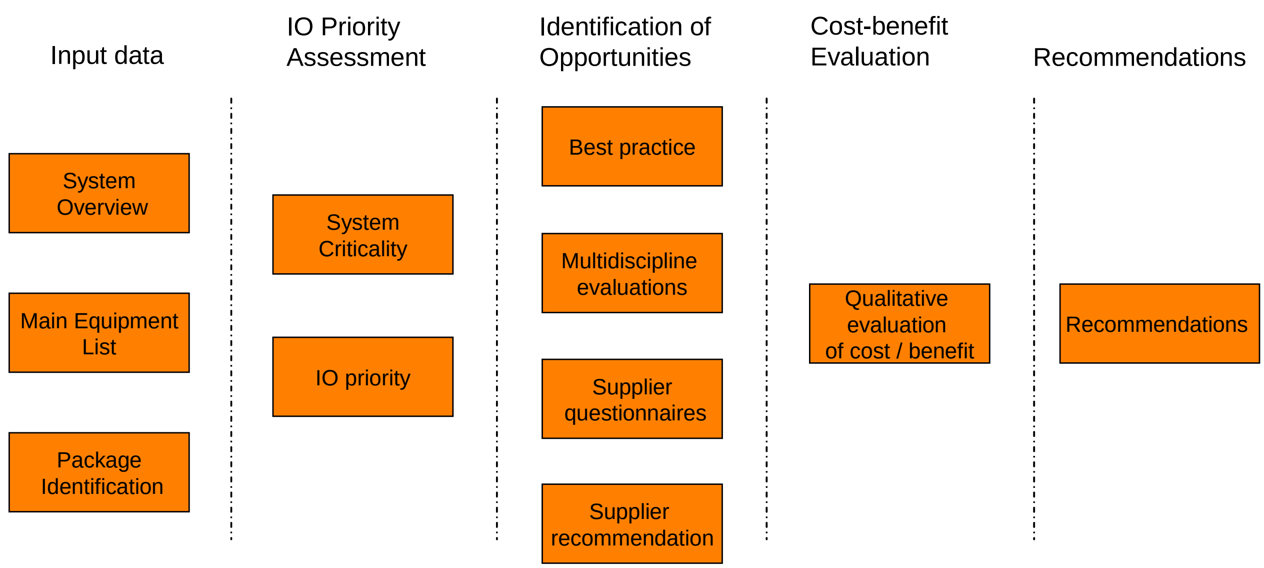

Figure 14 IO review methodology (Aker Solutions, 2010)

The various evaluations, selection criteria and steps in the methodology were done in collaboration with the customer (operator company). The first step of the methodology consists of collecting a data basis on the systems and performing equipment break down. The second step consists of a purely qualitative IO priority assessment for screening purposes, where an IO priority category is assigned to main equipment. The IO priority categories are based on criticality (production, safety and cost), condition detectability, measurable performance and remote control opportunities. Categories 1 and 2 are further analysed whereas 3 is disregarded. The third step consists of including supplier recommendations and experience into the analysis. In the fourth step a course and qualitative cost benefit analysis is performed based on a cost benefit matrix. The matrix can be seen in figure 15. The last step consists of creating the recommendations based on an overall engineering judgement from the previous analysis, which results in a check list on the plant systems. An extract from this check list can be seen in appendix 3.

Cost / Benefit of IO solution								
H = High, M = Medium, L = Low		**Benfits (Value Added)**						
		Increased Production		**Improved HSE**		**Reduced OPEX**		
Cost of investment (CAPEX)		High (>1%)	Low (<1%)	High risk reduction	Low risk reduction	High (>1MNOK/year)	Low (<1MNOK/year)
High	> 1 MNOK	M	L	M	L	M	L
Medium	100.000 <> 1MNOK	H	M	H	M	H	M
Low	< 100.000 NOK	H	M	H	M	H	M

Figure 15 Cost-Benefit matrix (Aker Solutions, 2010)

The strategic documentation containing the methodologies also refer to a maintenance engineering strategy which states that all critical equipment shall be based on CM principles where it is beneficial and feasible, including both condition and performance monitoring. The monitoring concept for each individual machine/item will be based on a cost benefit analysis.

The methodology also includes feasibility criteria:

- Equipment having gradual wear out period and where long-term trending enables extension of maintenance periods and better planning for maintenance execution.
- Equipment where online fault diagnostics enables reduction of rectification time or reduces the need to send personnel offshore.

Other aspects mentioned in the strategic documents are selection criteria, establishment of key condition indicators, CM management systems, CM specialist systems, equipment group requirements and integration of CM systems and CMMS. The P&ID review methodology were used at a later stage in the project that created detailed reports on functional requirements, monitoring opportunities and evaluation of equipment which could be used during design and procurement.

To summarize we can see that this methodology differ from the previous presented standards and practice, in that a limited amount of FMECA procedures, generic maintenance models or RCM analysis were used for deciding monitoring alternatives. The methodology is although similar and includes many of the same decision elements common in maintenance engineering. The main difference is that the model presented here is a simpler and less work demanding model where the decisions are more influenced by expert judgement based on experience from various parties. The methodology is based on the fact that a normal O&G project execution has strict limitations regarding cost, time and resources. A fast and practical approach is necessary in order to meet these challenges.

5. Survey

5.1. General

A survey was conducted to map operator needs, experience, goals, practices, challenges and views towards CBM. The survey is divided in two. The first part is a questionnaire that acquires general opinions on various statements related to CBM. This type of inquiry acquire information that is specific and easy comprehendible which makes it easy to conclude upon. The second part consists of an interview in order to add additional information. Representatives from 5 operator companies, 1 CM company and 1 drilling company participated in the survey. The representatives have central positions in the maintenance management organization and should serve as a fair representation of actual opinions and conditions within the maintenance environment. This survey can however not be regarded as statistical since the number of subjects is very limited. The companies and participants will remain anonymous to avoid conflicts on intellectual property and confidentiality. The actual answers and results can be seen in appendix 1 and 2.

The questionnaire consists of 13 statements, related to CBM and CM, with weighting into five grades of agreement and the opportunity to give text comments:

1. We have implemented CBM to a large extent on our/others assets
2. It is challenging to integrate CBM with current CMMS/SAP
3. End user software is too complex
4. It is difficult to plan the maintenance work orders generated by CBM
5. CBM too costly to implement versus the benefits gained
6. CBM is manpower demanding
7. CBM generates too much information to handle
8. CM detects root cause problems
9. The international standards on CM do not meet my requirements and needs.
10. There are too many condition monitoring equipment vendors with incompatible products
11. Sensor/transducer/monitoring equipment is not reliable
12. Analysing the data is time consuming
13. We encourage more use of CBM on new installations and major modifications

The interview consisted of 9 questions targeting the companies' experience and application on CBM, CM and maintenance:

1. What kind of systems they already have CM on, what systems they prioritize for CM, how they prioritize and what they believe to limit increased CM.
2. What the main purpose is for their already installed CM equipment i.e. how they use the functions that CM provide.

3. What benefits the currently installed CM equipment has provided
4. If they have strategies for selecting monitoring equipment, how they select and on what basis they select.
5. If they have any implementation strategy or procedures, if they acknowledge implementation issues and if they work to solve them.
6. What their level of CBM is to total maintenance efforts
7. What the main challenges with maintenance operation is today and if CBM can be used to solve them.
8. What their practice is when it comes to using the standards and other methodology on CM and CBM
9. How they prefer to evaluate the information and data that CM produce

5.2. Questionnaire results and comments

A summary of the answers can be seen in figure 16. A short summary of the grading and the comments will be given.

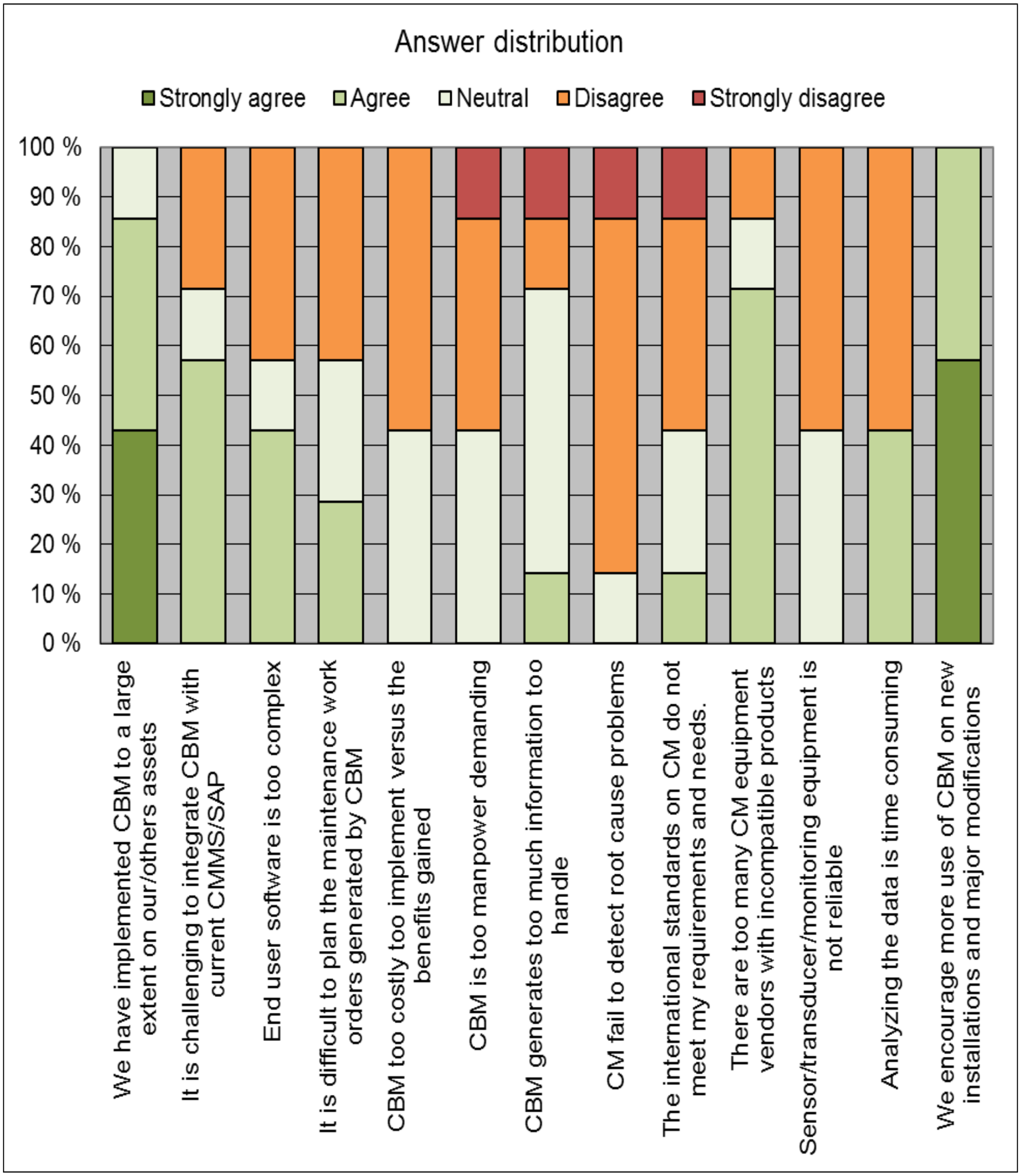

Figure 16 Answer summary of the questionnaire

Statement 1: Implementation of CBM

6 of the participants agree to have implemented CBM in their organization which indicates that a big focus has been put on adapting CBM procedures. One participant states that CBM is the preferred strategy and that equipment expected to have much maintenance is equipped with CM. CBM is dominating in their preventive maintenance programs. Another says that they have a strong focus on CBM and that performance monitoring has set clear requirements for the solutions they implement.

