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Preface

This master thesis was executed during the spring 2011 as a part of the master degree in Industrial Asset Management at the University of Stavanger. The work was carried out at Aker Solutions, which has been a valuable partner during this project.

A would like to thank my supervisors Rune Folstad and Jan Dybdal from Aker Solutions for their valuable knowledge, guidance and supervision. I would also like to thank my supervisor at the University of Stavanger, professor Tore Markeset for his valuable guidance.

I am especially grateful to Tom Svennevig for being my initial contact at Aker Solutions.

Finally I would like to thank my girlfriend and my family members for always being there for me and supporting me.

Abstract

During the last decade, condition based maintenance and condition monitoring have experienced a growing area of application. Along with the introduction of Integrated Operations (IO) in the Norwegian oil and gas industry, new opportunities in maintenance management emerged and IO became an important driving force for increased use of condition-based maintenance. Although CBM has a wide area of application, it will not be suitable for all equipment types in a process plant. CBM has to be feasible and cost-effective in order to be the preferred maintenance type. The main objective for this master thesis has therefore been to create a methodology for selecting equipment suitable for CBM during the project phase. The methodology is focusing on describing the work process to ensure a qualified and documented specification of equipment/systems suited for CBM, as part of the maintenance engineering. Although condition monitoring instruments can be installed on almost every piece of equipment, this thesis will focus on where CBM actually can create value.

Introducing condition based maintenance leads to new challenges within maintenance engineering. Both opportunities and challenges with CBM have been discussed. CBM offers potential benefits such as increased system reliability and availability, more cost-effective and a reduced number of maintenance actions. The potential challenges are technical complexity, organizational changes, responsibilities, competence, requirement for outsourcing and maintenance planning.

The success of CBM relies on multiple factors from design of sensors to the end-user’s work process. The use of condition monitoring will require focus with regards to the interaction between human, technology and organisation. In order to establish a methodology, decision criteria for selecting CBM have therefore been reviewed. The primary criteria that have been discussed are that CBM should be feasible, beneficial and cost effective. These criteria create a basis for the methodology.

The methodology is designed to provide input to both the maintenance program and the equipment/system design. The timing of performing the specification methodology has therefore been discussed. The analysis should be performed early enough to provide input for detail design and late enough to ensure proper data for performing the methodology. At an early stage of a project traditional methods such as RCM have been regarded as too demanding. A simplified, but still a qualified and documented methodology has therefore been developed. The methodology involves processes like data collection, criticality screening, technical feasibility and cost-benefit evaluation.

CBM puts more responsibility on the vendors to deliver support documents such as FMECA and to propose technical solutions for condition monitoring, including a proposal for condition based maintenance program. A short description of the operational implementation of CBM is also presented, but is not emphasized. Here, the challenges of planning maintenance actions will be an important issue. Other implementation issues such as vendor involvement and service agreements have also been briefly described.

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List of definitions and abbreviations

Term	Definition	Reference
Availability	“Ability to be in a state to perform as and when required, under given conditions, assuming that the necessary external resources are provided”	(BS EN 13306:2010)
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)
CMMS	Computerized Maintenance Management System: a system that can provide important information that will assist the maintenance management in planning, organising, and controlling maintenance actions.	(Kumar et al., 2000)
CM	Corrective Maintenance: “maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function”	(BS EN 13306:2010)
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)
Failure mode	“Manner in which the inability of an item to perform a required function occurs”	(BS EN 13306:2010)
Failure	“Termination of the ability of an item to perform a required function”	(BS EN 13306:2010)
FMECA	Failure Mode Effect and Criticality Analysis: “Quantitative method of reliability analysis which involves a fault modes and effects analysis together with a consideration of the probability of failure modes, their consequence and ranking of effects and the seriousness of the faults”	(BS EN 3811:1993)
Functional failure	A functional failure is the inability of a component to provide a defined performance standard	(Bloom, 2005)
KPI	Key Performance Indicator: “A KPI is the measure of performance associated with an activity or process critical to the success of an organization”	(Bower, 2003)
LCC	Life Cycle Costs: “All of the costs generated during the life cycle of the	(BS EN 13306:2010)

	item”	
Maintainability	“Ability of an item under given conditions of use, to be retained in, or restores to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources”	(BS EN 13306:2010)
Maintenance strategy	“Management method used in order to achieve the maintenance activities”	(BS EN 13306:2010)
MTTF	Mean Time To Failure: “MTTF represents the expected value of a systems time to first failure”	(Kumar et al., 2000)
P-F interval	The interval between a detectable potential failure and the point where it degrades to a functional failure	(Moubray, 1997)
Potential failure	“Potential failures are incipient equipment failures”	(Bloom, 2005)
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)
Predictive maintenance	“ Condition based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item”	(BS EN 13306:2010)
Reliability	“Ability of an item to perform a required function under given conditions for a given time interval”	(BS EN 13306:2010)
Repair	“Physical action taken to restore the required function of a faulty item”	(BS EN 13306:2010)

1. Introduction

1.1 Problem description

The main objective for this master thesis is to develop a methodology for selecting equipment suitable for CBM as part of the maintenance engineering during a project. Along with the development in technology, condition monitoring and CBM has a growing area of application. However, CBM will not be suitable for all types of equipment. There are many different factors to consider and a work process to ensure a qualified and documented selection of equipment/systems suited for CBM should be developed. The opportunities and challenges with the use of CBM should therefore be discussed in order to recognize the advantages and disadvantages when considering CBM. Subsequently, important selection criteria for CBM will be addressed. Finally, a methodology for selection of equipment suitable for CBM will be developed. The methodology should be applicable for an early project phase in order to provide input for detailed design and maintenance program development.

1.2 Limitations

The context in this thesis will be maintenance engineering for a typical Oil and Gas process plant. The focus on data management as well as the cost-benefit aspects will not be the most central parts of this master thesis. The focus will be on engineering aspects in early project phase. Maintenance planning and execution will not be emphasized, but end-users of CBM will be discussed.

1.3 Methodology

In order to complete this study, relevant information to address the subjects have been collected. Information is collected from internal Aker Solutions documents and presentations, journals and other academic literature (books) available at the University of Stavanger, magazine and articles and internet databases. Discussions with my supervisors at the University of Stavanger and at Aker Solutions have also contributed to a great deal of the relevant information.

1.4 Background

Condition Based Maintenance (CBM) is an increasingly used maintenance type in the Oil & Gas sector. A reason for this is CBM`s potential benefits, such as improved system reliability, more cost effective over time, and there is a opportunity for reduced number of maintenance operations (IAEA, 2007). The rapid development of information technology the last decades has resulted in many new interesting opportunities. During 2004-2005, The Norwegian Oil Industry Association (OLF) was an important driving force for the introduction of a new kind of working process based on communication technology, which was called Integrated Operations (Kobbacy & Murthy, 2008). Integrated Operations provided new and interesting opportunities in maintenance engineering, and was an important motivation force for the increased use of Condition Monitoring and Condition Based Maintenance (Kobbacy &

Murthy, 2008). CBM has traditionally been used for heavy rotating machinery and in high risk environments, but as a result of the rapid development in technology, today there are almost no limits for the area of application (IAEA, 2007). Even though CBM has many advantages, there are still many challenges. The challenges on the technical side in one thing, but just as important are the organizational and managerial challenges that occur when there are changes in how the maintenance is done. Robustness, system performance, criticality, competence, complexity, resources and workload are just some of the factors that may have to be considered. As the degree of condition monitoring increases, challenges may appear and maintenance management gets more complex.

1.5 Maintenance Management

Maintenance management is a term used to describe the activities to ensure that the assets operate at the required state and that maintenance is performed in order to achieve continuous improvements in reliability, maintainability and availability. BS EN 13306:2010 defines maintenance management 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”. Maintenance management can be done in three different levels (Kobbacy & Murthy, 2008):

- The first level is dealing with the formulation of the maintenance strategy so that is consistent with the other business strategies within the company.
- The second level is planning and schedule maintenance in order to ensure efficient maintenance operations.
- The third level is related to the execution and collection of data from the maintenance actions.

As maintenance has been an increasingly important discipline the last decades, improvement of the maintenance management have been the focus of attention. A common model for maintenance management today is one developed by the Norwegian Petroleum Directorate (NPD). The maintenance management model is shown in Figure 1-1.

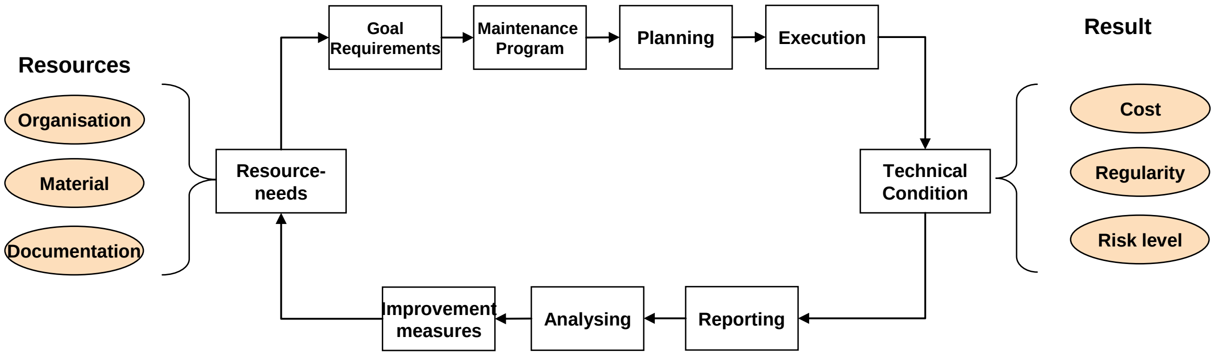

Figure 1-1. Maintenance management process (NPD, 1998)

This process covers the maintenance management process from design to the end of the lifetime of the asset.

1. *Goal and requirements:* Both the organization demands and the regulatory demands must be taken into consideration in order to develop the goals and requirements.
2. *Maintenance program:* Establishment of a maintenance program in order to ensure that the maintenance activities are performed in a safe, efficient and cost-effective way. A maintenance program should include maintenance tasks, intervals, resources, documentation and spare parts.
3. *Planning:* All the maintenance activities should be carefully planned. The maintenance activities is planned both in long-term and short-term as well as the work orders are managed.
4. *Execution:* The execution of the maintenance tasks has to be prepared and implemented and the data after the execution must be registered.
5. *Reporting:* The executed maintenance, technical condition, costs, regularity and risk should be reported.
6. *Analysing:* The reported data should be analysed in order to see if there are any improvement potential.
7. *Improvement measures:* In order to improve the work processes improvement measures are implemented.

During the process there will be a need for different kinds of resources. There are mainly three main types of resource needs: organizational, material and documentation. The result from the process is measured in terms of the assets technical condition and the related costs, regularity and risk level.

In order to ensure proper maintenance management, a proper maintenance strategy should be developed. Figure 1-2 illustrates the maintenance hierarchy. A maintenance strategy should give guidelines and requirements for how the maintenance should be performed. The maintenance activities should be performed in such a way that the organization's business goals are fulfilled. The business strategy including the business goals creates an important basis for the maintenance strategy. As well as the business strategy, the organization's maintenance philosophy and the maintenance goals and requirements will also be important when developing a maintenance strategy. The maintenance strategy will consist of different maintenance types. These will be further described in chapter 2.4 and 2.5.

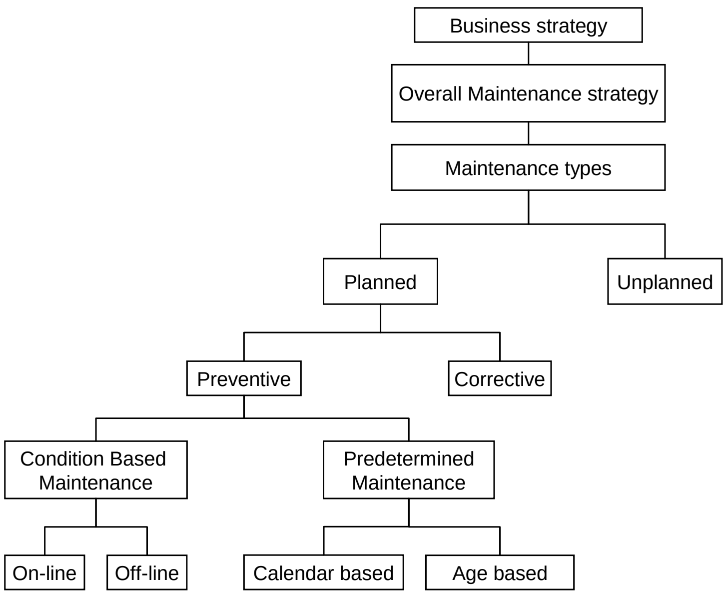

Figure 1-2. Maintenance hierarchy.

In a typical process plant there is a large amount of equipment to be maintained. The different equipment has different needs, and the best solution will therefore be to use a combination of different types of maintenance. The maintenance management process in figure 1-1 is mainly related to the operational phase. The focus in this paper will be the maintenance aspects in the project phase, which includes the design process and construction of new installations as well as modifications of existing installations. While the operational phase includes all the work processes in the maintenance management process, the project phase is mainly focused on the two work processes "Objectives & requirements" and "Maintenance program" as shown in figure 1-3.