Statement 2: Integration of CBM with CMMS

The majority states that integrating CBM into the current maintenance management systems is challenging. This issue is apparently well recognized and the companies are working on to solve it. One of the participants states that there is no good method to differentiate between different maintenance types in SAP (CMMS). Another participant states that it does not necessarily have to be challenging. He says that efficient and effective work processes is the basis for how to apply CBM and that automation of the work processes by the CMMS can be beneficial, but that it can be practiced without. The challenge is easy if the problems are understood, says another. He elaborates that many try to link raw data to the CMMS systems and drown in work orders and that only actionable data should be entered into the CMMS after an analysis by a decision support software or a CBM engineer.

Statement 3: End user software complexity

There are divided opinions on the CBM end user software's being too complex. The reason of the divided opinions seems to be on how you look at the problem. An untrained person will have tremendous problems using the end user software whereas a trained expert CBM engineer will have a big advantage. The participants seem to have this viewpoint. They say that CM is a complex matter and thereby may require complex software and that this is solved by having good acceptance criteria and support from engineers and equipment experts. One of the participants says that they will hire in 3rd party experts to take care of this, but that they want to manage most of the CM themselves.

Statement 4: Work order planning with CBM

Most participants are either neutral or disagree and make it clear that this depends. The participants say that it is important to develop good parameter limits through engineering skills, experience and tuning. Another participant agrees and states that this may be one of the biggest issues for not implementing CBM. They say that a compensating measure for this is to preplan all the other parameters or corrective measures in the CMMS very good. One of the participants established a feasibility requirement on the P-F interval of 60 days, to account for this issue.

Statement 5: Cost of CBM versus benefits

Whether CBM is too costly to implement versus the benefits seem to depend on what systems and equipment you decide to monitor. If everything is monitored it will not be very cost efficient as one of the participants states it: “if you try to monitor the hinges on a toilet door it will be too costly”. They mostly seem to disagree with this as long as the alternatives have undergone an analysis through methods such as a cost-benefit analysis, FMECA, and life cycle value/cost. Many 1st line maintenance and PDM activities can in many cases provide the same effects at lower cost, says one the participants.

Statement 6: CBM manpower demands

The respondents are either neutral or disagree to CBM being to manpower demanding. A respondent say that the manpower needs, being demanding or not, will be verified when developing work processes for the CM activities. One company states they are moving to more wireless systems by spending CAPEX to decrease OPEX. Another says that the manpower will be high in the beginning as the systems are new to the personnel, but that much manpower will be reduced with less physical PDM maintenance work.

Statement 7: CBM information processing

Most participants are neutral to CBM generating too much information to handle which is also an issue that depends on how you configure your CBM systems. One respondent elaborates on information generated from CBM execution i.e. after an activity has been performed for reviewing purposes: The need for analysis/reporting must be determined first. Then the information will be tailor made suiting the user’s needs, avoiding extensive feedback information. Another respondent explains that limits that are too high makes failures go unnoticed and limits that are too tight lead to the stated problem. The optimal configuration needs to be configured based on experience and that the avoidance of this problem depends on a good initial set up. One participant explains that they are developing an overall system indication system with traffic light alarms to decrease the amount of information. If it is a serious alarm they will go deeper into the cause generating this alarm and diagnose the incident.

Statement 8: CBM for root cause analysis

Most of the respondent’s disagrees that CBM detects root cause problems. They explain that CM is not meant to detect root cause problems, but merely to assist in the investigation of the machine condition. CM parameters are linked to the failure mechanism identified through an FMECA. The monitoring of root causes is of course recommended if they are obvious and easy to measure/detect. CM measures in most cases the symptoms, not the actual fault or cause mechanism. CM information can however assist in the investigation of root causes.

Statement 9: Satisfaction of standards

Most of the companies rely on the international standards, but it varies much to what standards are used and to what extent which may explain the spread in the answers. Most respondents disagree that the standards don't meet their requirements and needs showing that the standards are adequate. One respondents say that technology develops faster than the standards can follow, so many standards gets outdated or haven't yet been developed, but that the standards will prove effective as frameworks in the future.

Statement 10: Incompatibility of CM equipment

The majority thinks that there are too many incompatible CM products. One of the participants says that they have tried to standardize and narrow the choice of products from an early start which has resulted in avoiding this issue. One respondent claims that integrating the products is not that difficult and that they are currently doing it at their diagnostics centers. Another respondent agrees that this is an issue, but that they are designing an overall system that handles all information from the sensors which also have analyzing capabilities.

Statement 11: Reliability of CM equipment

The participants disagree to sensor equipment being unreliable; saying that most of the sensors have improved a lot the last 30 years and that they are very robust when looked after. Most issues have to do with cabling. Quality depends on the price you are willing to pay which is a problem with fixed price contract where the cheapest equipment is often selected, says one of them. The reliability should be subject to an assessment for critical equipment determining the need for the sensors to be a part of PM program, says another.

Statement 12: Data analysis

There is divided opinions on whether analyzing the data is time consuming, were one half agrees and the other don't. One of the respondents that agree is looking for methods and algorithms that can semi automate the analysis, reducing the efforts. The challenge with this is that you need to get to know the behavior of the equipment. The other agrees but point out that these activities is not as time consuming and costly as the consequence of not doing them. Another participant says that the analysis, time consuming or not, is well worth the effort and that it is done by dedicated resources. This concludes that the analysis part of CBM is time consuming, but that it is a necessity if it is done for the right reasons. One respondent says that the resources for analysis should made available and that it should not be regarded as time consuming.

Statement 13: Future prospects on CBM

Everyone either strongly agrees or agrees that more CBM is encouraged in the future which shows that the companies have a positive view towards CBM. One of the respondents claims that all oil companies in Europe encourage this. Another respondent says that their company strives to become the leader in the work of CBM and performance monitoring.

5.3. Interview results

Question 1: Selection, prioritization and limitations of increase for CM

There is one measure that the companies emphasize when determining the needs for CM which is criticality. There is some varying practice when it comes to determining the criticality and what criticality determines the need for CM. The respondents say that equipment classified as medium or high criticality should have CM, but what constitutes high/medium criticality were not provided. One respondent said they do not prioritize small and uncritical equipment. Other tools and factors used to determine the need for CM or not were cost benefit analysis and the FMECA. A big emphasis is also to have CM methods on safety related equipment. The fire water system is a common example from the respondents. Power turbines, pumps and compressors are types of equipment commonly monitored. The drilling company relied heavily on CM of their thrusters which was considered a very critical function on the rig for positioning. The CM company representative states that most equipment is monitored today, but what exactly, varies between companies. He says that much equipment has protective systems that prevents catastrophic break down when irregularities occur and that these systems also forms the basis for CM. The respondents don’t give clear answers to what monitoring techniques are prioritized, but some of them mention oil analysis, vibration monitoring, thermography monitoring and performance monitoring. The CM company focused much on utilizing wireless technology as an effective technique. The participants were asked what factors limited increasing CM:

- Retrofitting of equipment
- Many vendors to select between
- Maintenance engineering is involved too late in the projects
- Not good enough CM techniques on particular areas
- Planning the maintenance activities when there is a high level of CM
- Costs
- Low competence on CM
- Unsystematic utilization of CBM
- Identifying failure modes
- Maintenance of the instrumentation itself

Question 2: The purpose of CM

Most of the respondents use CM as a part of a CBM strategy, but also for process optimization. Only a few of them say that it is used for trouble shooting or scheduled maintenance optimization and that this was used only in a small degree. If it is used for interval optimization it should be done very carefully, says one of them. Many of them explain that CM is used to acquire information about the condition and to predict its failure development in time to restore it. Reasons for this, they say, is to be able to plan maintenance towards shut downs, have less down time and reduce scheduled maintenance. Main purposes were:

- Increase availability
- Provide information
- Pre warnings of degradation
- Prevent critical break down

Question 3: The benefits of CM

One of the operator companies was not yet in operation, but they were expecting increased availability as a result from the CM. They have a dedicated center that receives all maintenance and reliability data for analysis and were going to monitor performance indicators related to maintenance. Once they got into operation they would watch for increased maintenance awareness. On their new installation they were planning to have half manning to what is normal where CBM is a prerequisite. Their strategy consisted of creating maintenance campaigns based on input from the CM and PDM systems, which were continuously planned ahead. This would be performed by a land based operations center which will also surveillance and manage the asset. The drilling company reports that they have had reduced maintenance cost, increased availability and increased maintenance awareness. They had also started using much 1st line maintenance which consisted of daily check lists which had reduced the down time by 50 %. They considered this as a part of CBM. The company also continuously keeps track of the performance of corrective maintenance, preventive maintenance, CBM, costs and availability. One of the operator companies says that they have had cost reductions, but on a small scale. The respondent says the big savings comes from increased availability. He also says that they have had increased maintenance awareness and that it increases knowledge on process and equipment, but that it is difficult to estimate what savings this create. The CM company explains that they perform a cost benefit analysis on every maintenance action. The representative from this company explains that maintenance cost is reduced because CM prevents consequential damage, that planned shutdowns are optimized leading to better availability and that increased maintenance awareness is something that comes naturally with CM. These thoughts are in general the same for all of the respondents. One operator company says that CM creates the feeling of ownership of the equipment leading to increased maintenance awareness. Another says that CM makes it easier for the organization to make decisions.