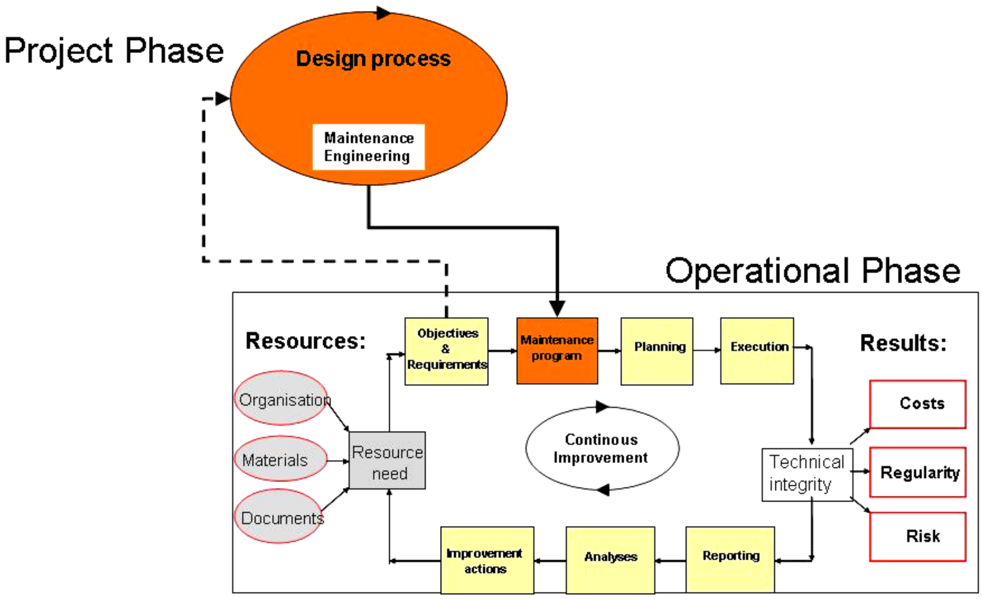

Figure 1-3. Project phase in the maintenance management process (Aker Solutions, 2010b)

1.6 Integrated Operations (IO)

Integrated Operations in the oil & gas industry, refers to new working processes for performing oil & gas operations, which has been facilitated by information and communication technology. IO integrates personnel, work process and technology in order to improve the overall value. The Norwegian Oil Industry Association (OLF) has been an important enthusiast for introducing IO to the Norwegian oil & gas sector. There are three key elements included in Integrated Operations (OLF, 2006):

- Utilization of Information Technology
- Modified work processes
- Changing the organization

People at different locations can interact with one another, and the use of information technology provides the users with new functionalities, a larger degree of automation, real-time data and collaborative technologies. This is illustrated in figure 1-4. IO provides more effective work processes and has a potential to provide more smart solutions. It makes it easier to allocate the tasks between onshore, offshore and vendors. (OLF, 2006)

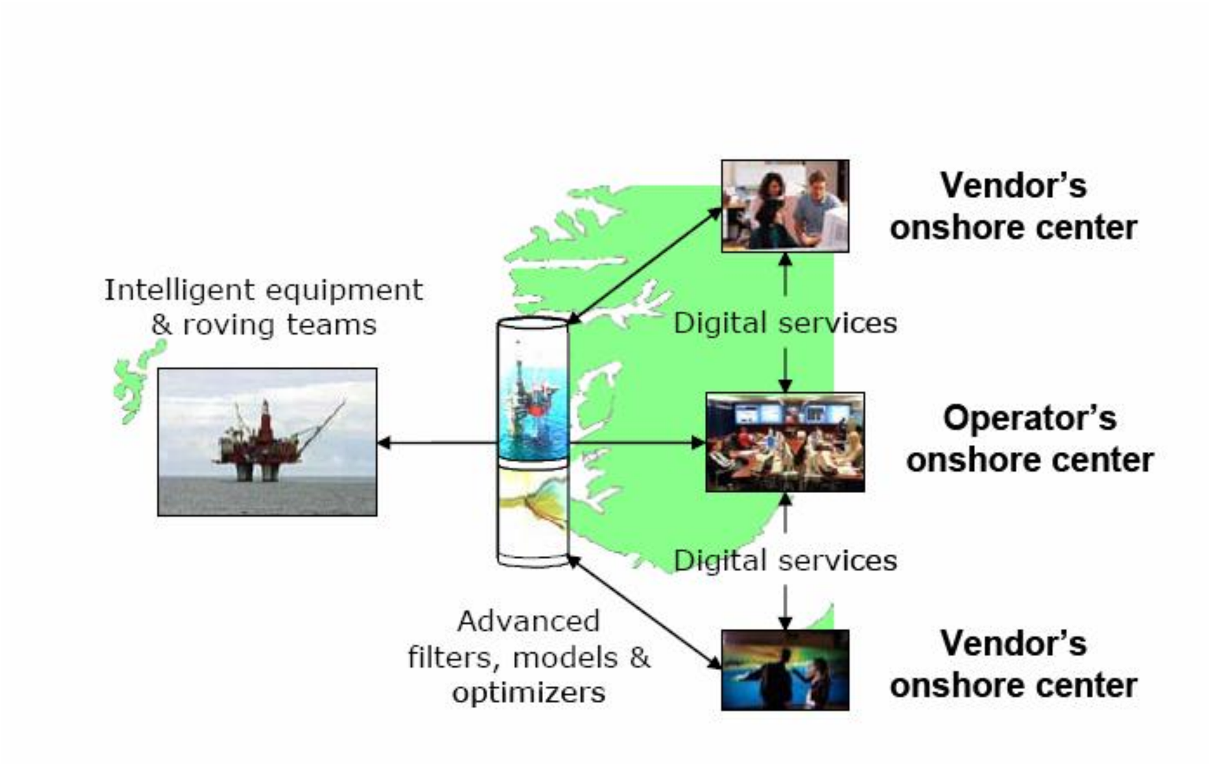

Figure 1-4. Concept of Integrated operations (OLF, 2003)

IO provides new and interesting opportunities in maintenance engineering, and is an important driving force for the increased use of Condition Monitoring and Condition Based Maintenance (Kobbacy & Murthy, 2008). The benefits of IO include increase in production level, increase in oil & gas recovery rate, reduced drilling costs and reduced operation and maintenance costs (OLF, 2006). The reduction in operation and maintenance costs can be seen as a result of better monitoring functions, increased uptime, remote control, and new ways of allocating and coordinate activities across the participants (OLF, 2006). CBM has to be seen in relation to the possibilities IO provides and that CBM is an important contributor to make IO a beneficial work process.

2. Maintenance Engineering

2.1 General

The general maintenance objective is to “keep optimum production level at lowest possible cost without compromising HSE” (Aker Solutions, 2010b). Maintenance engineering is a discipline where engineering concepts are applied in order to achieve this objective through criticality analyses, maintenance analyses and development of maintenance programs (Mobley et al., 2008). The function of maintenance engineering is to ensure that problems are identified and that appropriate actions are taken when problems take place (Mobley et al., 2008). As previously mentioned, this paper will focus on the maintenance engineering in project phase, as shown in figure 2-1.

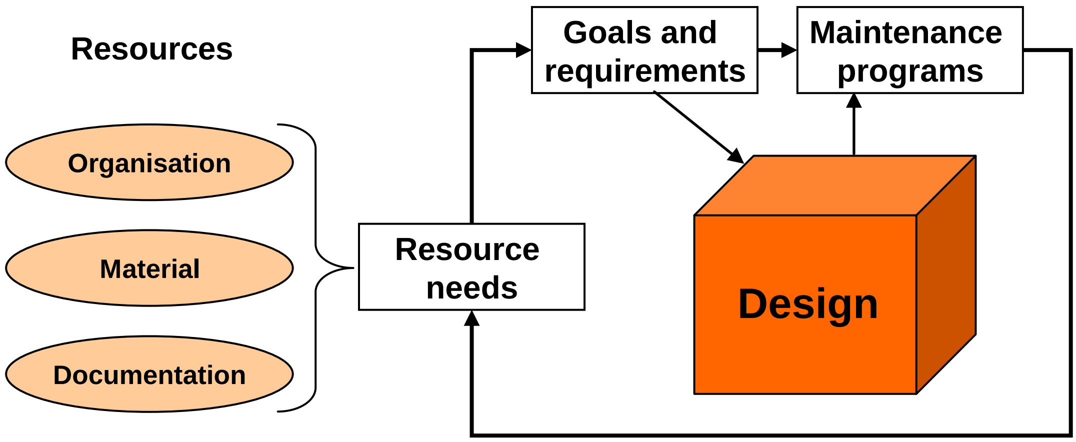

Figure 2-1. Maintenance engineering in project phase. (Aker Solutions, 2009)

Maintenance engineering in project phase includes establishment of goals and requirements, evaluation of the design solutions, and establishment of maintenance program, as shown in figure 2-1. Maintenance engineering is concerned with performing criticality analyses, maintenance analyses and developing maintenance programs. Due to authority requirements, maintenance engineering is always performed, and may be performed on new-builds or modifications of Oil & Gas facilities, but is also performed on assets during operations for optimization (Aker Solutions, 2010b).

The goals and requirements for maintenance should be clearly identified before starting a project, and may be based on authority requirements, design basis, Life Cycle Costs (LCC), maintenance strategy and operational experience. Evaluation of the design solutions within maintenance engineering is mainly focused on assuring adequate maintainability. Aspects such as material handling, access to equipment, preparation, resource need and working environment is considered as important in the design process. As figure 2-1 shows, goals and requirements as well as evaluation of design solutions are important for establishing a maintenance program. In chapter 2.3, a typical maintenance engineering work process for establishing a traditional maintenance program will be presented. In order to ensure that the design is optimised with high production efficiency and efficient capital investment RAM (Reliability, Availability, Maintainability) studies are executed. These analyses include a systematic evaluation of the maintainability, availability and reliability of equipment and systems in design phase (Aker Solutions, 2009).

2.2 Equipment in a typical O&G process plant

As mentioned, the context in the thesis is an oil and gas process plant. In such a process plant there will be huge amount of equipment. In this section the major types of equipment will be mentioned.

Rotating equipment

Rotating equipment is mechanical equipment that is used to move substances. This could be gas, liquid or solid. In an Oil and Gas process plant there is large amount of different rotating equipment. The major rotating equipment is:

- pumps
- compressors
- turbines
- blowers
- gears
- engines
- generators

Static equipment

Static equipment, as the name implies, is equipment that is stationary and that do not move any substances, but are still helpful in many process operations. Typical static equipment in an oil and gas process plant is:

- heat exchangers
- pipes
- tanks/vessels
- separators
- hydro cyclones
- scrubbers
- valves

Typical EIT equipment/systems

In an oil & gas process plant there are various electrical distribution, instrumentation and telecommunication (EIT) systems. Typical equipment/systems are:

- Safety and Automation System (SAS)
- Public Address (PA) systems
- Fire & Gas detection
- Transmitters (intelligent)
- Circuit breakers
- Heaters
- Uninterrupted power supply (UPS)
- Telecommunication surveillance and monitoring system (TSM)
- Switchboards
- Electrical motors

2.3 Preparation of a maintenance program

In order to ensure that the integrity of an asset is controlled, a maintenance program is developed. When introducing CBM, some changes and special considerations related to the maintenance engineering process may be done. The main objective of this thesis will be to identify these challenges and special considerations. It is therefore important to challenge the traditional maintenance engineering process in order to identify these changes. A traditional maintenance engineering work process in order to establish a maintenance program is shown in figure 2-2. The main activities will be shortly described below.

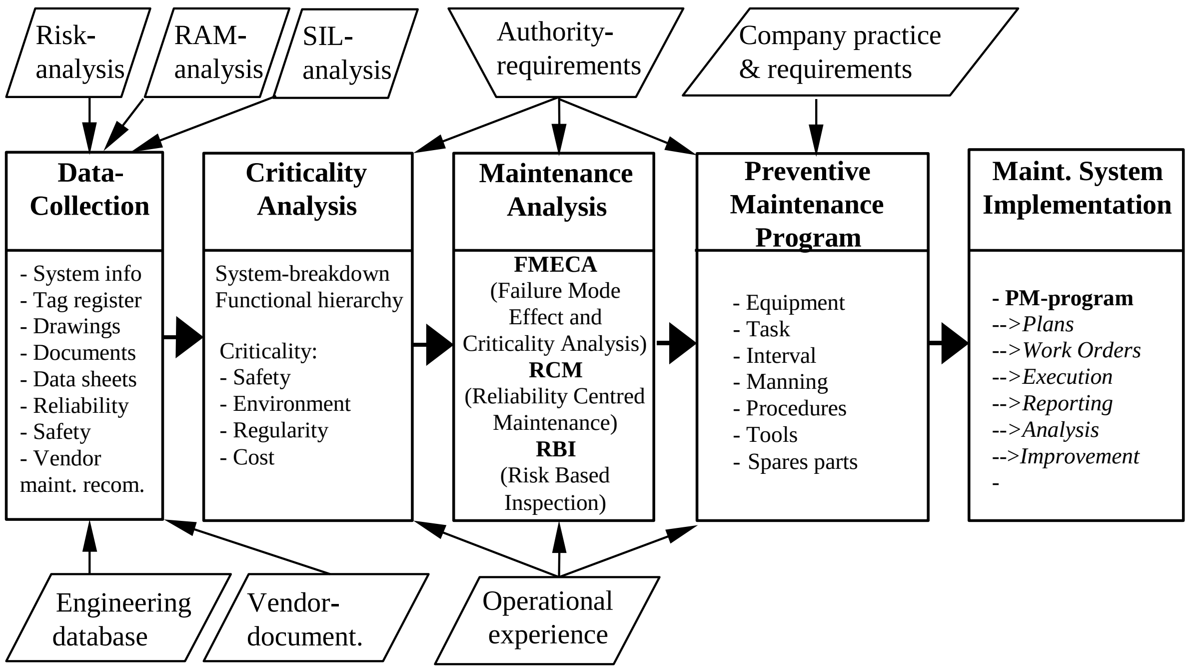

Figure 2-2. Maintenance engineering work process (Aker Solutions, 2010b)

2.3.1 Data Collection

The first activity in this process is gathering data and documentation on the equipment and systems. Input from different analyses and databases provide important information that creates a basis for the following activities. Important kinds of data are (Aker Solutions, 2010b):

- Operator data
- Engineering data
- Vendor data

Client data includes maintenance requirements, existing maintenance programs and generic concepts. Engineering data is related to tag register, P&IDs and other technical drawings. The vendor will provide equipment data, which includes design drawings, data sheets, user manuals and maintenance instructions.

2.3.2 Criticality Analysis

Criticality analysis is a classification of functional failures with regards to consequence for safety, environment, production and costs. Criticality analysis is performed in order to classify the systems and equipment for maintenance purposes. A risk ranking will therefore be an important prioritisation basis for the establishment of a maintenance program. Criticality analysis is often based on Norsok standard Z-008. This standard calls for criticality classification and ranking of equipment with regard to the consequences of functional failures (Aker Solutions, 2010a).

2.3.3 Maintenance analysis

Once the equipment and systems are classified, the next step in the process is using different methods for deciding what kind of maintenance that should be performed. Maintenance analysis includes methods such as Failure, Mode, Effect and Criticality Analysis (FMECA), Reliability Centred Maintenance (RCM) and Risk Based Inspection (RBI).

Risk Based Inspection (RBI) is a method for planning inspections based on risk quantifications of the systems. The inspection efforts are prioritized by the importance and the different deterioration behaviours of the components. RBI will not be relevant for this report, and will therefore not be further described.

Reliability Centred Maintenance is a method used to determine the maintenance requirements of equipment. The system functions, their failure mechanisms, and the criticality are carefully analyzed in order to provide a good foundation for the maintenance program (Bloom, 2005). Failures develop with different failure mechanisms and consequences, it is therefore necessary to analyze these in order to fully understand how to perform maintenance. The method is well established and is used as a starting point in defining the maintenance needs (Bloom, 2005).

RCM is a time- and resource consuming process and a selection of systems/equipment to be subject to RCM analysis therefore has to be performed (Aker Solutions, 2010a). This is often referred to as a screening process. A screening process for selecting RCM objects focus on identifying critical components important to safety, availability, reliability and maintenance costs. Based on the criticality analysis in the engineering work process critical components may be identified. Equipment with high criticality will be prioritized, but high technical complexity and high maintenance costs are important selection criteria’s as well (Aker Solutions, 2010a). RCM analysis is typically performed on new complex equipment. Existing equipment has usually been through a RCM analysis before, and will usually not be subjects for a new analysis (Aker Solutions, 2009). The items that are not subjects to RCM, is allocated to a PM program by making use of current practices and vendor recommendations.

Once the RCM objects are identified, a RCM analysis is performed in order to decide maintenance activities for the maintenance program. The main elements of a RCM analysis are FMECA and a decision logic. The motive for performing these activities is to identify the potential failures, how these errors will affect the system and how to establish effective maintenance actions in order to prevent or control these failures (Aker Solutions, 2010a).

A *FMECA* is an analysis method that helps identifying the potential failures and how these errors will affect the system. The analysis identifies the failure modes, effects, criticality and failure causes. The analysis starts with defining the system with the equipment functions and constructing the function hierarchy (Houmstuen, 2009). Then the failure modes and the related effects are identified before the severity of the failure modes is categorized. The FMECA also provides information of the probability of occurrence of the failure modes and an evaluation of the significance of the different failure modes (IAEA, 2007).

The maintenance types to be performed are further investigated in the decision logic, see figure 2-3. In the decision logic phase the detectability of failure and failure characteristics are used in order to define the maintenance type. Whether CBM, corrective maintenance or periodic maintenance is suitable for the specific failure mode is decided. The decision logic intends to ensure an optimal mix of different maintenance types (IAEA, 2007).

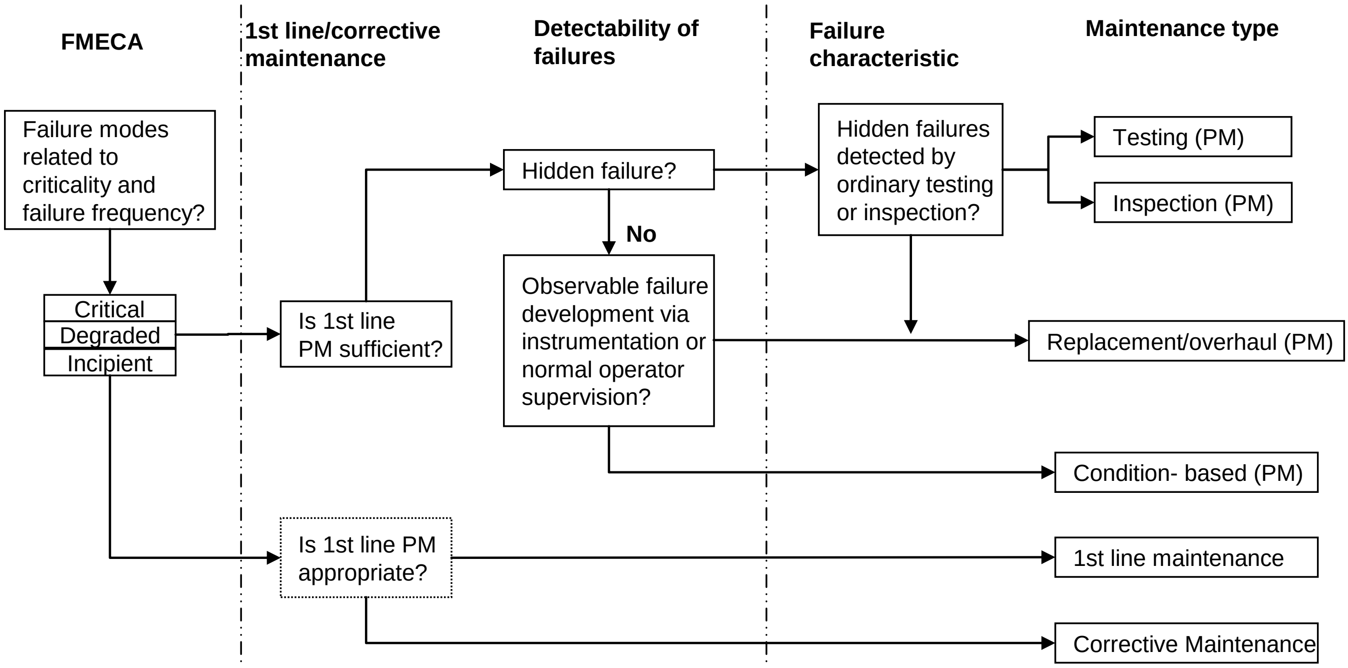

Figure 2-3. RCM decision logic (Aker Solutions, 2010a)

RCM with FMECA is a very good method for identifying which maintenance type that is suitable for each component. But RCM is normally used at component level, and would not be efficient at a facility level with numerous components. In O&G process facility the number of components is so high that performing a RCM analysis would not be efficient for all equipment. The process would be too complex as well as it would be a time- and resource consuming process. A simplified RCM process may therefore be needed in order to make use of the method at facility level. This simplified process will concentrate on asking important questions that has to be taken into consideration when selecting equipment suitable for CBM.

2.3.4 Maintenance program

The three prior activities have created a basis for designing a maintenance program. The selected maintenance tasks are then carefully planned in order to ensure that the activities is done efficiently. Then the maintenance work is scheduled, so that maintenance is done at the right time (Tomlingson, 1998). The equipment, the maintenance tasks, the maintenance intervals, the resources, procedures, tools and spare parts should be addressed in a maintenance program. Figure 2-4 illustrates an example of how a typical maintenance program looks like.

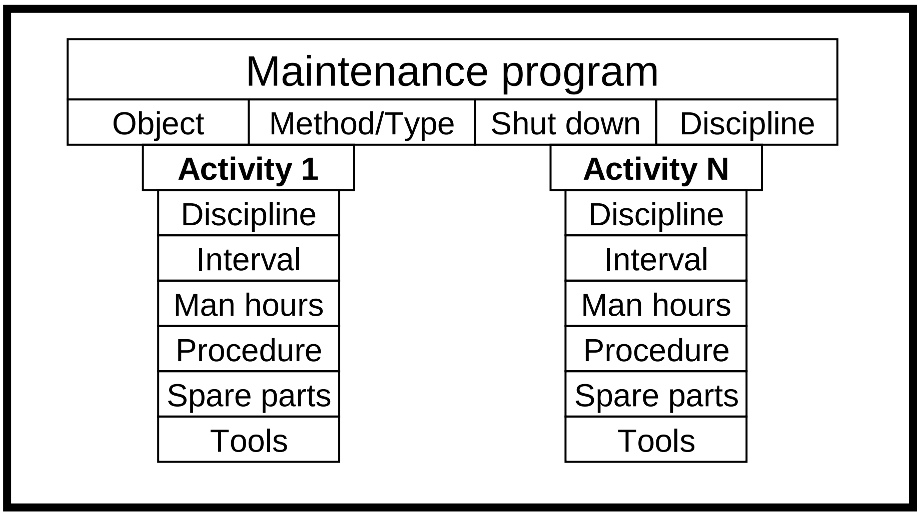

Figure 2-4. Typical maintenance program content (Aker Solutions, 2010b).

A typical maintenance program is based on corrective and predetermined maintenance actions. Most of the maintenance activities are therefore scheduled and maintenance is performed at predetermined intervals. The intervals, man-hours, spare parts, procedures and tools required for the different maintenance tasks in the maintenance program are based on the input data. A traditional maintenance program is carried out by following the scheduled activities and should be continually improved by learning from completed maintenance activities.

2.4 Corrective Maintenance

Corrective maintenance is when maintenance actions are carried out subsequent to an equipment failure (Moubrey, 1997) as shown in figure 2-5. This maintenance policy is also called "failure-based maintenance" because the asset is operated until it fails. Corrective maintenance is defined by BS EN 13306 as: "maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function". The complexity of the equipment is increasing and corrective maintenance tasks are for most types of equipment not economical. For non-repairable parts with insignificant consequences of failure, corrective maintenance tasks can still be the most cost-effective strategy (Kumar & Kumar, 2004).

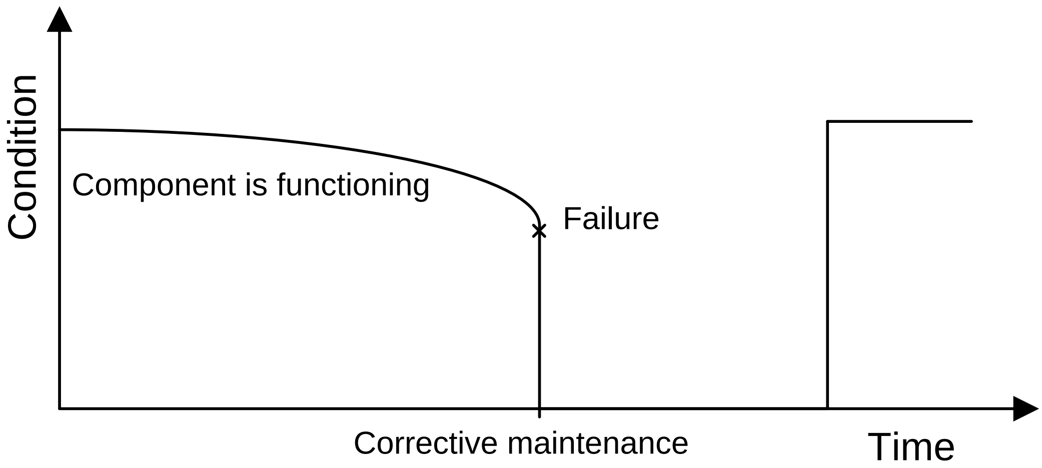

Figure 2-5. Corrective Maintenance

2.5 Preventive Maintenance

The idea of Preventive Maintenance (PM) is to prevent equipment failure, avoid breakdown costs and reduce downtime (Moubrey, 1997). In order to avoid corrective maintenance actions, preventive maintenance makes sure that maintenance is performed before failure occurs (Mobley et al., 2008). BS EN 13306 defines preventive maintenance as: "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". A short description of the different types of preventive maintenance follows.

2.5.1 Pre-Determined Maintenance

Predetermined maintenance is maintenance carried out on a regular basis at predetermined intervals. The maintenance actions are performed periodically in order to prevent degradation and failures. Figure 2-6 illustrates the idea of predetermined maintenance. The maintenance intervals can be calendar-based, where the intervals may be weeks, months or years. Another approach may be to base the intervals on the number of operating hours (run-time based). (Børresen, 2009; Pintelton & Puyvelde, 2006)

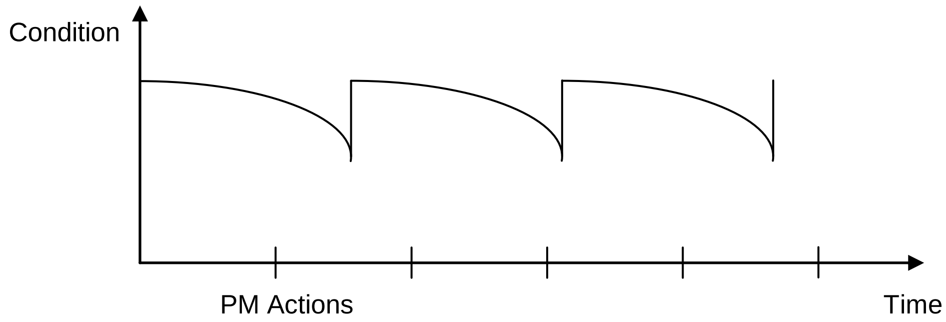

Figure 2-6. Predetermined Maintenance

2.5.2 Condition Monitoring and Condition Based Maintenance (CBM)

Condition Monitoring is a method for monitoring the condition of a specific equipment or system and forms the basis for Condition Based Maintenance (Rao, 1996). High availability and decreased number of shutdowns together with improved decision making and an objective analysis of the equipment are technical advances with the use of condition monitoring (Murthy & Kobbacy, 2008). A new trend in maintenance management is to use condition monitoring techniques to trig maintenance actions. Condition monitoring is most relevant when failures occur randomly. When dealing with condition monitoring there must be an apparent relationship between what is measured and the condition (Rao, 1996). The system must respond quickly and the values must be compared to base values. Systems for measuring and recording data must also be available.

It is important to clarify that equipment that is subjects to condition monitoring, not necessarily follow a CBM strategy. But on the other hand, condition monitoring forms the foundation of CBM and is an essential element of a CBM strategy.

CBM takes advantage of the equipment condition data available from condition monitoring to predict the maintenance requirement. The condition monitoring can be combined with inspections and tests in order to make a thorough analysis of the real condition (BS EN 13306). The triggering factor for maintenance action in CBM is the measured values which indicate the condition of the equipment and the preventive action is performed only when the condition data is indicating a developing failure (Holmberg et al, 2010; IAEA, 2007). As shown in figure 2-7, the condition based maintenance work process can be divided in three phases: observe, analyse, and decide. The observed condition is analysed both by expert systems and manually. If the measured condition deviates from the normal condition, a decision on what to do has to be made.

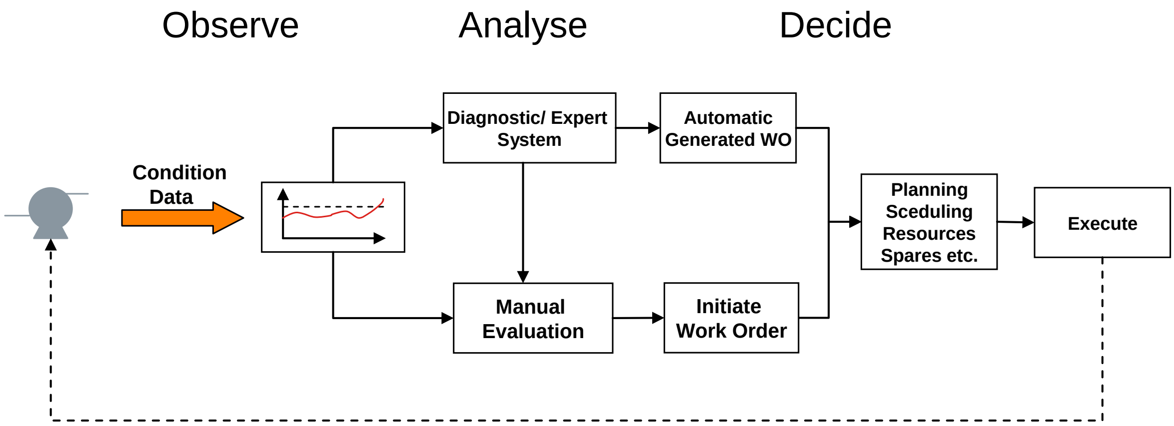

Figure 2-7. Condition Based Maintenance work process (Aker Solutions, 2009)

By the use of traditional predetermined maintenance, maintenance actions may be performed too frequent, while corrective maintenance is not performed before a failure actually has taken place. In order to avoid these problems, continuous knowledge of the condition of the parts will be helpful in performing maintenance only when it is needed (Gopalakrishnan, 2004).