Question 4: CM selection strategy

The use of internal, vendor or contractor strategy varies and most companies use a combination. It was not clear whether they had specific strategies. One says they relied much on the vendor, but with their own specific requirements and a contractor company that was responsible for the detailed engineering. Another company says that the FMECA was the vendor's responsibility. They relied much on well recognized maintenance contractors and invited them to partake in risk, responsibility and gains that follow with CM. One said they used vendor standards with requirements from them and that they did not use contractors for this task. The CM company says that the operator companies in most cases decide this. One of the operator companies said that they have developed a strategy for CM equipment selection and that they had specific requirements for equipment specifications. The vendor was involved when the vendor required it and that a contractor was used to a certain degree. Another operator company said that they kept these tasks in-house and used internal strategies for this.

Question 5: CBM implementation strategy

All of the respondents are aware of implementation issues, regarding this as the most challenging part, but many of them say they have implementation strategies. One of the operators says that if you implement the maintenance management loop, it's no task to implement CBM either. The representative from the drilling company answers that they cover implementation in their governing documentation. They have procedures on equipment selection, FMEA, cooperation with the rigs, reporting/analysis, work processes and planning. He explains that they have built the same workflow for CBM into their CMMS and that they have not received any impositions from the government on their maintenance operations. This company does not use the maintenance management loop, as they think it is confusing. The respondent from the CM service company explains that CBM was implemented retrospectively in the past, but that it is thoroughly planned today during FEED. He also says that it has been the big companies that have led the way on implementation and that other companies such as service providers had to follow them. One of the operators says they, because of experienced employees, don't need implementation strategies.

Question 6: The level of CBM compared to other maintenance efforts

Most companies say that they are moving away from PDM towards more CBM. One of them says that it is not important to put focus on the amount of each maintenance strategy or to have requirements on this. The appropriate level of each maintenance strategy will be revealed after analysis such as FMECA, risk analysis etc. The answers on what the level is today vary. One says that it is very low due to conservatism towards CBM, but that they are planning on increasing it. One of the other respondents are focusing on improving their existing CM systems, which is relatively low, and is therefore not planning to increase CBM. The other answers lie between 40-60% CBM. Estimated decrease of PDM is 7-10% per year, says one of them.

Question 7: Current challenges with maintenance operations

The question asked what the main challenges with maintenance operations are today and if CBM can be used to solve them. The participants mentioned these challenges:

- Maintain safety
- Having control over mechanisms that can lead to large consequences
- Barrier management as provided by maintenance
- Effective interaction between offshore and onshore operations
- Eliminate human errors
- Instrumentation that fails
- Startup problems with new installations
- Performs maintenance too often where much it is unnecessary PDM
- Reducing the amount of alarms
- Logistics and control

Clear answers on how to solve many of these issues were not obtained. One of the operators says that challenges are not solved by increased instrumentation, but with effective and efficient actions and mentions RAM analysis as an effective tool. Many of the other respondents say that CBM can solve some of these challenges by providing more information and that it has the ability to reduce PDM.

Question 8: Standards and guidelines used in relation to maintenance and CM

All of the companies use internal models/strategies that are based on relevant standards. They also rely on governmental requirements. Many of the companies focus on using/developing generic maintenance models or templates and use RCM when this does not exist. RCM is also used on new installations and equipment that is unknown. Many of them say that a light RCM is used. The participants referred to these standards related to maintenance and CM:

- DNV-RP-G101 - Risk Based Inspection of Offshore Topsides Static Mechanical Equipment
- Norwegian Petroleum Safety Authority: Guideline regarding the activities regulations
- NORSOK Z008 - Criticality analysis for maintenance purposes
- NORSOK Z006 - Preservation
- ISO14224 - Collection and exchange of reliability and maintenance data for equipment
- ISO 20815 - Production assurance and reliability management
- NORSOK Z013 - Risk and emergency preparedness analysis

- NORSOK S005 - Machinery working environment analyses and documentation
- ISO 17359 – Condition monitoring and diagnostics of machines
- IEC 60300 – Dependability management
- ISO 15926 - Industrial automation systems and integration. Integration of life-cycle data for process plants including oil and gas production facilities

Question 9: CM data analysis

It varies from company to company how they prefer to analyze CM data, but a combination of internal, 3rd party or vendor resources are used. The equipment vendor is the least involved. Many of them are determined to keep as much analysis to them selves in order to have control and knowledge over their asset. One participant also requires involving the equipment vendor more. It varies if they have dedicated work processes for CM analysis.

6. Discussion & Conclusion

The two main purposes for installing additional monitoring equipment, besides instrumentation for protection, safety and process control, is condition monitoring for the determination of maintenance and process performance optimization. Monitoring for machine protection purposes will be disregarded as this is specified in machinery standards. Justifying monitoring for performance optimization can be done through cost-benefit analysis, but the fact is that much monitoring equipment is already installed generically to monitor the process for control and safety reasons. Instrumentation for control, surveillance and safety reasons is more or less standardized. For maintenance purposes you need to determine what additional monitoring is needed and what part of the existing monitoring can be used to determine maintenance needs. Most recommended procedures for this include either full use of RCM or extensive use of FMECA, but this has proven to be challenging during project execution because of the impracticality of specifying monitoring and instrumentation at later stages of a project.

It is clear that CBM is the optimal choice if failure modes do not have a distinctive wear out phase (random failure probability). Failure characteristics are in most cases linked to failure modes of components and not equipment failure. Data has to be available and FMEA has to be used, which means that this may not be practical to use as a criteria. Technical feasibility is the most important criteria that will assure applicable and effective CBM solutions. Criticality analysis is the most commonly used step in determining the best maintenance strategy. The easy part with the criticality analysis is allocating equipment of low criticality not posing any economical or HSE risk. This equipment will have a corrective maintenance strategy, run to failure or some kind of PDM because these options are in most cases the most cost efficient. The challenging part is determining if medium/high critical equipment should have CBM or PDM. Criticality does not exclude or recommend any of these maintenance policies which are why further analysis is needed. Since extensive RCM or FMECA analysis is not feasible in the front-end phase of a project, other methods must be used. Cost benefit analysis and LCC analysis can be used to determine the most appropriate strategy, but this requires a lot of input data which is hardly available.

A cross industry survey found that predictive maintenance is 8-12 % more efficient than PDM (ABB, 2011). A government study showed that CM decreased unscheduled shut down time by 75% and increased total profits by 1.2%. The survey also reveals that the costs of setting up CM were 1% of equipment cost. This consists of CM equipment, training and operational experience costs (Rao, 1996). Another survey found that costs, from successfully implementing a predictive maintenance strategy, were reduced by 50%. The survey also found that unexpected failures were reduced by an average of 55% and that repair time was reduced by 60 % (Mobley, 1990). This and the high cost of production loss and the high focus on safety in the O&G business, indicate that an economical analysis on CBM selection for medium/high critical is irrelevant. This leads to the conclusion that if

CBM is feasible and that it has a high/medium economical criticality it should be the selected strategy, given that suitable and feasible monitoring methods exist. But not all failure modes will have available effective monitoring options and increased monitoring can lead to increased complexity and reduced benefits, as previously stated.

The survey contradicts some of the problems and reveals some challenges apparent with CBM, but it does not provide special inputs to how CM selection should be performed or what specific monitoring solutions give high benefits. A more detailed experience analysis is needed to achieve this. The survey reveals that a majority of the companies have matured on the subject of CBM. They are aware of the challenges with CBM and are actively trying to solve these. Most of them have CBM as the preferred strategy, but this does not mean instrumented CBM only, but it also includes inspections. The results seem to reveal that most companies are ready to handle increasing monitoring and also encourage it. Some of the companies states that they did struggle with conservatism before, but that they have clear strategies and procedure to avoid this problem. An explanation of why CBM is experiencing greater acceptance and success can be because of the introduction of IO which greatly supports the operation of CBM and that more experience has been gained on CM and CBM over the years. Another may be that younger people familiar with computer technology is becoming more involved. CM technology has also been improved making CBM more attractive. The conclusions is that current monitoring may contribute to making maintenance more complex, but that the companies are not in general experiencing disadvantages because of it. The biggest challenges with CBM, based on the companies' experience, seem to be:

- Incompatibility of CM equipment
- Integration of CBM systems with CMMS

The companies are aware of the other challenges, but they seem to believe that these do not pose huge difficulties as long as you treat them correctly. The interview also reveals that most companies have experienced benefits in form of increased availability, increased maintenance awareness and reduce maintenance cost. These results should influence an increased use of CBM. The companies also state that main reason for having CM is mainly for CBM purposes.

The two main challenges above should be considered when CM solutions are selected in the future. The two challenges are related and the solutions that are selected, if they are of different products and manufacturers, should be based on common frameworks or standards. A solution to the first challenge is using standardized infra structures and equipment compatible with the infra structure. Wireless and local area network configurations exist, but these solutions are associated with the risk of being hacked, giving unrestricted access. This limits the use of these solutions and other less standard systems is more used which may explain incompatibility challenges. This a good example of the many practical challenges associated with CM. Another practical challenge is warranty and vendor requirements which limit the use of CM in many cases. These challenges illustrate the importance of having standards which cover all associated issues and not only technical and general topics. The second challenge is a software issue. The CMMS is in general an administrative software tool. This software was previously not meant to include CBM analysis functions. ISO 13374 provides a standard for the purpose of standardizing information flow within a CM system which can aid in the integration process and there is also currently much research on this issue.

The companies state that all equipment having either medium or high criticality should have CM, but this only a general strategy. Equipment having high or medium criticality should be further evaluated for CM. The survey revealed that the companies prioritize the loss of safety functions and production loss as reasons for installing CM. Goals on implementing CM should evidently contain these reasons. We see that the survey results influence CM selection to certain degree, but not specifically determining effective monitoring.

Based on the findings in the thesis there are two main methods to use when selecting CM:

1. The “IO review” methodology presented in chapter 4. This method is based on the fact that you have time constraints and limited data available when selecting instrumentation for CBM. This means that you have to use more experience and less analysis to determine what monitoring should be implemented. This methodology does not seem to be problematic as long as experienced engineers from contractor, customer, vendor and CM experts are used in the analysis and that the maintenance strategy is part of a continuous improvement process.

2. The other alternative for determining CM applicability is RCM. The survey reveals that many companies prefer to use RCM analysis or FMEA to determine applicability of monitoring and CBM and that many of them used RCM or a light RCM on their projects. To reduce the efforts of performing an RCM, they relied on creating or using generic maintenance strategies. Generic maintenance strategies are developed on the basis of experience from working maintenance strategies.