The early warning of the starting deterioration provides the operators and other maintenance personnel with the possibility to schedule maintenance activities when it is cost-effective (Kumar et al, 2000). Monitoring parameters such as vibration, temperature, wear particles in lubricant, and process flow provides information so that the planning of maintenance action can be done more efficient. This leads to higher probability of preventing failures. As long as the failure is a gradually mechanism, with a detectable deterioration process and the condition can be monitored, CBM can be a useful tool (Gopalakrishnan, 2004). Most mechanical failures occur gradually. Failures that occur instantaneously are difficult to detect, and CBM may not be the most cost-effective maintenance type.

CBM is closely related to predictive maintenance that will be described in the next section. Predictive maintenance and Condition-based maintenance often used interchangeably, but British Standard EN 13306 defines it like this: “Predictive maintenance is condition based maintenance carried out following a forecast derived from repeated analysis or known characteristics and evaluation of the significant parameters of the degradation of the item”. This paper will use the terms predictive maintenance and condition-based maintenance as defined by BS EN 13306.

2.6 Condition Monitoring Technologies

Some of the main condition monitoring technologies will be briefly described in this section. In addition to these technologies there are many other techniques as well: radiography, visual inspection, thermodynamic condition monitoring, ultrasonic testing, flux leakage and magnetic testing.

2.6.1 Vibration Monitoring

Vibration monitoring is a technique used to measure the repetitive motion of mechanical equipment (IAEA, 2007). This technique is using the vibration of rotating mechanical equipment to determine the condition. Vibration monitoring is regarded as one of the most frequently used monitoring techniques (Mobley et al., 2008). The main reason for this is that a great population of the equipment in an oil and gas plant consists of rotating equipment, such as turbines, pumps, compressors and engines. Rotating machinery provides various vibration frequencies and the vibration of an object is dependent on the force causing the vibration. These forces are dependent on the equipment's condition. The cause and severity of the potential faults can therefore be diagnosed by measuring the vibrations of the equipment (White, 1997). Figure 2-8 shows a simplified vibration monitoring process.

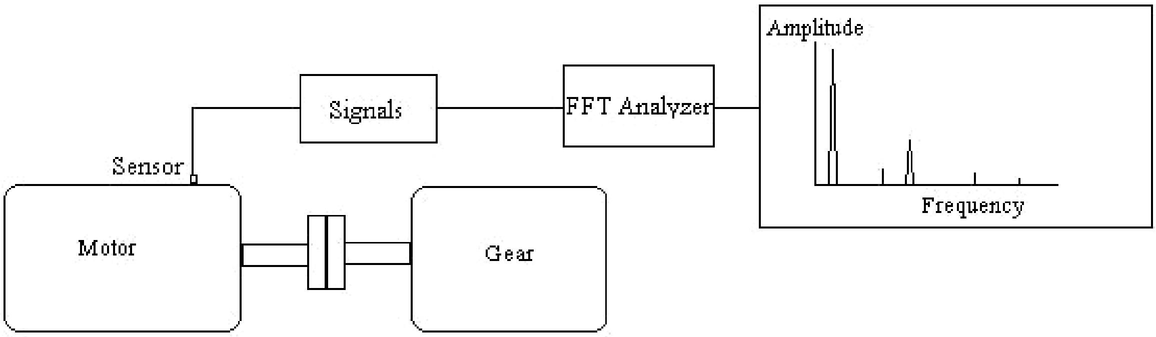

Figure 2-8. Vibration Monitoring

There are many different faults that can be detected by vibration monitoring (Wowk, 1991):

- Imbalance
  - Coupling problems
  - No uniform density of material
  - Gain/loss of material
  - Porosity of material
- Misalignment
  - Parallel misalignment
  - Angular misalignment
  - Combination of parallel and angular misalignments in horizontal and vertical directions
- Bearing defects
  - Ball defect
  - Cage defect
  - Outer race defect
  - Inner race defect

2.6.2 Thermography

Infrared radiation indicates the object's surface temperature. By measuring the infrared radiation the operational condition of the equipment can be determined (Mobley, 1990). As the temperature increases the infrared energy will also increase, as shown in figure 2-9 (IAEA, 2007). Abnormal values of infrared radiation indicate initiating problems making it possible to locate and define the problem at an early stage. This makes it possible to perform maintenance actions in advance of a severe failure (Mobley et al., 2008).

In order to detect the infrared radiation one need proper infrared monitoring equipment and diagnostic software. The emissivity of the target surface has to be known in advance of the monitoring in order to get accurate measurements (IAEA, 2007). Instruments that are used to measure the infrared energy are infrared thermometers, line scanners and infrared imaging (Mobley, 1990).

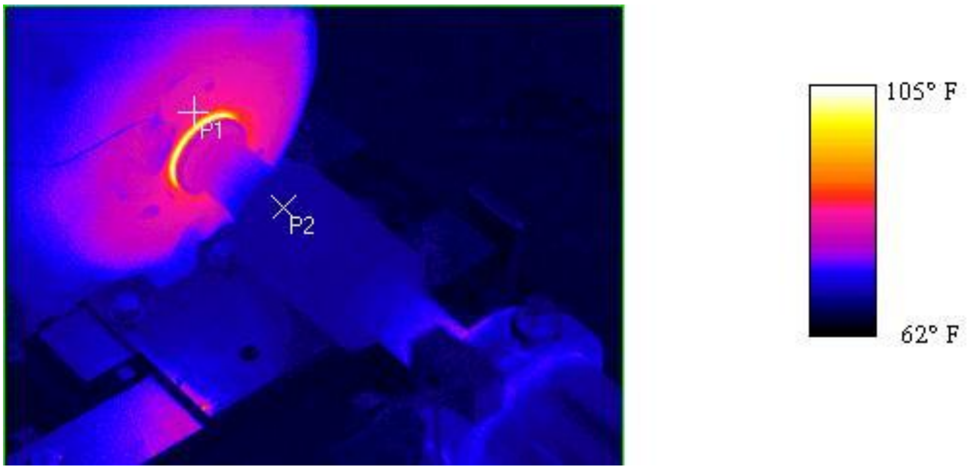

Figure 2-9. Thermography (Shreve, 2003)

The temperature measurements from thermography can be stored and trended so that an alarm level can be set. Failures that can be detected by thermography includes leaking valves, rotating machinery faults, piping leaks, restricted flow, and insulation degradation (Lewis, 2007).

2.6.3 Oil debris monitoring

A lubricant creates a thin film between interacting surfaces and helps reducing friction, heat and wear. But a lubricant has a secondary function as well, which is to remove contaminants and protect solid surfaces (IAEA, 2007). If lubricating oil used in mechanical and electrical equipment contains trace metal or other particles indicating wear pattern, this may be an indication of initiating machine failure. If these contaminants are detected and analyzed, it will provide an early warning of potential deterioration of equipment (Mobley, 1990). Oil analysis may also be used to base the lubrication intervals on the condition. Figure 2-10 shows the process of oil analysis and clearly shows where to take a sample for analysis.

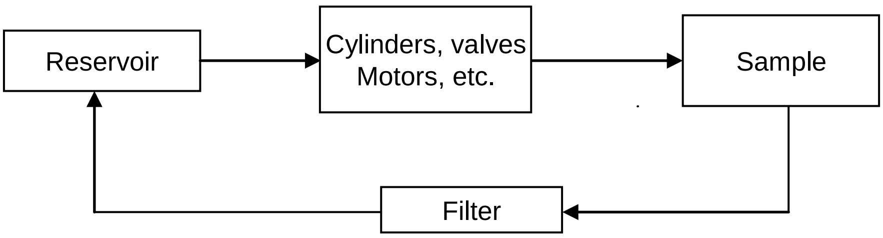

Figure 2-10. Oil Analysis

Wear particles can provide important information about the condition of the specific mechanical equipment. The shape, composition, size and quantity of particles can provide important information of the wear process. In order to analyse the particles in the oil one will often use methods such as spectrography and ferrography. Spectrography is a method often included in wear debris analysis. This is a technique that determines the chemical constituents in the oil. Ferrography is very similar to spectrography, with a couple of exceptions. The particles are separated by a magnetic field, and not burning like spectrography. Ferrography can detect particles larger than 10µm, which is not possible in spectrography because they can not be burned successfully (Rao, 1996). For more details on oil analysis, see (Rao, 1996).

2.6.4 Performance monitoring

In order to fully understand the equipment's condition, the operating condition has to be known. This is found by knowing the process parameters such as flow, pressure, energy consumption and temperature. The measurement of these parameters can provide enough data to calculate the efficiency of the equipment. Measuring the process parameters will often require additional instruments. In order to find the causal connection, fault finding and diagnosis is often carried out by considering the combination of the equipment condition monitoring and the measured process values. (Mobley, 1990)

3. Potential opportunities and challenges with CBM

When introducing CBM one has to be aware of the challenges as well as the many opportunities. In order to justify the use of CBM, one needs to be aware of the pros and cons. This chapter will highlight the most important potential opportunities and challenges with CBM.

3.1 Opportunities

3.1.1 System reliability

Condition monitoring provides the users with information of the actual condition of the equipment. Early detection of initial equipment failure is an important factor in preventing serious damage to a system. By using CBM, the condition is regularly monitored, and the number of unexpected failures can be reduced. The reduction in unexpected and serious damages to the system increases the system's operating life and the reliability (IAEA, 2007). Figure 3-1 shows the "bathtub" curve which illustrates the general life cycle of a machine. Due to run-in problems, there is a high probability of failure in the early phase. In the normal life period of the equipment, the probability of failure is low and components fail randomly. As the end of the life period approaches the probability of failure increases significantly.

When equipment is replaced or repaired at fixed intervals, unexpected random failures in the normal life period and early/premature failures in the early phase can take place. Using condition monitoring to track the condition during its life period, the failures may be detected in advance and unexpected failures can be prevented (Bloom, 2005). Frequent testing and repairs may also cause wear and tear to the equipment. CBM may reduce the amount of maintenance, increase the possibility that the equipment last longer and increase reliability.

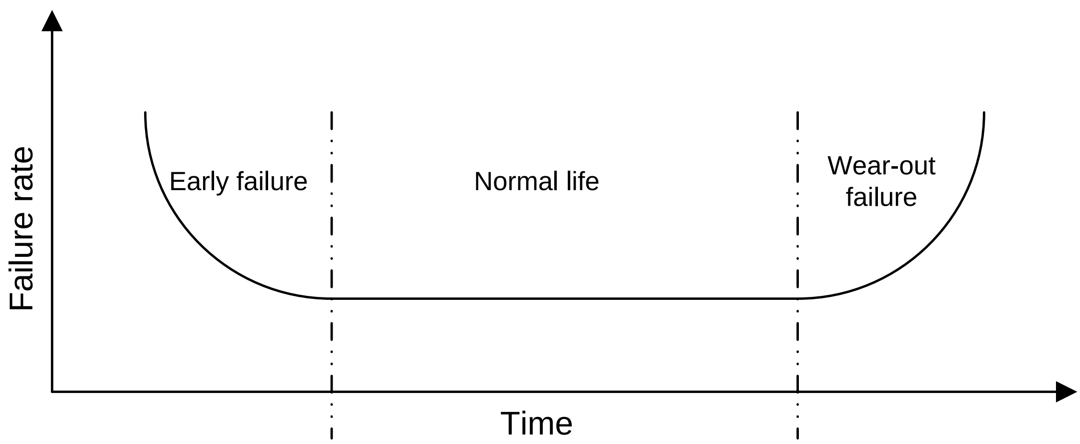

Figure 3-1. The "Bathtub" curve

3.1.2 System availability

“Availability is the ability to be in a state to perform as and when required” (BS EN 13306). The primary task of maintenance is to retain and restore the state of equipment so that it can perform the required function. Maintenance therefore plays an important role in assuring availability.

The use of CBM can resolve some of the availability issues that may be present with traditional maintenance. The condition monitoring provides information of the condition of the equipment, and maintenance operations are only performed when it is required and the number of unnecessary maintenance actions is reduced. CBM provides early detection of deterioration and therefore enough time for appropriate planning. Better planning where the machine’s loading and condition is taken into account may improve the maintenance actions, so that damage and failure caused by repairs and replacements are reduced (Holmberg et al, 2010).

The condition data can provide knowledge of which part that has to be repaired or replaced and what parts of the equipment that need special attention. This could make it easier to plan the maintenance actions, but due to the dynamic maintenance intervals, CBM will also introduce some challenges for the maintenance planners. This will be further described in chapter 3.2.5. Several of the repairs that normally are included in traditional corrective and periodic maintenance can be eliminated with the use of CBM (IAEA, 2007) and the total downtime of the equipment can be reduced (Gopalakrishnan, 2004). As illustrated in figure 3-2, it is difficult to schedule maintenance at the right time. With predetermined maintenance the maintenance is often scheduled either too early or too late (Markeset, 2008). Outcome A in the figure illustrates a situation where the failure occurs before the scheduled maintenance take place. Outcome C illustrates the situation if a failure occurs subsequent to the scheduled maintenance point. The ideal situation will be outcome B, where the scheduled maintenance is well timed. With the use of CBM, the failures can be detected at an early stage, which will enable us to plan and schedule maintenance well ahead of functional failure and can increase the time between maintenance (Markeset, 2008).

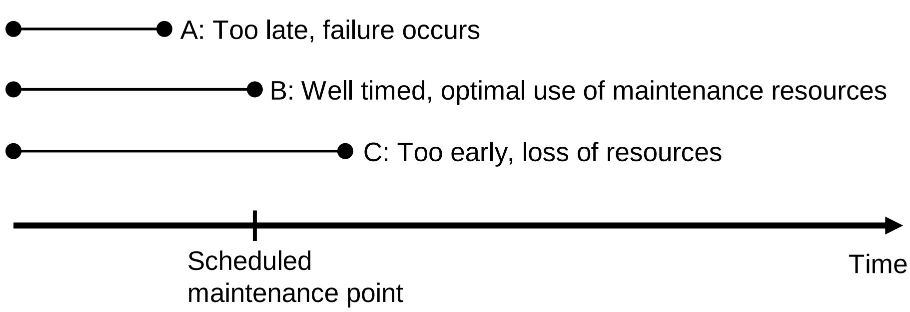

Figure 3-2. Timing of scheduled maintenance with respect to failures (Markeset, 2008)

3.1.3 Spare parts

The condition data available can also be used to predetermine the required spare parts. Spare parts inventory can be reduced, and the parts can be ordered as needed so that the spare parts costs may be reduced (Mobley, 1990). Better spare parts inventory planning may increase the availability of spare parts and can thus reduce the downtime and logistic cost. However, the time from a potential failure to a functional failure may be shorter than the lead time of purchasing the spare parts. It may therefore be necessary to hold spare parts in stock in order to have the parts available when a maintenance action is triggered. For pre-determined maintenance spare parts is ordered so that they are available in time for the predetermined task. Due to the lead time of spare parts, ordering as needed when using CBM may not be sufficient. So, although spare parts management may be easier with CBM, challenges may appear as well.

3.1.4 Safety

Plants that have a condition based maintenance program may experience higher safety level. High pressure, high temperature and flammable fluids are factors that can cause serious damages if they are out of control. Using condition monitoring, failures can be detected at an early stage and give a warning of impending dangers (Gopalakrishnan, 2004). However, more instrumented and complex plants may actually influence safety negatively as well.

3.1.5 Costs

A major portion of the operating costs of production plants is related to maintenance (IAEA, 2007). It is therefore important to reduce the maintenance costs and at the same time make sure that the system is safe. With traditional maintenance redundant maintenance actions may be carried out. Performing traditional predetermined maintenance, parts will be repaired and replaced at fixed times. Hence, it is a possibility that perfectly fine parts that could still be operable for a longer period are replaced. Unnecessary use of spare parts and workforce result in higher maintenance costs. But here the maintenance costs are related to increased down-time and improper planning.

Using CBM, maintenance tasks are scheduled based on the actual condition of the equipment. Maintenance is therefore performed only when it is necessary and the repairs can be better planned. The result is a reduced number of maintenance operations (IAEA, 2007). Reduced consumption of spare part, reduced number of maintenance operations, and an increase in reliability and availability can lead to a reduction in production costs. The increased running time for the equipment can make up for the investments of the condition monitoring systems. So instead of being a “necessary evil”, CBM enables maintenance to be a contributor to the company profits (Holmberg et al, 2010).

3.2 Challenges

3.2.1 Organization

The traditional maintenance organization is based on predetermined maintenance tasks and corrective maintenance actions. Changing to a more condition-based maintenance strategy, difficulties in letting go of the old organization structure may appear. With the use of a CBM strategy, the organization needs to be able to respond to changing environments. The organization has to be able to respond, monitor and foresee threats to the normal operations. A recent study of five large firms in the process industry in The Netherlands done by Veldmann, Klingenberg and Wortmann (2011), shows that the organizations generally have a unsystematic approach to CBM and it is unclear how problems are being identified and how decisions are made. These are issues that are considered to be very important aspects of CBM.

The organization should always fit the purpose, i.e. supporting CBM. The effectiveness of CBM is influenced by the decisions and quality of the organization. Many organizations are used to traditional maintenance strategies, and the use of CBM as a part of the overall maintenance strategy can be a complex challenge to deal with. The responsibilities and the established routines must be changed, and there must be willingness to do these changes within the organization (IAEA, 2007). Resources have to be moved from the traditional maintenance role to a condition-based maintenance role, with reduced number of maintenance actions and more focus on data interpretation and analysis (IAEA, 2007).

Considerations of the resource need is also a bit more challenging than with traditional maintenance as the timing of maintenance actions are more unpredictable. The ability to create a working environment that optimizes the use of resources, maintenance work processes, employee skills and technology is very important for an organization. When utilized correct, CBM may lead to fewer breakdowns, lower consumption of spare parts and fewer maintenance actions. A CBM strategy will therefore cause changes in the priorities of maintenance work, and thereby changes in the use of resources (Sundberg, 2003). The priority of labour hours and allocation of resources will change as the maintenance activities are less frequent and more dynamic.

The study done by Veldmann, Klingenberg and Wortmann (2011) did also show that none of the five companies that were studied made use of clearly defined procedures for condition-based maintenance. Although, this study was made in The Netherlands, it indicates that there are organizations out there that are not concerned with following strict procedures for CBM. But in order to ensure quality of the CBM strategy it is recommended that strict procedures are defined. The procedures should define the methods, the schedule, the data collection, analysis of data and decision making (Veldman et al, 2011).

Roles and responsibilities in the execution of CBM should also be clearly defined. Decisions about the roles and responsibilities will affect the effectiveness of the CBM strategy. One must assure that the responsibilities are understood and supported by the different individuals. The main responsibility for the offshore facility lies within the operator, but the operator often allocates responsibilities to external expert groups as well. This will lead us to another important organizational aspect, which is the organization of maintenance activities. The different maintenance activities should be allocated in such a way that the maintenance is performed as efficient as possible. With the use of a CBM strategy more responsibility will be put on expert groups and the different responsibilities therefore has to be clearly defined.

3.2.2 Training

The quality of a CBM strategy relies on the interpretation of the data and the analysis of the observed condition (IAEA, 2007). The new priorities of maintenance work as well as increased technical complexity will change the focus of employee skills and competence. In order to perform CBM the personnel has to be experienced, well qualified and properly trained (IAEA, 2007). A significant issue of training personnel is to continuously train personnel so that the competence level is acceptable as new technologies are introduced, and at the same time keep the costs related to the training at an acceptable level. Another important issue is the allocation of competence between the oil company, vendors and other service providers. The allocation of competence has to be addressed so that it is clear what the personnel should be trained in.

3.2.3 Increased instrumentation

Using condition monitoring as a tool for determining the maintenance actions, additional instruments are required. This will contribute to an increase in the number of components at the plant. The additional instruments do also need attention with respect to operation and maintenance. Calibration of installed equipment may be required and along with maintenance and operation of these instruments there will be a need for extra workload and costs (IAEA, 2007). If the CBM strategy is done wrong, the increasing use of additional instruments may also reduce the robustness of the asset. In order to use a CBM strategy it may be important to take a look at how the monitoring instrument will affect the robustness. If the robustness is severely reduced, it may be smart to reconsider the selection of a CBM strategy, modify the monitoring instruments or the way the instruments are configured.

3.2.4 Data management

Data management is a new and important aspect when CBM is a part of the maintenance strategy (IAEA, 2007). Data acquisition, analyzing, and planning the maintenance action based on the condition data are for many new and unfamiliar tasks. The maintenance personnel must be able to understand and trust the data from the condition monitoring systems. The basic idea with CBM is to use the measured condition data to give a useful output so that the correct maintenance action is taken (IAEA, 2007). An important issue in data management is therefore how to use the data gathered in order to perform the correct maintenance action. Effective responsiveness to alarms and indications of impending deterioration has a great influence on the success of CBM. Included in data management is the challenge of data security. With a lot of communication and transactions going over internet, there are several security concerns. In some CBM systems these alarms are integrated in the CMMS. When the condition is at the trigger level, the CMMS could automatically create a work order (Ellis, 2009). False alarms/indications will occur and it is important to be aware of this and manage them so that future false alarms are reduced to an absolute minimum (Sethiya, 2005). CBM will require interaction between human, technology and organisation. CBM is not only dependent on the technology, but also in manual interaction.

Another important challenge that needs to be considered is the implementation of CBM in a CMMS system. A CMMS system, such as SAP, has to be modified in order to support the use of CBM. Without any modifications of the CMMS system the work process may be crippled and the use of CBM may not be that efficient.

3.2.5 Planning of maintenance actions

A major difference between pre-determined maintenance and condition-based maintenance are the planning of maintenance activities. The planning change from static intervals in periodic maintenance to dynamic intervals in condition based maintenance (Sethyia, 2005). In periodic maintenance the time intervals are predetermined, while in CBM the time intervals will change. There are several challenges with the planning of CBM. First of all are the unpredictability of when a maintenance action is triggered and the availability of time and resources (Sethyia, 2005). Planning the maintenance actions with CBM, requirements for the lead time for spare parts etc. should also be considered. Maintenance actions initiated from CBM are performed when needed and it may therefore not always be as easy to plan.

3.2.6 Outsourcing

Many industrial organizations prefer to outsource maintenance, instead of developing internal maintenance groups and competencies (Kumar & Kumar, 2004). Then they enter into service agreements with service providers that are specialized in maintenance. The first challenge with outsourcing the maintenance is to find a supplier that can be trusted and that follows industrial standards. When outsourcing CBM activities one must be able to rely on the capabilities of the service providers. The service agreements between the end-user and the contractor have to clearly define the allocation of maintenance operations and should be beneficial for both parties (Kumar & Kumar, 2004). When outsourcing CBM activities, an important issue is to make sure that both parties have access to relevant information (condition data, data sheets, drawings etc.).

3.2.7 Accuracy

The sensors used to measure the condition should be able to monitor the actual physical state. These parameters have to indicate the equipment’s deterioration. In order to have an effective CBM program it is important that the measurement precision is at a level that can present a correct image of the equipments condition. Accuracy is also required for the monitoring systems which process and analyse the data from the sensors. Different prediction models should reflect the real physical state and these models will have limited ability to reflect the real physical process.

4. Criteria for selecting equipment suitable for CBM

4.1 General

CBM is a maintenance type that is not appropriate for all kinds of equipment applied in an oil and gas process facility. In order to utilize CBM, some selection criteria should be applied. The primary selection criteria are shown in figure 4-1. The first criterion is that CBM should be feasible. The feasibility of CBM should be clearly defined in order to find out if it is possible solution. The second primary criterion is that it should be *beneficial*. This criterion will be primarily focused on how CBM will be helpful in order to support maintenance and how it can add value. The third criterion is that a CBM solution should be *cost-effective*. CBM should be economically justifiable, so that the benefits of CBM outweigh the costs.

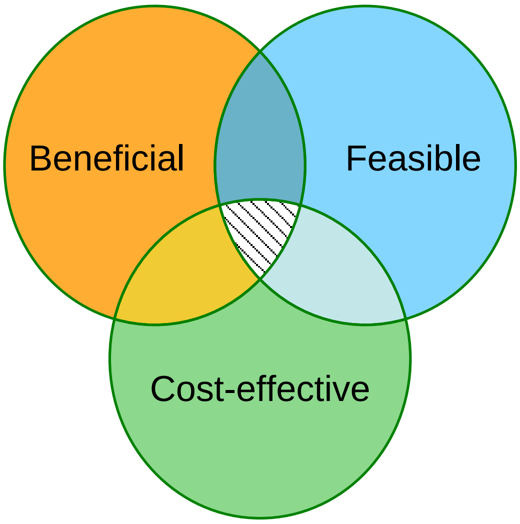

Figure 4-1. Primary selection criteria for CBM (Based on a figure from Aker Solutions (2011)).

Different combinations of the criteria may take place. But in the context of this thesis, CBM is only considered suitable when all three criteria are fulfilled, as illustrated by the highlighted area in figure 4-1. A more detailed description of the selection criteria for CBM will follow.

4.2 Feasibility

4.2.1 Operational feasibility

In Chapter 3.2, the challenges with the use of CBM were discussed. Just as important as technically feasibility criterion is that operational challenges are known and that they are overcomed. In order to succeed with CBM as a part of the overall maintenance strategy, these challenges have to be dealt with. Important operational feasibility criteria are:

- <u>*Organization structure:*</u> In order to use CBM to its potential, there needs to be a appropriate organizational structure, which will support CBM as a part of the maintenance strategy. The organization therefore needs to be able to respond to changing environments and needs to be flexible. The ability of the organization to be responsive to changes and to respond, monitor and foresee threats to the normal operations are important criteria that must be considered when applying a CBM strategy.

- *Resources:* New priorities of maintenance work will require that resources must be moved from a traditional maintenance role to a maintenance role where CBM is a bigger part of the overall maintenance strategy (IAEA, 2007).
- *Competence and training:* Use of CBM results in a high demand of skilled workforce with a high degree of special knowledge. Competence and training of personnel is essential for succeeding with a CBM strategy (IAEA, 2007). Internal and external expert groups have different competencies and the allocation of responsibilities have to be carefully considered. The competence location (operator, vendor or contractor) should therefore be clearly defined.
- *Performance:* The use of CBM may increase the reliability and availability, and thereby also the performance of an asset. An important presumption for introducing a CBM strategy is therefore to have a proper management for the key performance indicators (KPI). In order to see how the maintenance affects the performance of the system and thereby also the profitability of the company, relevant and observable KPIs should be developed (Holmberg, 2010).
- *Workload:* CBM strategy performed in the right way should reduce the maintenance, but one disadvantage is that introduction of several components may lead to high complexity and extra work. If the organization can't handle the workload that comes with extensive use of CBM, a CBM strategy will no longer be efficient and maintenance work and costs may not be reduced. The organization therefore has to recognize this challenge when considering introduction of CBM.

4.2.2 Technical feasibility

In order to be an appropriate maintenance type, CBM must be both technically feasible and economically justifiable. The economical aspect will be further described in chapter 4.4. Technical feasibility is a criterion that has to be fulfilled in order for CBM to be possible. The technical feasibility of CBM is dependent on the failure mode characteristics as well as the P-F interval (Sethiya, 2005).

Failure Modes

Failure modes and their characteristics have to be known in order to determine if the failure can be detected through condition monitoring (Rao, 1996). In order to detect a failure through condition monitoring, an identifiable physical condition that indicates a developing failure should be present. Not all abnormal conditions can be detected by the use of condition monitoring and some failures occur without measurable degradation (Rao, 1996). Understanding the failure mode characteristics is therefore important in order to identify the detectable and non-detectable abnormalities. FMECA is a method that can be used to map the failure modes of the equipment/systems.

Measurement accuracy

The measurements from CM should be highly correlated with the actual condition. Although a potential failure may be detectable, it is not guaranteed that the available CM techniques can provide accurate measurements of the actual condition. It is therefore important to assure that there are CM techniques available with good precision, so that the measurements can present a correct image of the actual condition.

P-F interval
If a potential failure condition indicates a developing functional failure, a P-F interval defines the time interval between the detection of a potential failure and the functional failure (Sethiya, 2005). The P-F curve shown in figure 4-2, illustrates how this P-F interval looks like. In order for CBM to be technical feasible the P-F interval has to be reasonably consistent and it should be long enough to take preventive actions. In order to detect potential failures, the interval for condition monitoring tasks has to be less than the expected P-F interval (Sethiya, 2005). It is recommended that condition monitoring tasks should be performed at intervals no longer than half the expected P-F interval. Failure with small P-F intervals is not a good candidate for condition monitoring and thereby CBM will not be technically feasible. A P-F interval can be determined based on operational history, continuous observation, research results or on the basis of judgement and experience (Moubray, 1997).