The practice from the engineering company and the ones presented through the survey therefore coincide where both of them incorporate more experience into their choices.

From reviewing the standards it appears that ISO 179359, general guidelines on CM, is the only standard that describes an overall CM selection process with recommendations to what analysis to include and specifics on applicable monitoring, if the IEC 60300 covering RCM is disregarded. The standard also describes how to operate a CM system in practice and many related activities and thereby slightly describe parts of an implementation. The associated ISO standards within CM describe specifics of monitoring techniques, prognostics, analysis and training and are relevant at a later stage than selection of CM. The IEC and NORSOK standards do not specify anything on CM equipment selection, but explains how to decide the appropriate maintenance strategy through FMEA, RCM and criticality. The API standards have detailed specifications on typical machinery and specify monitoring for the purpose of machinery protection. These standards also contain specifications on responsibilities of user and vendor. None of the standards mentions implementation entirely nor do they provide guidelines to how to develop the maintenance program in relation to CBM. The basic CBM feasibility requirements are only mentioned in the IEC 60300, which are essential when screening for CBM. The reason why specification on instrumentation for maintenance purposes don't exist may be because you cannot standardize monitoring due to big differences on equipment and installations and that appropriate monitoring can only be identified through analysis.

The companies stated that they relied on some of the reviewed standards, but they relied more on internal documentation. It is believed that the standards are used on an as needed basis and not followed to the letter. The methodology that were used by the engineering company did not seem to follow any standard and we can see that the intended purpose of standards have little effect on CM selection in the O&G industry. The standards do however mention that the standards on CM are only meant as recommendations and guidelines, not standard required procedures. This can explain why their use is not consistent in the industry and that the industry uses them only as a source of knowledge. The survey revealed that the current standards seemingly cover the needs of O&G companies, but the inconsistent use of them indicates that they should be developed further.

The survey revealed that the companies have experienced benefits with their current CM solutions and encouraged increasing use of CM. This indicates that challenges associated with increasing monitoring does not need as much focus as previously believed during the selection process. Many of them must however be accounted for when implementing the solutions through documented strategies, which many of the surveyed companies stated they did.

There exist numerous factors to account for when making sure you obtain a successful CBM exploitation and important prerequisites for a successful CBM utilization have been found to be:

- The awareness of challenges, advantages and disadvantages when implementing and selecting CM solutions
- The use of clear implementation strategies
- Clear relationship between what CM solutions are selected and why they are selected
- Involvement of all parties (contractor, vendor, operator) both during design and operation
- Effective incorporation of CBM into IO
- The use of continuous improvement in all maintenance activities
- High focus on CBM feasibility with low tolerances
- Applying CBM in accordance with established criteria, requirements and goals
- Expert CM experience

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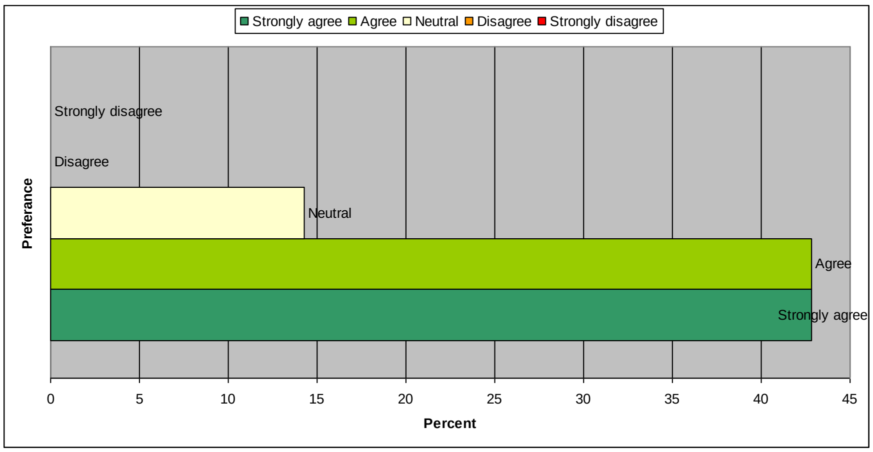
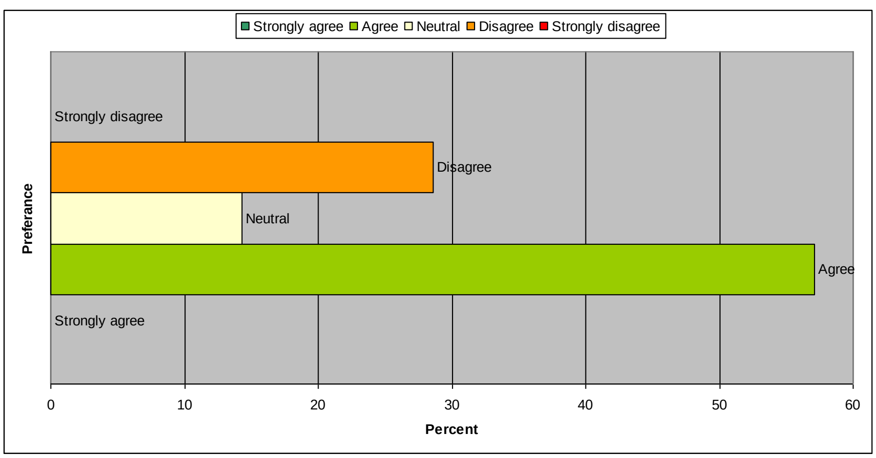
Appendix 1

Questionnaire results

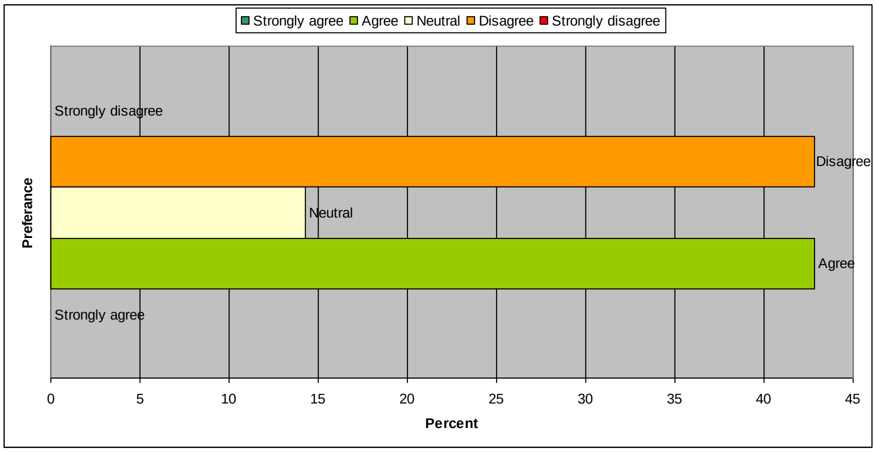
1. We have implemented Condition Based Maintenance to a large extent on our/others assets



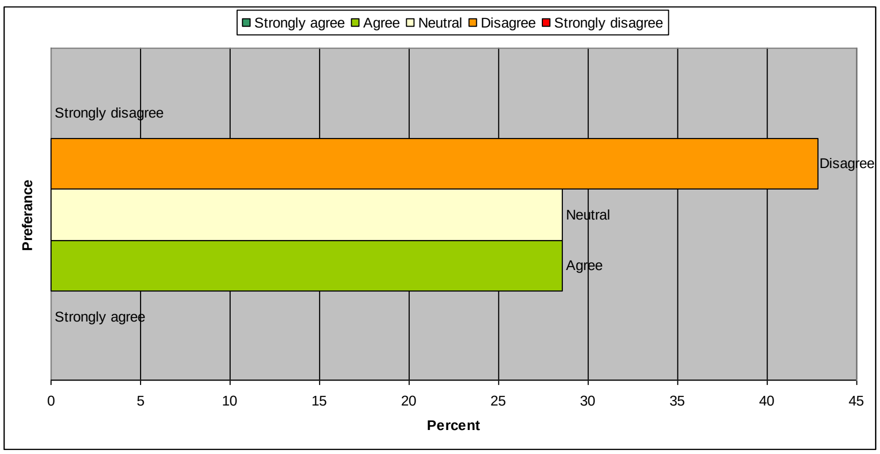
2. It is challenging to integrate Condition Based Maintenance with current Computer Maintenance Management System/SAP



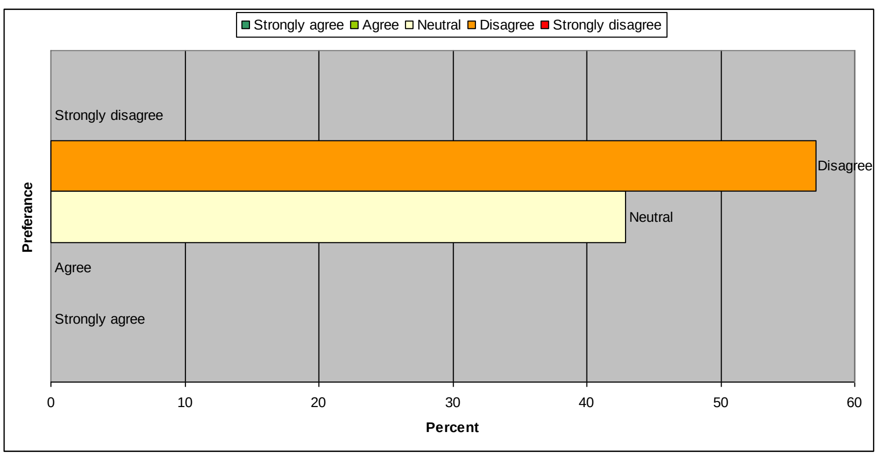
3. End user software is too complex



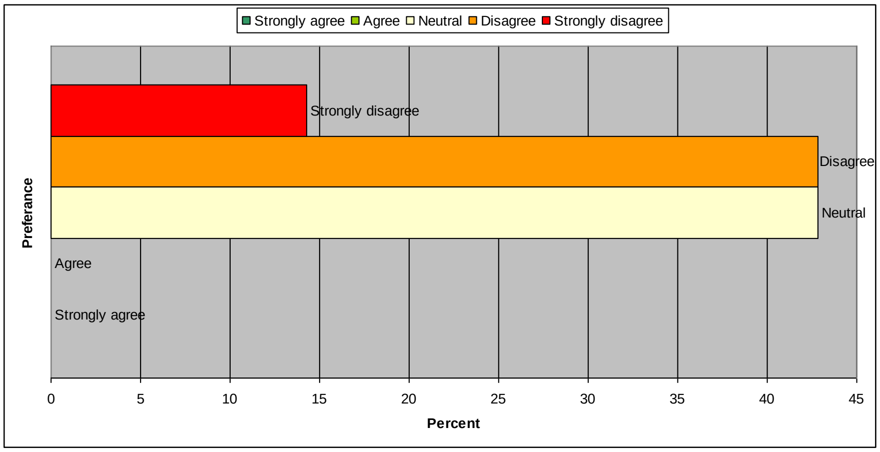
4. It is difficult to plan the maintenance work orders generated by Condition Based Maintenance



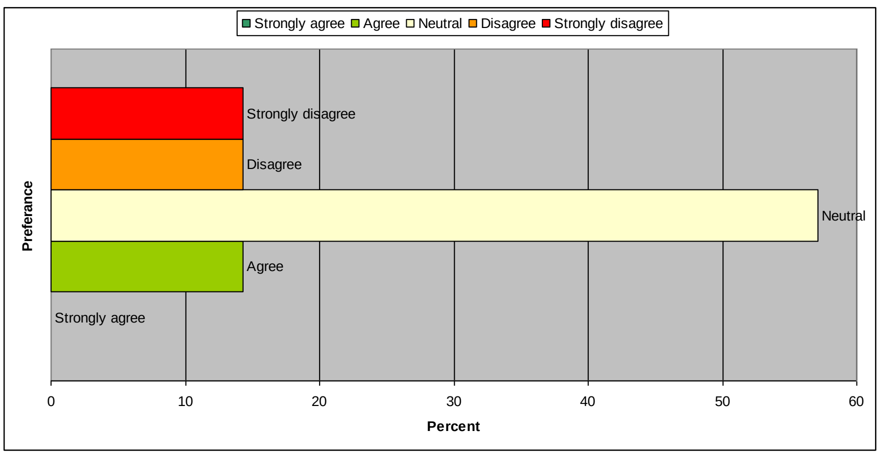
5. Condition Based Maintenance too costly to implement versus the benefits gained



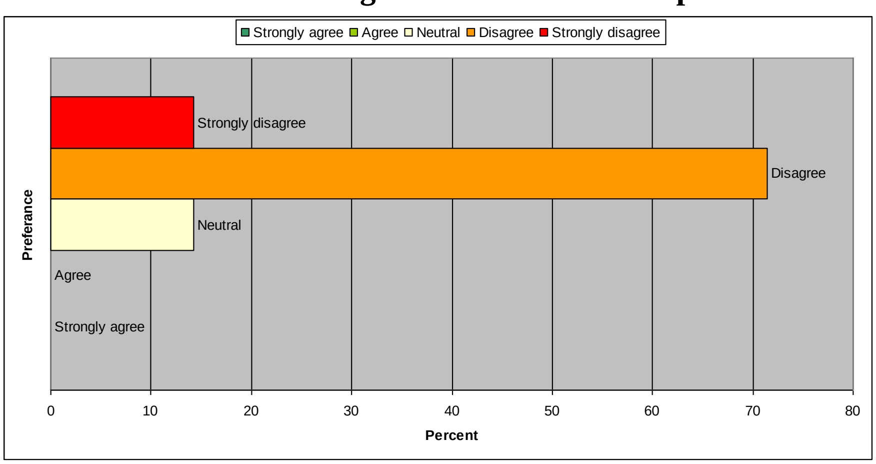
6. Condition Based Maintenance is too manpower demanding



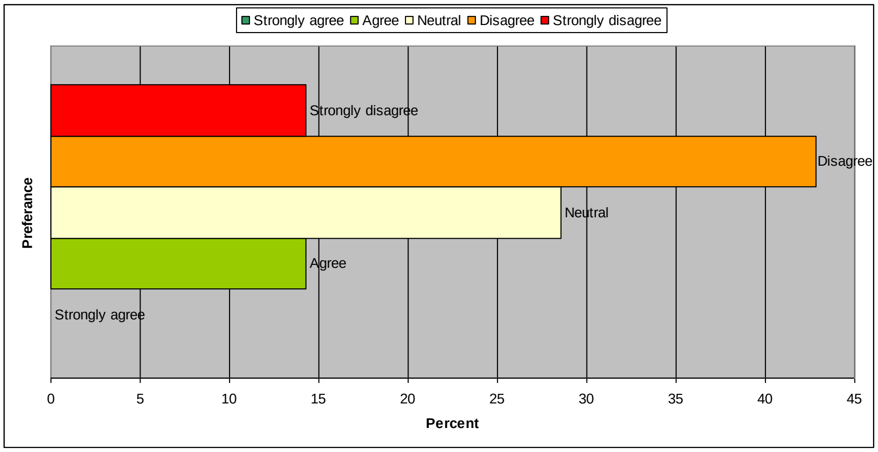
7. Condition Based Maintenance generates too much information to handle



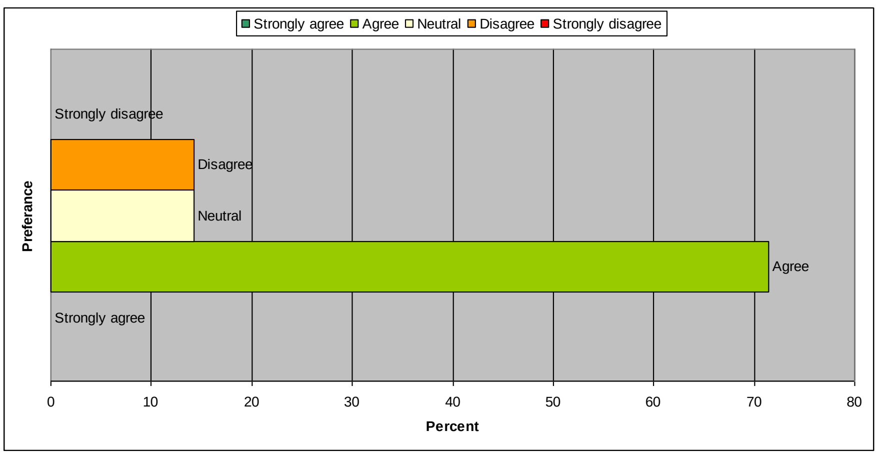
8. Condition Monitoring can detect root cause problems



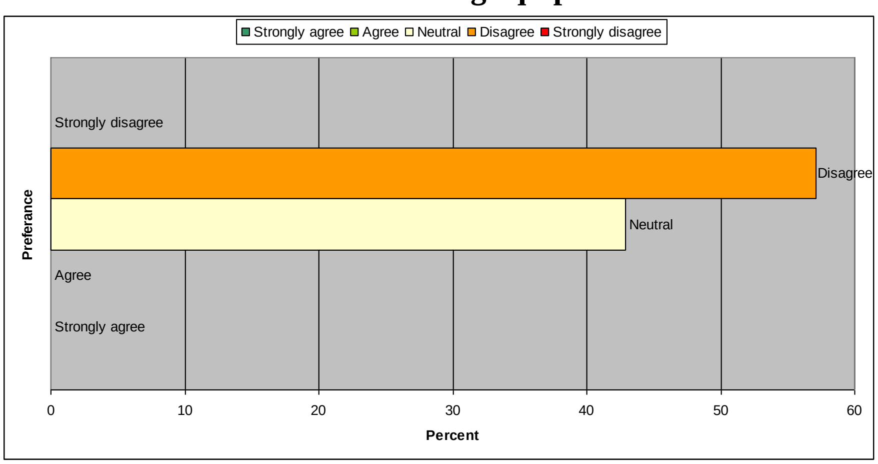
9. The international standards on Condition Monitoring do not meet my requirements and needs.



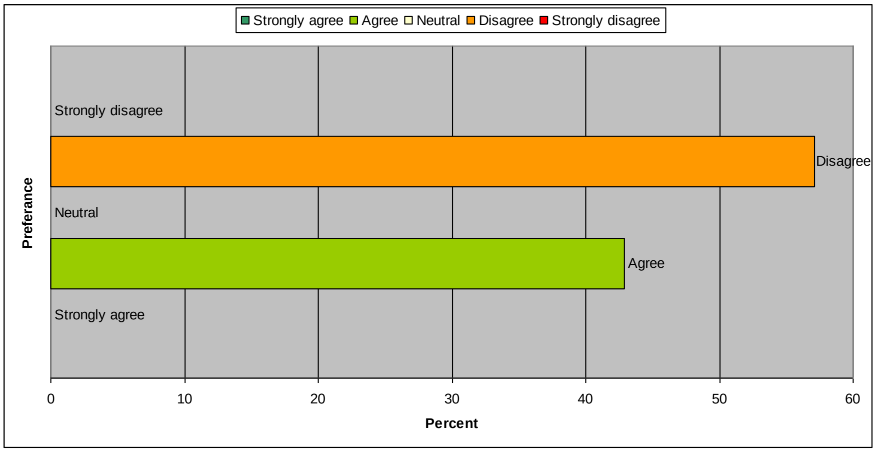
10. There are too many condition monitoring equipment vendors with incompatible products



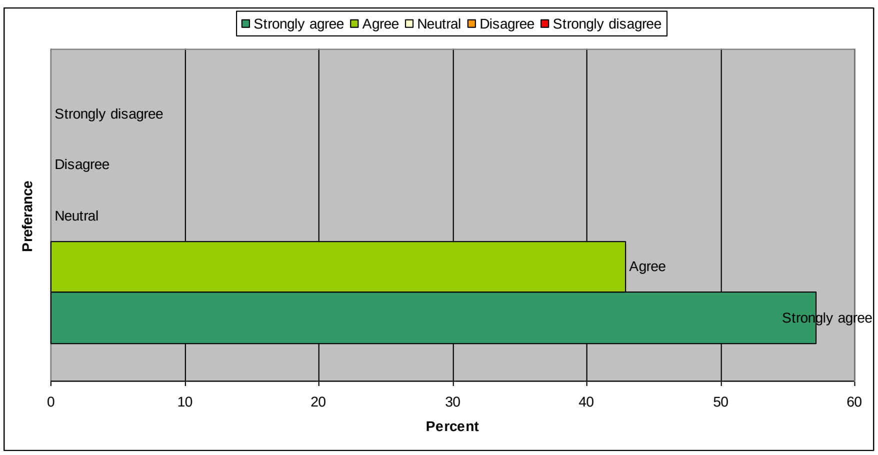
11. Sensor/transducer/monitoring equipment is not reliable



12. Analyzing the data is time consuming (frequency analysis, performance analysis, vibration analysis, prognostics etc.)