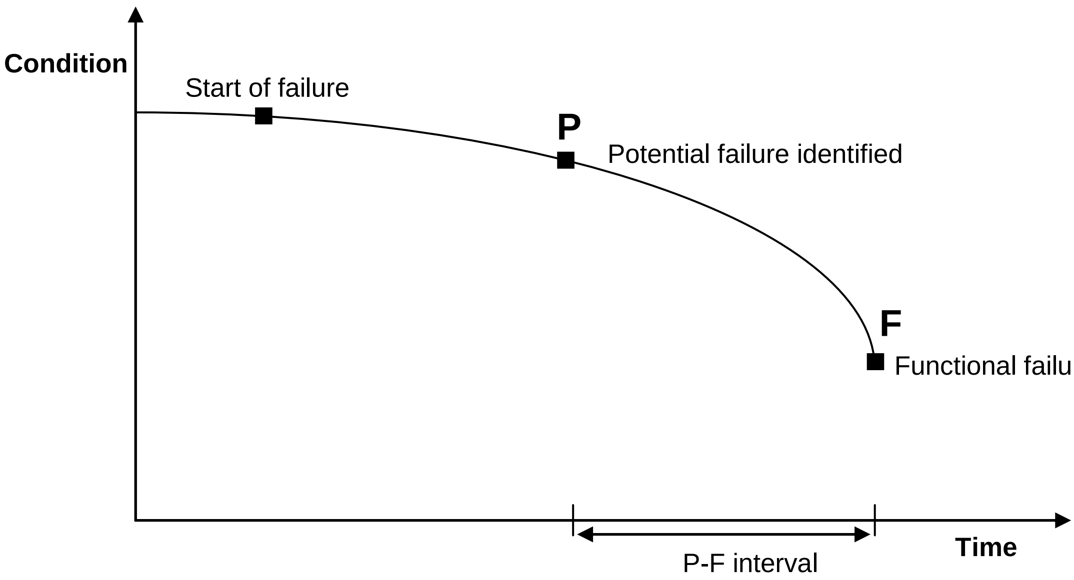

Figure 4-2. P-F Curve

4.3 Beneficial

4.3.1 Criticality

CBM should be applied to critical equipment and should fit the purpose. Some condition monitoring techniques are expensive and it would not be beneficial to utilize this kind of technology in every part of a process plant. It is therefore important to evaluate the criticality of the components (Holmberg, 2010). If a component is not considered as critical, the consequences of a failure would probably not justify the costs related to condition monitoring techniques. Condition monitoring will therefore not be beneficial for non-critical items. But if the component is critical, condition monitoring would probably be more useful due to the related losses and CBM may add value. Generally, criticality can be divided in to three categories (Holmberg, 2010):

- Health, Safety and Environment (HSE)
- Production
- Economics

The criticality with regards to HSE is, as the name implies, related to potential injuries, fires, pollution etc. The production category is associated with consequences of potential production loss, while economics are related to the consequences of the costs (exclusive costs of production loss). In order to achieve complete understanding of the criticality, detailed criticality analyses should be performed. But in an early project phase, detailed criticality analyses are not practicable. In the methodology presented in chapter 5, assessments regarding criticality will therefore be limited to a coarse criticality screening.

4.3.2 Availability

In order to be beneficial CBM should improve equipment availability. A primary goal of CBM is to optimize the availability by determining the maintenance actions based on the monitored condition. Availability can be improved by utilizing CBM to establish the most probable time of failure (Gopalakrishnan, 2004). Condition monitoring will provide better control of the system performance, and potential weaknesses and faults can be easier to identify (Markeset, 2008). This may provide the possibility to plan and take action at the right time. Figure 4-3 illustrates the lifetime distribution including average life expectancy (MTTF), which represents the mean time to failure.

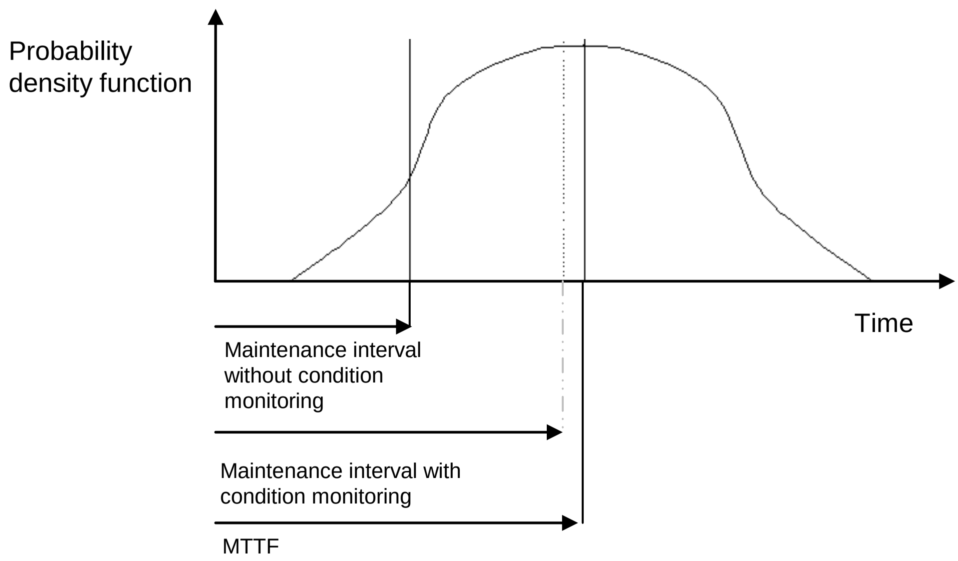

Figure 4-3. Lifetime distribution (DNV, 2001)

Failures may occur before it is expected, i.e. MTTF. Maintenance may therefore in some cases be performed either to early or too or too late. With the use of CBM the failure may be detected at an early stage and the time between maintenance can be increased, resulting in less downtime and reduced maintenance costs (Markeset, 2008).

4.4 Cost-effectiveness

In order for CBM to be appropriate for equipment, economical evaluations should also be performed. An important tool for justifying CBM economically is cost-benefit analysis. Cost-benefit analysis (CBA) is an assessment of the cost effectiveness of different options in order to see if the benefits outweigh the costs. This method can be used in order to compare different maintenance types. In this thesis the focus will be to create a simplified methodology in order to select equipment suitable for CBM. A detailed cost-benefit analysis for evaluating the suitability for CBM may be too demanding for a typical project in most cases.

In a CBA all the costs related to the options are compared to all the benefits of the options (Rogers, 2001). Figure 4-4 shows a simple example of a cost-benefit analysis result. In this example the costs outweigh the benefits, and the result is a loss of money due to higher monetary values of costs than benefits. Although cost-benefit analysis is often used to compare different alternatives, the method can also be used to simply determine if an investment is profitable or not.

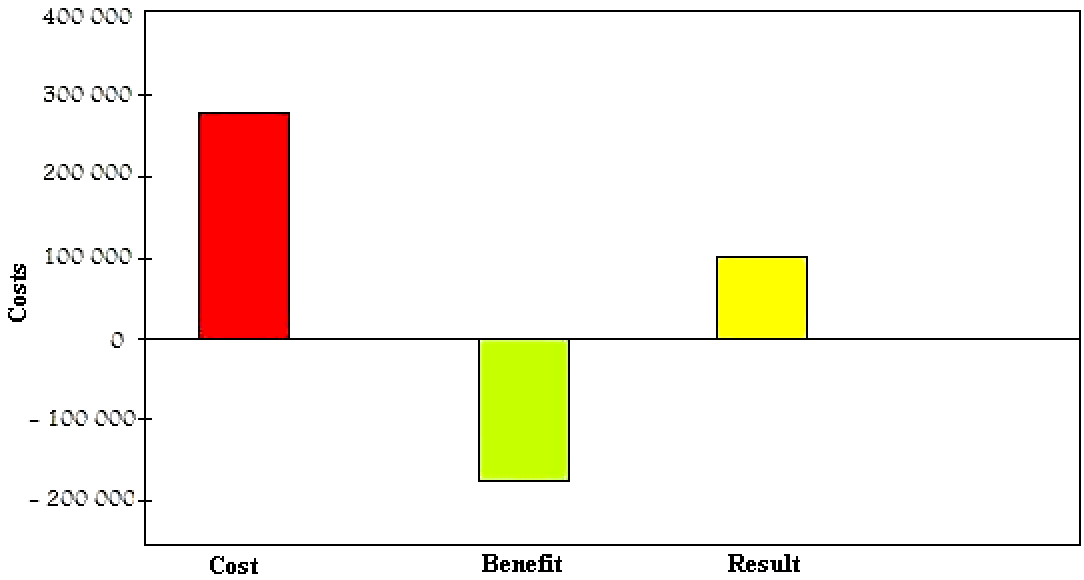

Figure 4-4. A simple example of results from a cost benefit analysis

Typical cost-benefit analysis

Performing a detailed quantitative cost-benefit analysis is a demanding process. Nevertheless, in order to understand how a typical cost-benefit analysis works, a brief description of how it can be performed will be presented. A typical procedure for performing cost- benefit analysis is (Rogers, 2001):

1. Identify option(s)
2. Identify costs and benefits
3. Assigning monetary values to the costs and benefits
4. Assessment of the costs and benefits
5. Decision

Performing a cost-benefit analysis will first of all be about identifying the option(s) and recognizing the costs and benefits of the option(s). These two steps will require in depth knowledge of the option(s) in question. In order to perform a proper cost-benefit analysis both costs and benefits should ideally be expressed in a common unit. The most convenient unit is monetary value.

The costs are often calculated according to a LCC model, which includes estimating all major costs during the entire lifetime. Assigning monetary values to the benefits are the often the most critical step in a cost- benefit analysis, due to difficulties of quantitatively estimate the benefits. In order to correct for yearly interests and inflation of the monetary values, the principle of net present value (NPV) is introduced (Houmstuen, 2009).

As the three first steps are accomplished, one can start with the assessment of the costs and benefits. An assessment often includes methods for comparing and analyzing the costs and benefits (Rogers, 2001). The most used technique is NPV, but also other techniques such as equipment annual worth (EAW), internal rate of return (IRR), sensitivity analysis, and benefit/cost ratio (B/C) may be used. For more in depth information of different assessment techniques, further reading of (Rogers, 2001) is recommended.

The final stage of a cost-benefit analysis is to make a decision. Decision-making is done on the basis of the assessment. A cost-benefit analysis is a purely economic analysis (Rogers, 2001) and it is important that in order to make decisions that other criteria is considered as well.

The focus in this thesis is selection of equipment suitable for a CBM strategy. The major costs and benefits with a CBM strategy are:

Costs

- Investment costs
    - Engineering
        - Planning
        - Specifications
        - Evaluations
    - Procurement
        - Hardware and Software
        - Monitoring equipment
    - Installation
        - Installation
        - Testing and commissioning
- Operational costs
    - Personnel
    - Training
    - Measurement and analysis
    - Maintenance cost of the condition monitoring system
        - Hardware and software
        - Monitoring equipment

Benefits

- Reduced pre-determined maintenance
    - Longer maintenance intervals
- Reduced corrective maintenance
    - Fewer unplanned breakdowns
- Reduced downtime costs
- Increased plant life
- Improved safety
- Reduced personnel risk
- Improved profitability

5. Methodology for selection of equipment suitable for CBM

This chapter will focus on describing a methodology to ensure a qualified and documented selection of equipment suitable for CBM. The selection criteria for CBM described in chapter 4 will create a basis for the specification methodology. One thing is to develop a methodology, but another important factor to consider is the timing. The timing of the execution of the methodology will affect the effectiveness and quality. The methodology should provide important input both for the maintenance engineering and the design. Information regarding CBM candidates should therefore be available prior to a detail engineering phase. Several of the equipment packages are ordered early in detail engineering and some of the packages may be ordered even as early as at the end of the FEED phase. The specification methodology should therefore be executed late enough in the FEED phase to assure enough input and soon enough to provide input for detailed engineering. The methodology should therefore take place close to the end of a FEED phase prior to the detail engineering as illustrated in figure 5-1.

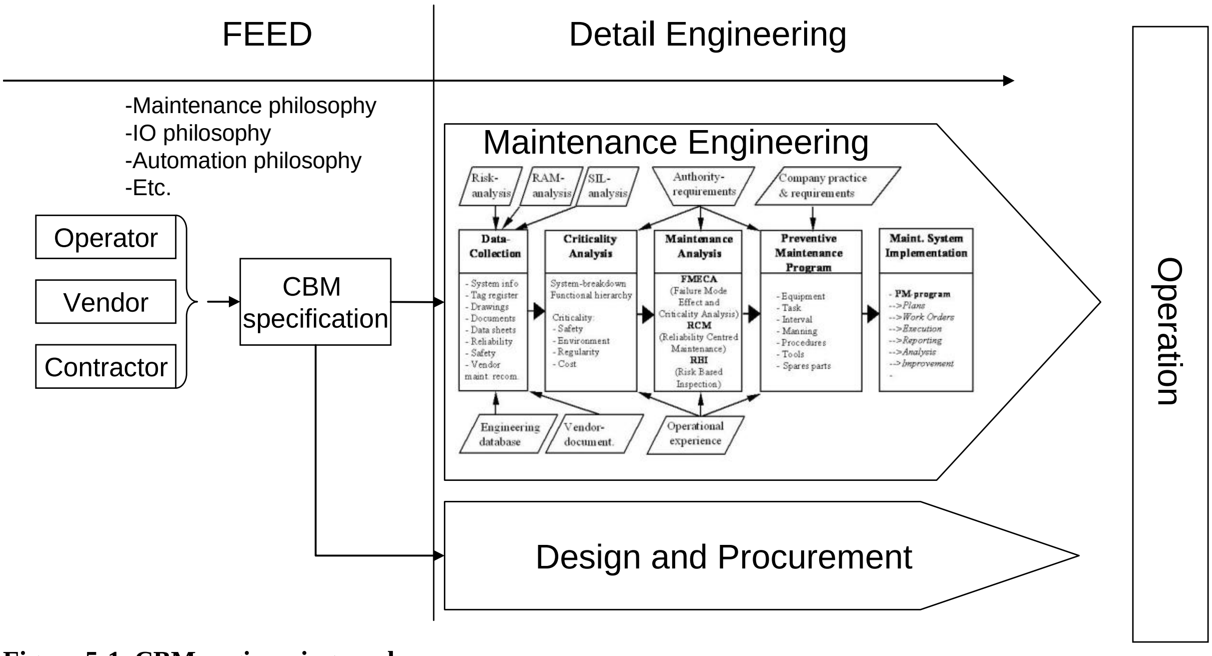

Figure 5-1. CBM engineering work process.