13. We encourage more use of Condition Based Maintenance on new installations and major modifications



Appendix 2

Interview

1. What type of equipment/systems is monitored on your asset? a. Is some equipment prioritized more than other? b. Is some specific monitoring prioritized more than other? c. What limits increasing monitoring?	
Operator Company 1	We have one subsea installation that we operate, which is a gas producer. This is tied up to an FPSO. It consists of one template with one well producing. It has double tubing to avoid the formation of hydrates. It has no specific monitoring instrumentation. We test the tubing by measuring pressure difference (annulus). We have scheduled testing of the downhole safety valve and other valves. Various parameters by testing give us indication of the condition and if it's functioning. So it is a corrective/condition based maintenance strategy depending on how you define it. "Pit stop" is a good metaphor for efficient maintenance. With Formula 1 racing they constantly watch for irregularities and factors that may decrease the race cars performance. When this is detected the car enters the pit stop to fix the problems. At the pit stop it is important that every activity is planned and performed as fast as possible. The same goes for maintenance. We have an installation under development which is an oil producer with gas and water re injection. It will be connected to 7-8 templates. It has internal oil storage and no drilling capabilities. It has a processing plant and 65% of the energy demand is supplied from land by electricity. You gain important knowledge through an FMECA. The NORSOK Z008 on criticality is not always that good to use. PTIL`s guidelines should be followed, but not to the letter. There are certain requirements in the standards that specify instrumentation for CM. We have used a lot of efforts to reach a high level of CM, so that IO can be utilized for its fullest potential. This has to be done through an FMECA analysis. We have CM to a large degree on rotating and static equipment. On the flow lines and riser we have no specific monitoring. We use ROV to inspect them and the templates. We use CM on equipment that has a high consequence evaluation and on safety critical equipment. Factors that limit increasing monitoring are costs versus benefits. Another factor is that maintenance engineering is involved too late during the project because the strategy is not developed earlier.

<table>
<tr>
<td>Drilling Company</td>
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We monitor equipment such as:

Thrusters
Main machinery
Derrick functions
Mud pumps
Safety systems (fire water pumps, watertight doors)
Piping

a) We prioritize thrusters at rigs that have dynamic positioning since this is vital function of the rig and safety critical systems:

Vibration monitoring; 1 rig has continuous monitoring and others have 3 month inspection intervals. Readings require identical conditions when the inspections are performed.
Oil analysis
Seal oil consumption
Lube oil consumption

It is important to account for operating conditions when the analysis is performed.

Mud pumps:

Crosshead clearance on piston pumps
Oil sampling
Performance measures

Piping:

NDT techniques based on simple RBI. 3rd party performs this using DNV inspection program

b) Competence on CBM and CM, unsystematic operation of CBM (without trending, follow up) and identifying failure modes and monitoring failure development and applying this in an FMECA. We are working on improving this but it is slow because of low competence.

We were able to double the lifetime of a thruster with CBM and achieved saving in the 100 million class. We use data from the CM to schedule restoration of the thrusters. Much has been learned over time when implementing CBM.
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Operator Company 2	a) We prioritize equipment based upon criticality: • Safety aspects • Fire hazard systems containing combustible liquids. HVAC not necessary. • Do not monitor so much safety systems and systems that are not in continuous operation, but we do inspect fire pumps e.g. once per week. • We do not prioritize simple equipment, but big and expensive equipment. b) Vibration monitoring is prioritized. c) Costs of instrumentation and maintenance of the instrumentation
CM Service Company	Almost everything is monitored and equipment monitored varies much from company to company. Prioritizing is based upon criticality. Protection systems that prevent catastrophic failure use monitoring which is also used to create CBM. a) Wireless unwired systems is preferred which are not on line because of battery usage. These systems can have inspection intervals of 1 month with a battery life of 5 years. The shorter inspection intervals create more efficient and accurate monitoring. The wireless solutions are still not state of the art, but will be. Our newest project is the first with all wireless solutions. b) There exist two types of monitoring used: • Condition monitoring of equipment for maintenance purposes • Process monitoring for optimizing efficiency c) The main limitation is cost even though monitoring equipment has become less expensive the last 20 years. The main reason is that a monitoring set up needs engineering before it is installed (feasibility analysis, P&ID`s data collection, planning etc.). These costs can be reduced with wireless solutions that also have the option to be relocated to where the need is.
Operator Company 3	a) We monitor mainly rotating machinery such as power turbines, compressors etc. Safety systems are prioritized and undergo an SIL analysis. Other equipment undergoes a criticality analysis and they prioritize depending upon criticality. b) Vibration monitoring and temperature monitoring are the most used methods. c) Too much information. Low criticality. We also use a cost-benefit strategy to determine CM.
Operator Company 4	The systems that we monitor are:

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• Our biggest turbine packages
• Production critical equipment
• Safety related equipment (firewater pumps are tested every 3 months)

We do not use criticality analysis to prioritize equipment. We know the equipment we already have very well when it comes to CBM selection. But we are working towards using criticality assessments.

We use a lot of vibration analysis where we use Bentley Nevada system 1 which we consider the industry leader. This system compares actual values against a modeled performance which triggers if the actual values deviate to a certain limit. We use this mostly on big rotational machinery.

Our installations are old and what limits increased monitoring on these installations are limited resources to do so. Installation and retrofitting is resource demanding. On new installations we have developed a philosophy on how equipment should be instrumented. Challenges on new installations are that there are many vendors which are why we are trying to standardize what we select. Another challenge is to get this work early enough into the projects.
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<tr>
<td>Operator Company 5</td>
<td>
We monitor equipment that has a high criticality. We have a goal that 60% of all maintenance hours are triggered by condition state. The specific monitoring is vendor based where the various techniques are incorporated into the equipment specifications. We have performed a full RCM analysis on our project.

A lack of monitoring techniques and that the existing techniques are not good enough limits increasing monitoring. Monitoring of separators is challenging and lacks efficient techniques, since you cannot see the inside. Another limitation is that it gets difficult to plan the maintenance work as with 60% CM triggered hours. Many maintenance activities are triggered simultaneously, which requires good preparation and planning.
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2. What is the main purpose with the condition monitoring equipment installed today?

a. Condition based maintenance (predictive maintenance)
b. Trouble shooting
c. Optimization of scheduled maintenance (preventive maintenance)
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<tr>
<td>Operator Company 1</td>
<td>
The main purpose is to identify condition degradation in time to restore and avoid the failure. It gives you the ability to take action in time. This avoids scheduled intervals. CBM is the main purpose of the CM activities. It is sometimes used for troubleshooting by storing CM information. This is done reoccurring events, trending and for larger amount of information on an as needed basis. It is important to plan what information that will be recorded. There is no point in recording a lot of data that is never used. Every activity with the implementation of CM needs to be planned and have a specific purpose. We do not have PM in addition to CM for optimization purposes. There is no point in having this.
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Drilling Company	The main purpose with CM is to get information on the equipment condition for achieving maximum availability. We use the CM to plan and schedule PDM. The CM monitoring triggers work orders. Another purpose is full surveillance of safety critical equipment. We try to optimize the maintenance by looking at recorded maintenance data, but historical data is currently not being used actively.
Operator Company 2	We use all of the alternatives in combination and also use CM for process optimization.
CM Service Company	The main purposes are: • Protection system monitoring to prevent catastrophic consequences • Condition based maintenance that prevent catastrophic breakdowns The monitoring is also used for root cause analysis and to detect and prevent reoccurring failures. The optimization of scheduled maintenance is done but very carefully. It is done on components that have clear failure characteristics such as a bearing failure. An inspection of the bearing can be deferred or canceled depending on the input from the monitoring. Maintenance activities that are not recommended to change are lube oil inspections and visual inspections.
Operator Company 3	We mainly use it for trouble shooting but also CBM to a certain degree. The monitoring is analyzed by a 3rd party CM service company in cooperation with the discipline mechanic that reports on a monthly basis. All of their monitoring equipment is on-line. The monitoring data triggers (not automatically) predetermined maintenance activities.
Operator Company 4	We use our monitoring systems to actively reveal and predict degradation in advance in order to have increased up time. It also optimizes operation. By using monitoring we plan all maintenance towards planned shut downs. On turbines we do however have requirements from the vendor that inspections should be performed every 8000 hours. It also prevents minor failures to develop into serious ones.
Operator Company 5	We regard optimization of maintenance intervals, production up time, having enough information and having pre warnings of degradation as main purposes.

3. What benefits, if any, has the currently installed condition monitoring equipment created?

a. Reduced maintenance cost

b. Increased availability

c. Increased maintenance awareness

Operator Company 1	We have a low experience because of limited CM. We should have performed a cost benefit analysis on the subsea template and analyzed the maintenance. We have certain requirements to the cost benefit. The other installation is not in production yet.
Drilling Company	CM has achieved all of the above. The cost has in general been reduced since the implementation of CBM. We have had great maintenance improvements after systematically applying first line maintenance activities. This has reduced down time by 50%. Mud pumps,

	roughnecks etc. are routinely inspected with check lists, routines every day. We also have follow ups that verify that these first line routines are performed and performed correctly. We consider this as part of CBM. We also actively record and trend availability, corrective maintenance, PM, CBM and the costs associated.
Operator Company 2	a) We have had cost reduction of maintenance costs, but on a small scale. b) The big savings comes from increasing availability. A course number on savings from increased availability lies around 500 million NOK per year for an installation. We also have a focus on regularity. c) We have had increased maintenance awareness, but it is difficult to put a price tag on savings from this factor. CM leads to an increased understanding of process and equipment. Process optimization leads to a reduction in our energy usage, less pollution and increased production that ultimately increase our revenues.
CM Service Company	We receive feedback from every triggered maintenance action to determine the cost benefit relation. a) Maintenance cost is reduced because consequential damages is prevented that often leads to long lead time, more maintenance work, lack of spare parts etc. since the consequential damage is not preplanned. The breakdown of one component can often lead to sequential damage that is far more expensive to repair. b) Planned shut downs are optimized leading to greater availability. Planning of maintenance activities generated by CM used to be difficult, but this has improved because of integrated operations where multidiscipline teams work together instead of taking care of problems separately and with having difficult lines of communication. c) Maintenance awareness is a part that comes along naturally with CM because you have more details about the maintenance operation and it creates more discussion about various issues. It also increases communication between maintenance supervisor and mechanical supervisor. We also provide continuous improvement reliability software. This software use live data to detect “bad actors” that are components leading to lowered reliability, monitor failure rate, failure intervals. It also aids in root cause analysis.
Operator Company 3	a) We do not measure the maintenance cost but acknowledge on a subjective level that maintenance cost is reduced. We plan to add maintenance cost as KPI for each equipment vendor but not directly linked to CBM. b) CM allow them us plan maintenance work against planned shut downs creating greater availability. We have not had any major problems with planning the maintenance activities. c) We have experienced that maintenance awareness is increased because CM creates the feeling of ownership for the equipment. Personnel working closely with equipment have a positive effect towards increased maintenance efficiency (experience, using their human

	senses etc.)
Operator Company 4	It has led to increased availability and increased understanding of the complexity of machines for our personnel on shore. It has led to increased savings because of short and efficient shut downs. The monitoring allows us to predict and plan all activities that will be performed during the shutdown. It has absolutely increased maintenance awareness for both offshore and onshore personnel. It makes it easier to make decisions and to take action on events that occur and it makes it easier to sell to the rest of the organization.
Operator Company 5	We are currently not in operation with our asset yet, but we have goals of increased availability. We have an internal performance indicator strategy. We also have a center in France that receive and analyze all maintenance and reliability data. We will keep track of maintenance awareness when we get into operation. We are planning to have a very low fixed staffing on our installation with 17-20 people as opposed normal staffing of around 45 people. Instead we create maintenance campaigns that are continuously planned ahead. When the campaigns are performed we staff up on required crew. This demands an efficient use of CBM. We will also have an integrated operations center onshore that supervise and monitor the asset.
4. Do you have a strategy for selecting condition monitoring equipment? If yes, please explain. a. Specific design requirements b. Vendor driven c. Defined by contractor	
Operator Company 1	We have a strategy that states that CBM is the preferred option. We use cost benefit analysis and FMECA. We request that equipment vendors to participate on the FMECA analysis. They know their equipment best. It is important with team work. The design time should also be included in this analysis. It is important to consider global/local effects of your choices. We rely on recognized maintenance contractors and use them during both operation and engineering phases. We invite suppliers of various services to partake in responsibility, risk and gains that follow CM. We seek to have many long term maintenance contracts.
Drilling Company	We decide upon criticality and input from equipment vendors. On larger equipment we use vendor standards, but with additional requirements from us. We do not use contractors for this task. All equipment is selected early in the project with small alterations further down along the project.
Operator Company 2	A maintenance strategy that is based upon criticality and FMEA analysis decides maintenance types, but not the selection of equipment. In most cases the operator company decides this sometimes with input/cooperation from us. We focus on protection systems and wireless solutions.

CM Service Company	a) We use a general global strategy for selection of CM equipment. We also develop specific CM strategies for each installation. We have certain requirements for the specification of equipment. b) The selection is vendor driven if the vendor requires it. A compressor package from GE requires the usage of Bentley Nevada CM. c) Contractor collaboration when selecting CM equipment is done to a certain degree
Operator Company 3	We have an internal strategic document that dictates what equipment should have CM and what instrumentation it requires. Much of it is built upon experience from what has been beneficial. We try to challenge our vendors to create solutions for us that they haven't thought about. There does not exist on line CM for diesel engines for example which is something we want. We are aware on selection procedures and keep this mostly in house.
Operator Company 4	We created a document on requirements based upon a market survey and what was done at another oil field. We had the following requirements: • Less staffing without routines which requires more online monitoring • Monitoring of production critical equipment (static equipment and rotating equipment) and the 60% requirement. We evaluated all equipment which created challenges in the engineering phase. • Specific engineering and not a general type which meant that all engineering were done with high detail. We were criticized on this point, but this was required because of our high dependency on CBM and other goals. The detailed engineering was performed in a cooperative fashion between the three. Much was vendor driven, but with our own specific requirements.
Operator Company 5	N/A
5. Do you have a condition based maintenance implementation strategy? If yes, please explain. a. Equipment b. Organization/work processes c. Information systems (support)	
Operator Company 1	Yes, and this is the biggest challenge with CBM which is to put it into practice. It is very important to define work processes, enable IO, have a good cooperation, define responsibilities and to put focus on the end product of CBM (condition). The SAP/CMMS system is a system for automating various processes and an administration system. For CM and CBM you need additional support systems. We rely heavily on PTIL`s maintenance management loop and if you implement this you

	have implemented CBM.
Drilling Company	We have a strategy for implementing CBM that is part of our directives and governing documentation. We have procedures on selecting equipment, failure mode analysis, cooperation with the rigs, reporting/analysis (kartsen moholt) and work processes. We have built systems on selecting CBM and PM, performing FMECA, planning. The same workflow and procedures is implemented into our CMMS. We have developed a good strategy on managing maintenance since it was launched in 2000 and we have not had a single imposition from the government. We do not use the maintenance management loop developed by the government because we find it confusing. On oil analysis we are working on a global general procedure but we have our own on Norwegian sector. The oil analysis data is recorded in a shared system.
Operator Company 2	We have developed main guidelines towards implementation, but we focus on improving the systems that are already in operation. The Gjøa field has extensive CM and we focus on keeping this system working. On turbines e.g. we have washing system that is decided by CM which we consider CBM. We use the CM system much for trouble shooting purposes to evaluate the situation and equipment condition, to decide if it is instrumentation errors, to diagnose problems etc. This information is used to plan maintenance and spare parts orders. We use CM in a combination with PDM, based on hours of operation. By using CM we increased the maintenance interval of the turbines by 6 months without having any noticeable faults, but this is as far as we can stretch it because of vendor requirements. A problem with CM is that it cannot detect all faults and the consequences of faults which need to be inspected.
CM Service Company	CBM was implemented retrospectively in the past, but are now more thoroughly planned. The CBM implementation is planned during the FEED phase taking into account factors such as equipment characteristics, reporting, IO and CMMS. The operator company decides how it's done together with SKF. It has been the big companies that have led the way when it comes to implementing CBM where small companies had to follow up.
Operator Company 3	We have an implementation strategy where equipment selection is included. Many organizations have a CBM implementation strategy and acknowledge that implementing CBM is a challenge. Details regarding the implementation (organization, work processes and information systems) lack. It is difficult to put the implementation strategies into practice. Their CBM implementation strategy is under development. There is a problem with many CM computer systems and CM vendors
Operator Company 4	We do not have any written implementation strategy but implementation is based on mainly production criticality and HES. Our people and organization are aware of in what order work is performed and what work processes are needed. We consider ourselves as very clever people. All employees have a good sense over their responsibility and discipline and we cooperate well together. Information systems are not my field.
Operator Company 5	We evaluated the standard on the equipment today and created a list of requirements. We investigated what technology existed which was discussed together with Aker Solutions. We wanted to avoid over specification that leads to retrofitting. We had high requirements, but it

	is important that we don't act as a dictator, but have a dialog on our vision. We have planned specifics of organization and work processes when it comes to CM/CBM. Offshore cooperates with onshore facilities were a limited of CM activities is performed off shore. We will have 6 technicians that perform inspections on shore. 5-6 people stationed on shore plans and prepare the maintenance campaigns. We will evaluate conditions daily. On critical systems we have are planning to have a 3rd party that evaluate CM data. Here we are planning 4-5 contractors. In SAP we want the CBM system to act exactly as a PDM system, but without any start date. That means that the intervals are open and determined by the CM and not calendar based. We will have a 1 to 1 relationship between the CM information and the work orders. All maintenance is pre planned where the CM triggers the work order. We that this will create less maintenance and we want to move away from PDM as much as possible, since PDM creates a lot of unnecessary maintenance.
6. What is the level of condition based maintenance compared to total maintenance efforts?	
Operator Company 1	It is not important to put focus on the level of various maintenance efforts. There should not be any requirements that CBM should be 40% or 60% etc. We have various tools such as criticality analysis, FMECA, risk analysis etc. that determines if CBM/CM is applicable or not. These tools together with reviewing the system will determine the correct percent. 40-50% of the equipment on our new build have CM. Reports on the effectiveness of the program is important.
Drilling Company	Very low because of conservative attitude towards CBM, but we have goals to increase CBM.
CM Service Company	Most maintenance is small activities on non-critical items and equipment which is why we have low level of CBM. We do not have any major plans on increasing the level of monitoring. We focus on improving the existing equipment systems.
Operator Company 2	CBM is on the increase while PDM is on a decrease. Expect that PDM will decrease by 7-10% per year. At a specific field the CBM maintenance has increased to 40%.
Operator Company 3	We do not have a certain number on this, but we plan to have this as a KPI. We have good history/data on work packages that is performed whether it is triggered by CBM, PDM or corrective/replacement.
Operator Company 4	We have not performed any studies that quantify this, but it is 50% if you count RBI. We have been discussing if we should perform a study on this.
Operator Company 5	Within two years we plan to have: • 60% CBM • 30% calendar based

	• 10% brake down maintenance
7. What are the main challenges with current maintenance operations? a. Can condition based maintenance solve any of these and how?	
Operator Company 1	Main challenges: • Maintain safety • Having control over mechanisms that can lead to large consequences • Barrier management as provided by maintenance • Effective interaction between offshore and onshore operations • Eliminate human errors It is important to have effective maintenance management in order to have high production availability. RAM analysis is an important tool for improving maintenance and is closely related to maintenance in three ways. Reliability has to do with the quality of the product i.e. how often it breaks down. Availability is linked to the effectiveness of the maintenance activities (includes lead time, spare part ordering etc.) and the reliability. Maintainability is linked to how efficient the maintenance can be performed. Challenges are not solved by increased instrumentation, but by effective and efficient actions.
Drilling Company	Cannot specify any specific problems, but CBM reduce a lot of unnecessary PM. It gives you valuable information about technical condition of your asset and it leads to a better condition.
Operator Company 2	Instrumentation that fails is a challenge. We should have had more instrumentation, but not everyone is comfortable with this.
CM Service Company	Question is too wide to give a good answer. This is very specific from platform to platform. They have different equipment and different maintenance issues.
Operator Company 3	Startup problems with new installations where CM data/information can help with these types of problems.
Operator Company 4	Our main challenges are that we perform maintenance too often much of it being PDM that is not necessary. We are planning to make full use of CBM and then we expect the maintenance to be reduced. We do not have much random failures because we perform maintenance quite often. The use of CBM will prove that much of the maintenance is not needed.

Operator Company 5	We believe the main challenges to be: • Logistics and control. Managing spare parts. Much time will be used on tracking down spare parts. This is the challenge with campaign maintenance. • Reducing the amount of alarms. This will be done by trending and setting warning limits our self. We will create algorithms on a set of parameters (neural network etc.). We will avoid single parameter alarms. We need to be very careful with this to avoid drowning in alarms.
8. What standards, guidelines, frameworks or strategy do you use in relation to maintenance and CM? a) ISO standards or other standards b) Internal models c) Reliability centered maintenance (RCM)	
Operator Company 1	We rely on governmental requirements and internal requirements. These are created for all installations, but we also create installation specific requirements that are adapted to the conditions. We use: • ISO3000: RCM • DNV: RBI • PTIL: Aktivitets foreskriften kap. 9 • NORSOK: Z008 • NORSOK: Z006 • ISO14224 • ISO20815 • NORSOK: Z013 • S005 • OLF080 Håndtering av iso standard We also use the MM loop very actively and this is an effective tool for managing maintenance and for having continuous improvement. The loop can be linked to CBM and guide the implementation of an effective and efficient maintenance program. The loop is linked to the ISO 9000 standard.
Drilling Company	We use the following standards: • ISO 14224 - Collection and exchange of reliability and maintenance data for

	equipment. It is recognized standard and PTIL refer to it. • ISO 17359 – Setting up condition monitoring program. • DNV – Classification requirements • ABS – Classification requirements • IEC 60300 – Contains parts of CBM We have developed our internal models quite extensively and consider them to be very good. We also focus on simplifying our models by creating generic models and templates which can have a big potential, but this is limited by big companies such as Statoil because of risk factors. We have also been in contact with a contractor for creating simplified generic maintenance models. We also utilize RCM and a full RCM on new rigs and all the processes behind IEC 60300.
Operator Company 2	We use internal models.
CM Service Company	The operator companies decide the standards and vendors and other parties have to follow them. API standards are much used. We also use a SRCM (shortened RCM) and templates if the equipment is known to reduce the amount of work. So we use internal models as well, but we do not perform these analyses too often. If is important to adapt the criticality and RCM output to changing conditions in the operations (reduced production). These processes needs to be open and reviewed.
Operator Company 3	We don't use the standards directly but our procedures are based upon ISO standards and NORSOK standards. If a generic model, which is often used, doesn't exist on the equipment a light RCM is used to determine maintenance needs. RBI analysis is used on static equipment. Our procedures are illustrated in logical flow charts to determine the maintenance needs. Failure mode characteristics are evaluated in our models.
Operator Company 4	We have internal standards that have been developed by our headquarters. We do not use RCM because our equipment is very old and that we have good experience with this. We have communicated to our contractor that we want as much CBM as possible. Our internal standards are based on the international standards. We also use NORSOK standards and DNV standards on RBI.
Operator Company 5	We have some internal guidelines and have gone through the standards. The standards related to CM have a good framework but are often outdated. There does not exist anything on static equipment such as separators yet. There is research on probes for this and there exist methods for this. We take part in developing this. • OLF112 • ISO 15926 We are working on creating a 3D model of the asset in high detail that will support maintenance operations and aid cooperation between staff on site and the IO center. This 3D

	model system will be integrated with SAP so that all relevant information about a system, component is easily available. We perform RCM analysis.
9. How are condition based monitoring data evaluated? a. Internal resources b. Third party experts c. Equipment vendor	
Operator Company 1	We have the responsibility for the technical condition, HMS and production availability and therefore prefer to do this internally. We are currently evaluating if we should involve third party experts for example on large turbines. We have not been good to involve equipment vendors. We have trouble with receiving reliability data, FMECA data and SPIR (spare parts and interchangeability records). Experience should be exchanged.
Drilling Company	Our maintenance systems have all been developed internally but in collaboration with equipment vendor (Rolls Royce), classification organizations (DNV, ABS). The condition monitoring and analysis is performed by a 3rd party (karsten moholt). Their computer systems are linked to ours. We will continue to develop our maintenance strategies internally. Expert systems: We have a positive view towards expert systems, but you have to be deliberate on what it/you do. We do have an expert system, but we are drowned in parameters. We try to develop this further. We offer good expert systems but as stand-alone systems without integration possibilities or provide packages.
Operator Company 2	We use all three of them in cooperative fashion. We use mostly internal resources for this, but we have requirements that the vendors take part in this. We have specific service agreements on CM. Expert/automated CBM systems: Can work on simple equipment such as heat exchangers and filters but not on big critical equipment. This is because these expert systems need repetitive faults that can be learned. Most faults are random and vary.
CM Service Company	Statoil – internal resources. They have their own diagnostic center. They regard this as core competency. BP – Third party experts Condition monitoring vendors and equipment vendors are normally not interested in or evaluating condition monitoring data. Expert systems/automatic CBM is not recommended now because equipment is too diverse even between installations in the o&g business. Here you need an extensive set up and these systems do not account for changing operating conditions. This is more suitable for projects that contain many of the same equipment e.g. wind turbines. But as the development of monitoring (sensored bearings which give a true reading) it can be more suitable.

Operator Company 3	We use a mixture of all three. Third party experts have the largest amount of evaluation. They use equipment vendor when they require it. They don't have dedicated CM evaluation internally, but internal functions cooperate with the others. General comments: CBM has a big potential, but the full potential is not utilized efficiently. In new projects we pursue increasingly continuous monitoring. We are skeptic to the concept of having automated generated maintenance where the computers produce all maintenance instructions to allow for less staffing at the installations. We do not support this concept. We do however support IO, but not less staffing of maintenance personnel to save expenses. It is difficult to maintain an overview of the maintenance processes with increasing automation. Having active maintenance personnel on site has a positive effect.
Operator Company 4	We use about 70% internal resources and 30% equipment vendors. We want to keep most of the control and knowledge of the asset and equipment to ourselves. General comments: We are positive to automated expert systems but want to have human involvement and not systems that automatically produce work orders that can lead to much unnecessary work. We have a system that stores all monitoring data where we have the possibility to configure the analysis ourselves. This has been a deliberate choice on our part. We are also working on improving SAP in order to integrate CM analysis programs into it. We have dedicated internal experts working together with SAP institute on development.
Operator Company 5	This will be a combination between internal and 3rd party resources. We want to have as much knowledge about the operation of the asset ourselves. We want to be sure of actual conditions and situations. We want to learn and to know indications of faults. General comments: We want to avoid removing equipment for restoration. 80% of the equipment does not have degradation when PDM is performed. We have automatic scanning systems that give alarms with not normal conditions. We are positive to try new things when it comes to CM. The CBM implementation in our organization has been difficult, but we have gained big enthusiasm know.

Appendix 3

System	System Description	P&ID / FD # (ELDS-AK-U-)	Item Category	Tag #	Tag description	Package	Criticality	Opportunities & Comments	Recommendations	Benefit/Cost (L/M/H)
010	Wellheads	00300	Choke Valve	91HCV10112	Production Choke		H	Monitoring of Cv vs theoretical Cv N/A due to insufficient instrumentation. (Applies to all chokes on wellhead east [typical P&ID]).		
010	Wellheads	00300	On/off valve	91HV10117/19	Production on/off		H	Exposed to scaling.	To be included in on/off valve study (Applies to all on/off valves on wellhead east (P&ID is typical).	
010	Wellheads	00301	Choke Valve	91HCV11612	Production Choke		H	Monitoring of Cv vs theoretical Cv N/A due to insufficient instrumentation. (Applies to all chokes on wellhead west [typical P&ID]).		
010	Wellheads	00301	On/off valve	91HV11617/19	Production on/off		H	Exposed to scaling.	To be included in on/off valve study (Applies to all on/off valves on wellhead west (P&ID is typical).	
010	Wellheads	00351	Choke Valve	91FV13025	Water injection flow-valve			1-phase liquid through valve. Flow measurement, and PT's available.	Monitoring of Cv vs theoretical Cv should be implemented.	H
010	Wellheads	00352	Choke Valve	91FV13625	Water injection flow-valve			1-phase liquid through valve. Flow measurement, and PT's available.	Monitoring of Cv vs theoretical Cv should be implemented.	H
110	Production manifold	00405	Separator	95-00001	Production separator		H		Company to decide if a solution for Tracer Injection shall be implemented.	
110	Production manifold	00405	VIEC		VIEC				Condition parameters shall be available from the local VIEC PC (if VIEC is installed).	
140	Test manifold	00410	Separator	95-00002	Test Separator		H			
200	Separation gas	00430	Heat Exchanger	41-00001	Gas Cooler			Flow available on gas side. T on all lines. dP on gas side to be computed based on separator inlet gas pressure and scrubber downstream pressure (minus the mesh internal dP).	Performance monitoring to be facilitated for.	H
200	Separation gas	00431	Scrubber	95-00003	Gas Scrubber		H		Company to decide if a solution for Tracer Injection shall be implemented.	
200	Separation gas	00432	Centrifugal Pump	67-02003/4	Condensate Recycle Pumps			Flow measurement missing. Implementation of performance monitoring of these small pumps is not considered cost-effective.		
270	Gas Injection	00450	Electrical Heater	27-02101	Gas Recovery Heater		L	Heater is not critical but frequently in use.	Possibilities for condition monitoring to be investigated with supplier.	
430	Separation oil	00490	Centrifugal Pump	67-02001/2	Production Pumps		H	Large pumps w/VSD. 2 x 100% (only 1 pump running at a time). Flow measurement + P2 available. P1 to be computed based upon oil outlet line from prod.separator. Needs to be corrected for altitude difference (density from Fiscal) and est.friction loss.	- Performance monitoring to be implemented. - Vibration monitoring on motors to be implemented. - Perf.monitoring of motors to be investigated.	H
430	Separation oil	00490	VSD		VSD		H	VSD's on 67-02001/2.	Monitoring solution to be considered.	M/L
180	Produced Water	00419	Filter	35-00011/2	Produced water filter		H	Critical filters. Flow+dP available.	Monitoring of clogging to be implemented.	H
180	Produced Water	00419	Hydrocyclone	35-00001/2	Hydrocyclone		M	Sample points upstream and downstream for off-line performance monitoring.		
180	Produced Water	00422	Heat Exchanger	41-00002	Reject Cooler		L	Cooler is uncritical but exposed to fouling. Fluid compositions vary alot which makes performance monitoring difficult.		
180	Produced Water	00423	Separator	95-00005	Reject Separator		H	- Sampling stations at various levels for sampling and removal of heavy oil build-up in interface area. Off-line follow-up. - Potential bottle neck in system 180.		
180	Produced Water	00424	Centrifugal Pump	67-02044/5	Reject separator oil pump		M	Critical but small pumps fully instrumented for performance monitoring. FCV opens at certain pressure, criteria for performance monitoring is that FCV is closed.	Performance monitoring to be implemented.	H