The specification methodology will be based on input data from the operator, the vendors and the contractor. Due to the timing of the methodology limited use of time and resources are required. Maintenance selection methods that utilize RCM or other time and resource consuming processes would therefore be too demanding. The specification methodology should be a simplified approach which should be effective, but still be a qualified and well documented process.

Equipment which is not regarded as suitable for CBM will be subject for other maintenance types such as predetermined or corrective maintenance. If neither predetermined nor corrective maintenance are suitable, a possibility will be to redesign (design out) the component in order to eliminate the failure mode. The analytical team performing the evaluation process should consist of personnel from operation and maintenance disciplines, process disciplines and instrument/SAS disciplines from the operator and contractor. If possible, representatives for the vendor(s) should also be present.

The methodology is illustrated in figure 5-2. The approach is based on the selection criteria previously described and is divided into 5 main stages which in the end results in the two stages of input to design and maintenance program. The methodology does not include any complicated calculations, and should primarily be based on easy available input data. A detailed description of each stage in the methodology will be presented in the following subchapters.

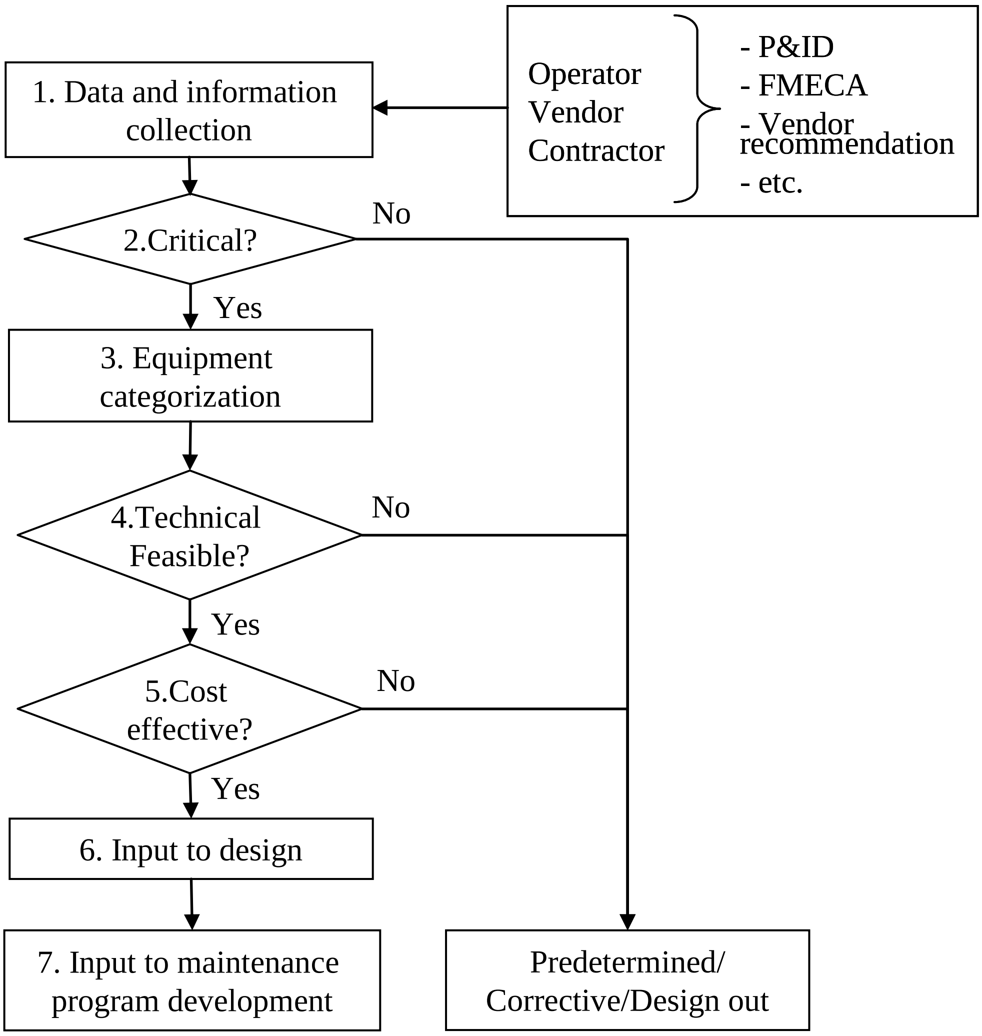

Figure 5-2. Methodology for selecting equipment suitable for CBM.

5.1 Data and information collection

In order to create a basis for the methodology, relevant data must be assembled. Data collection is a critical stage and the quality of the methodology will in a large degree be dependent on the available data. Decision- making should be based on engineering judgement along with appropriate data to support the decisions regarding criticality, technical feasibility, and cost effectiveness. Before the methodology is started it would therefore be necessary to assemble and collect as much relevant data as possible in order to provide useful information to the analysts. One should ensure that necessary data is available before continuing the working process. Different types of data may be necessary for the process:

- P&IDs
- Master Equipment List (MEL)
- Flow diagram
- Maintenance philosophies
- Vendor support
    - FMECA
    - Failure data
    - Operational statistics

The operator, contractor and vendor should be able to provide the different input data. The contractor needs to be in charge of the specification methodology. Vendor support will be especially important at this stage. In a RCM analysis, FMECA is a separate stage of the process. But in this context, it is suggested that the vendor should be requested to provide FMECA in order to save time and resources. As well as providing important documents regarding failure data and operational statistics, the vendor should provide recommendations for CBM. Asking the equipment vendor what they propose and to review these proposals during the selection process may be a useful method.

5.2 Criticality screening

Due to the fact that a detailed criticality analysis is not available at an early stage of a project, engineering judgement along with the available data should be used in order to evaluate the criticality. A criticality screening should be a coarse evaluation of the consequences of equipment failure in order to screen out the insignificant objects. Engineering judgement should be used as a decision method. This will not be a detailed criticality analysis and therefore engineering judgement should be sufficient in this context. But an important presumption is that the personnel performing the criticality screening have experience and sufficient knowledge of the equipment. The Master Equipment List (MEL) should be used as a basis for the criticality screening.

The criticality screening is represented by three questions related to different criticality issues. The screening is based on yes/no questions. But it is important to clarify that in order to answer yes or no to these questions acceptance criteria should be clearly defined. These criteria should be discussed with the operator and may vary from project to project. The criticality screening is illustrated in figure 5-3. The three criticality factors that should be considered in the criticality screening are:

1. Safety and environment: A potential failure could have major impact on safety or the environment. The severity of a failure would determine the criticality of the component, and failures that has significant affect on the safety or environment will be regarded as critical.
2. Production: A potential failure may also reduce the production level of a system and can also cause considerable downtime. If a reduction in the production level is considerable, it may be critical for the operation of the facility. It must therefore be evaluated further in order to see if CBM may reduce the probability of decreased production.
3. Economical: Unplanned stoppages, replacement, severe damage of the facility, or high maintenance costs of equipment due to failure could incur consequential economic losses. Severe economic impact may be just as critical as severe impact on safety or production. An evaluation of the economical impact is therefore necessary in a criticality screening process.

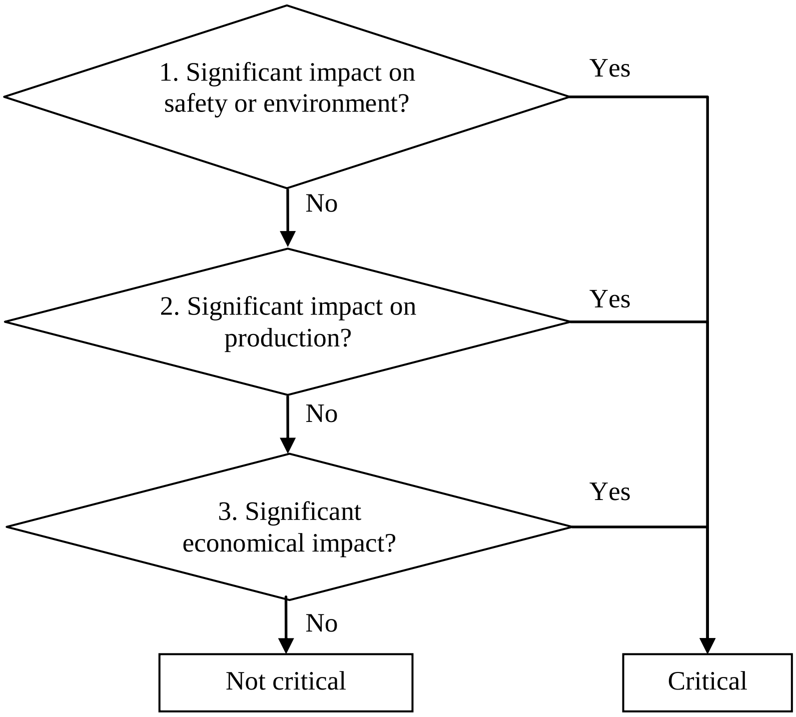

Figure 5-3. Criticality screening.

The acceptance criteria should clearly identify at what level a failure will have “significant impact” safety, production or economy. The criteria may vary from project to project, but here is a simple example of how they can be set:

- Safety: “Loss of human life”
- Production: “Downtime more than 12 hours”
- Economy: “Costs over 5 mill NOK”

In the criticality screening it is enough if only one of the three issues is considered critical. The equipment in question will then be subject for further evaluation in the methodology. For example, if a component is considered critical because of significant impact on production, but not safety or economy, it will still be critical and should be subject for further analysis in the methodology.

5.3 Equipment categorization

In order to provide a clearer overview of the equipment, a generic categorization of equipment should be performed. Equipment should be categorized according to its major functionality. Equipment that serves the same functions often has similar failure modes as well. Similar equipment will therefore require the same maintenance types, and by categorizing these types of equipment you may evaluate the technical feasibility for CBM for several objects at one and same time.

Table 1. Equipment categorization

Main Group	Group
Rotating equipment	Combustion engine
	Compressors
	Electrical generators
	Electrical Motors
	Gas turbines
	Pumps, centrifugal
	Pumps, diaphragm
	Pump, reciprocating
	Steam turbines
	Turbo expander
	Fan
Mechanical/ Static equipment	Heat Exchanger
	Heaters and Boilers
	Vessels
	Piping
	Winches
	Valve, Control
	Valve, ESD/PSD
	Valve, Manual/Check
	Valve, PSV
	Valve, Solenoid
	Filters
Electrical distribution, instrumentation and telecommunication (EIT)	Telecom equipment
	Electrical equipment
	Instruments

The table is a just an example how the equipment grouping could be done. BS EN ISO 14224:2006 describes a variety of equipment classes of similar types of equipment units. The equipment categorization will vary for different projects and BS EN ISO 14224:2006 clearly states: “Any applied categorization should be appropriate for the intended use and purpose of the data being collected”. Categorizing equipment require relevant knowledge about the functions and failure modes of the equipment. Engineering judgement can be used as a decision method, but the decision should also be supported by relevant data, such as FMECA provided by the vendor. A FMECA would help mapping the functions and failure modes in order to categorize the equipment.

5.4 Technical feasibility

Previously, RCM has been described as a process used to determine maintenance requirements, but performing a RCM is a resource consuming process. It is therefore suggested that a simplified approach should compensate for a RCM analysis. This process is mapping the technical feasibility of CBM. It is a process very similar to a RCM process, but with some simplified modifications. First of all, it is suggested that the vendor should be requested to provide FMECA for their equipment. Rather than evaluating the list of questions for each component, we here evaluate the equipment groups. Figure 5-4 illustrates the technical feasibility process.

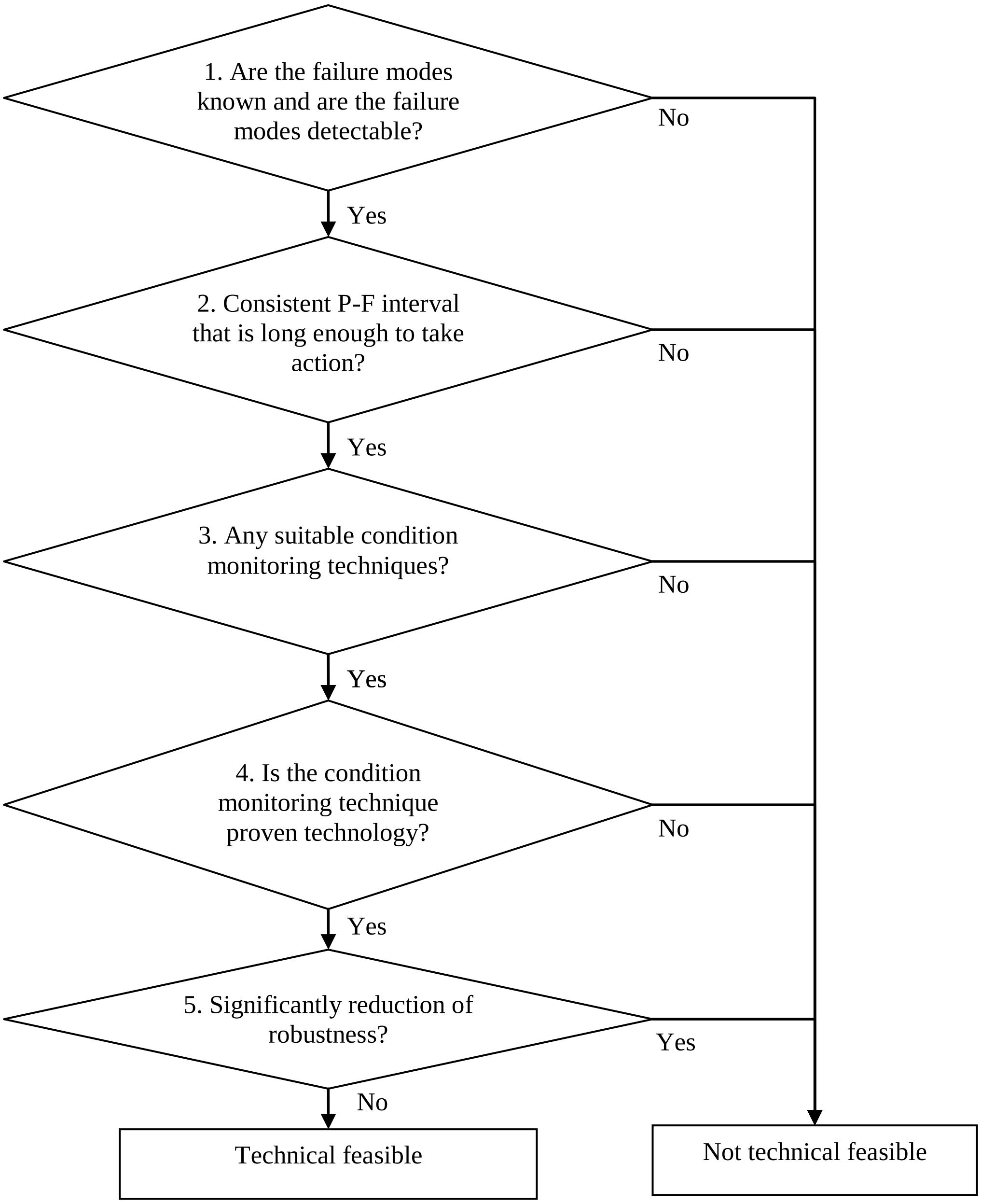

Figure 5-4. Technical feasibility process

Just like the criticality screening, some of the question in this step will also require some acceptance criteria. Take the question regarding reduced robustness for example. The introduction of condition monitoring instruments will at some level reduce the robustness of the equipment. But the question is if it will significantly reduce the robustness. The same question should be asked with proven technology. It must be defined at what level technology actually is considered proven. The technical feasibility process includes 5 questions that should be answered. A brief description of the 5 issues reflected by the questions will follow:

1. The first step is focused on whether the failure modes are known or not. In order to perform CBM, the failure modes must be known and they should be detectable through measurable parameters. Defining these failure modes would require FMECA. It is assumed that the vendor provides FMECA.
2. The second step requires a P-F interval or input data that can be used to easy determine the P-F interval. The interval should be consistent and long enough to take action. How long an interval is determined based on experience and engineering judgement. Operational history, research results and continuous observation are possible input information for estimating, but usually experience will be the most available input. An equipment vendor will usually attain operational experience of their equipment and should therefore be able to make estimates of P-F intervals. If the vendor can not provide a P-F interval, they should at least be able to give some basic information of how rapid a failure develops.
3. Whether there are condition monitoring techniques available to detect the failure modes should be determined. Experience and engineering judgement as well as an overview of different condition monitoring techniques should be available in order to answer this question.
4. If there is any suitable condition monitoring techniques, the technology should be proven. It is difficult to decide how much experience is enough in order to call the technology proven. But some experience with the technology is required in order to assure of quality of CBM.
5. Introduction of CBM will cause introduction of additional instruments. This step is therefore focused on if the additional instruments will affect the robustness and the availability of the equipment. Asking the vendor to confirm that condition monitoring technique will not reduce the robustness may be a helpful tool in this case.

5.5 Costs-Benefit Evaluation

In order to decide whether CBM is cost-effective or not, a cost benefit evaluation should be performed. A cost-benefit evaluation should compare CBM to more traditional maintenance types like predetermined maintenance (PM) and Corrective maintenance (CM). The evaluation should identify where CBM would reduce costs and be a cost effective alternative. Being a cost-effective alternative CBM should:

- Reduce costs associated with predetermined maintenance
- Reduce costs associated with corrective maintenance

Detailed quantitative cost-benefit analyses, as briefly described in chapter 4.4, will not be executed in this context. The reason is simply because of the time/resource limitations and the complexity of performing LCC calculations. The accuracy of cost benefit depends on the accuracy of the costs and benefits. And at this stage it may be difficult to calculate accurate values of especially the benefits, but also operational and maintenance costs. Uncertainties of quantifying the benefits and some of the costs may result in a more qualitative approach. Some factors may be easy to quantify, while others are more difficult to quantify. Rao (1996) suggest a cost-benefit model where both quantitative values and qualitative factors are considered. As shown in figure 5-5, the model is divided in two major stages: initial cost benefit and factored cost-benefit.

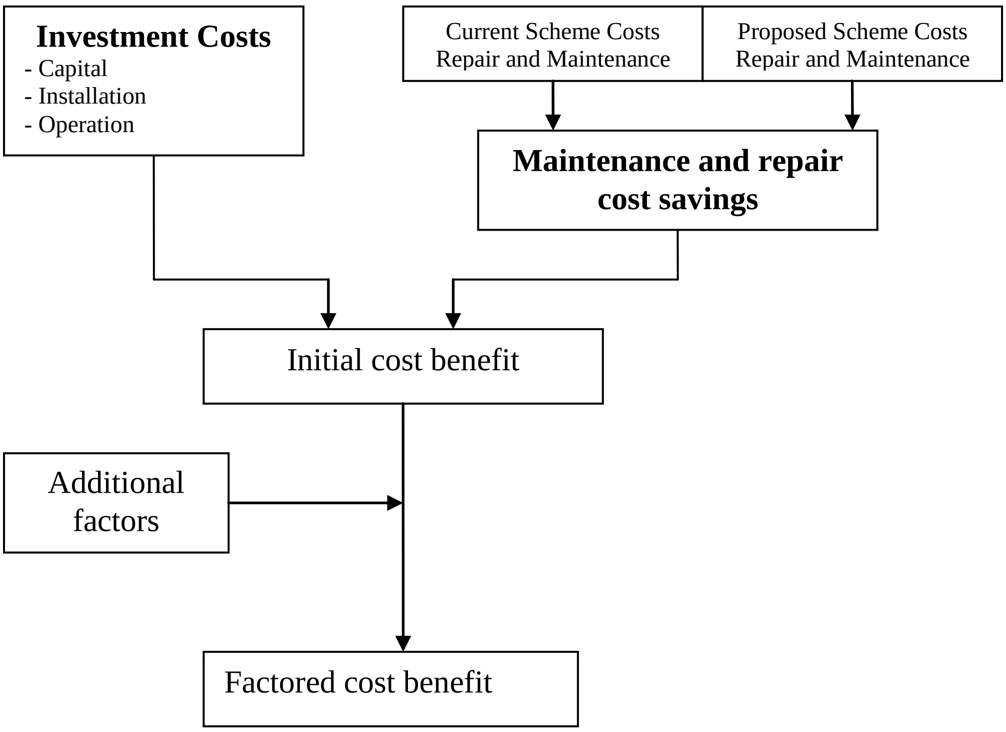

Figure 5-5. A cost benefit approach presented by Rao (1996).

The principle of the model is to first calculate the investment costs of CBM. The investment costs are in this model related to the purchasing of instrumentation on equipment, installation of equipment and costs of operation. Then the repair and maintenance costs with and without CBM is calculated and compared in order to estimate the maintenance and repair savings. The initial cost-benefit is expressed like this:

Initial cost-benefit = Cost savings – Investment costs

When the initial cost-benefit is determined, the model utilizes additional factors taking into consideration safety, operational and technical issues (Rao 1996). The additional factors are given a value between 0 and 1 and should reflect the importance of the different benefits. If a factor is considered unimportant it is given 1 and if it is considered important it is given a value close to 0 (Rao, 1996). For example, if CBM is totally unacceptable with regards to safety, and would have great influence on the outcome of the benefit, it would be given a value close to zero. If, on the other hand, CBM would not affect the benefit, it would be regarded as unimportant and given a value close to 1. When the different benefits are given a value, all the values are multiplied with the initial cost-benefit:

Factored cost-benefit = Initial cost-benefit x Factors

DNV (2001) has suggested a similar approach to cost-benefit evaluation of condition monitoring, but without the factored cost-benefit. The method can be performed in two different situations: based on experience data or based on estimated cost and benefit data. The costs included in this method are investment costs (projects, purchasing, installation, and training) and condition monitoring operating costs (measurements and analysis, maintenance on condition monitoring system). These costs will then be compared to the benefits. The benefits included in the analysis are related to reduction in predetermined maintenance, corrective maintenance, and down time costs. Reduced energy costs and higher safety level is also mentioned, but are not a part of the analysis, due to difficulties of measuring these kinds of benefits. For more details regarding this approach it is recommended to study the DNV document “DNV-RP-A203 - Qualification Procedures for New Technology”.

Existing cost-benefit approaches, such as those presented by Rao (1996) and DNV (2001), may be effective in theory. But a cost-benefit evaluation in this case should be practically feasible in an engineering context as well. In reality, calculating all the costs and benefits for each equipment group would be a time and resource consuming process. Although such approaches to cost-benefit evaluation may be very accurate, it would probably represent a bottleneck for this selection process.

In an engineering context, minimal estimations should be performed, so that the evaluation could be done quicker and more efficient. The vendor, contractor or operator may provide important input data for costs of CBM. It is therefore important to ask the different parties if such data is available. If such data are available it will increase the quality of the evaluation. The vendor could for example be able to provide capital costs of monitoring equipment, and the contractor may document installation costs. Input data of operational and maintenance costs would maybe be a bit more difficult to obtain. These costs would include costs related to personnel to operate the monitoring system, training, maintenance of the monitoring system, and enhancement costs related to hardware and software. But the vendor may also provide input data for training costs, manpower costs, and service costs as well.

Potential benefits with CBM should be discussed with the vendor and operator. But as previously mentioned potential benefits of performing CBM are related to cost saving due to potential reduction in maintenance frequency, maintenance induced faults, spare parts, lost revenue, maintenance costs, and reduced outage. For example, with use of traditional maintenance you may experience 20 predetermined maintenance actions and 4 unplanned corrective actions during a 10 years period. If CBM was used, the number of preventive actions may for example be reduced to 10, and the number of unplanned corrective actions may be reduced to 1. The number of maintenance actions has been reduced and the total downtime is reduced as well, which is leading to potential cost savings.

Ideally, cost savings estimations should also be available from experience data before a cost-benefit evaluation in order to save time. Data should not be impossible to obtain, but it would require some extra effort. If experience data is not available, the costs savings has to be estimated. A suggested way of estimating these cost savings are:

Cost Savings = $(MI_0 * CP - MI_1 * CP) + (UC_0 * CC - UC_1 * CC) + DTP + DTC$

MI_0 = Maintenance intervals without CBM
MI_1 = Maintenance intervals with CBM
CP = Cost of predetermined maintenance action
UC_0 = Unplanned corrective maintenance without CBM
UC_1 = Unplanned corrective maintenance with CBM
CC = Cost of corrective maintenance action
DTP = Downtime costs predetermined maintenance
DTC = Downtime costs corrective maintenance

Some of these parameters will however not be easy to quantify. Defining the cost savings may therefore be one of the most difficult factors to consider in a cost-benefit evaluation. Another approach for identifying cost savings and other benefits may be to use available KPI values. If KPIs are available, the historical maintenance performance can give an idea of cost reductions etc. KPIs will be of great value in order to compare traditional maintenance with CBM. If KPIs are available it is recommended to use these as simple information sources for defining the benefits.

There are several methods for cost-benefit evaluation and two of them have been briefly described in this subchapter. Most of the available methods require quantitative cost estimations. Performing detailed quantitative costs-benefit analyses will often be to demanding. A common solution is therefore to perform coarse and mainly qualitative cost-benefit analyses. In such cases investment costs may be indicated, but the cost-benefit methodology will be mainly based on qualitative engineering judgement.

5.6 Input to design

A CBM specification needs to be developed before detail design, i.e. during FEED. The results from this specification methodology will be important input for the detailed engineering design. The main reason for performing the methodology at an early stage is to highlight the CBM opportunities prior to the detailed design and for purchasing of equipment packages. The specification methodology should influence the design in order to highlight the maintenance requirements with regard to CBM. Information regarding the need for sensors, transmitters, computers and other hardware and software for condition monitoring is important input for design and procurement. The methodology should also provide input for organization and documentation needs as well as need for additional instrumentation. It is important that the methodology will provide enough information so that the maintenance documentation will be available in due time.

5.7 Input to maintenance program development

As well as being an important input for the detailed design phase, the selection process for CBM will also be important input for the maintenance program. In order to establish a maintenance program the maintenance need should be determined, maintenance tasks should be clearly defined in order to determine the best response, and the selected maintenance tasks should be carefully planned in order to ensure that the activities is done efficiently. The CBM tasks, monitoring specifications, procedures, tools and spare parts should be addressed in a maintenance program. Input such as vendor recommendations, P-F intervals, suitable condition monitoring techniques, failure analysis and cost-effectiveness is important for addressing these factors. Establishment of a CBM-based maintenance program would be different than a traditional maintenance program which was described in chapter 2.3.4. The major difference is that the maintenance intervals will not be predefined, as illustrated in figure 5-6.

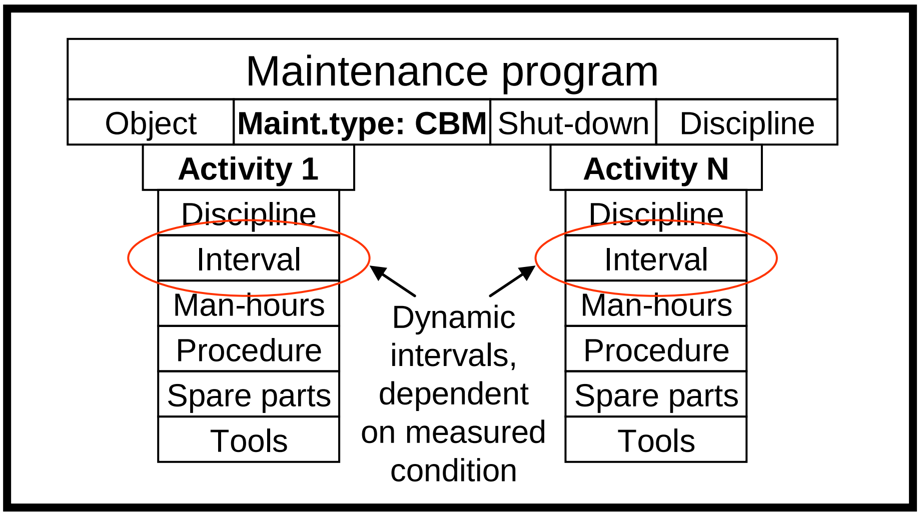

Figure 5-6. Maintenance program with CBM (Based on figure 2-4, Aker Solutions, 2010b)

The activities in a CBM-based program will be triggered by the monitored condition. The activities will therefore be unscheduled until the condition monitoring indicates initial failures. The challenge of establishing a CBM-based maintenance program will therefore be mainly related to trigging and scheduling of maintenance activities. This issue will be further discussed in chapter 6.

6. Implementing CBM

A complete study of the implementation of CBM is not in the scope of this project, but some important issues of implementing CBM will be briefly discussed. Further studies are required to get a full picture of how to implement CBM.

CBM introduces new maintenance work processes and utilization of CBM is usually not a straightforward process. An important aspect of introducing CBM is therefore the implementation process. A complete maintenance program often combines predetermined maintenance, corrective maintenance and condition- based maintenance. CBM lead to increased technical complexity and focus on employee skills and competence. The introduction of CBM leads to new ways of performing maintenance and cause changes in the maintenance management process. As shown in figure 6-1, the measured technical condition is a direct input to the maintenance program (activity, scheduling, trigging) as well as the planning and resource needs. The technical condition will provide important information that can be used as a direct feedback to maintenance program, planning and the resource need.

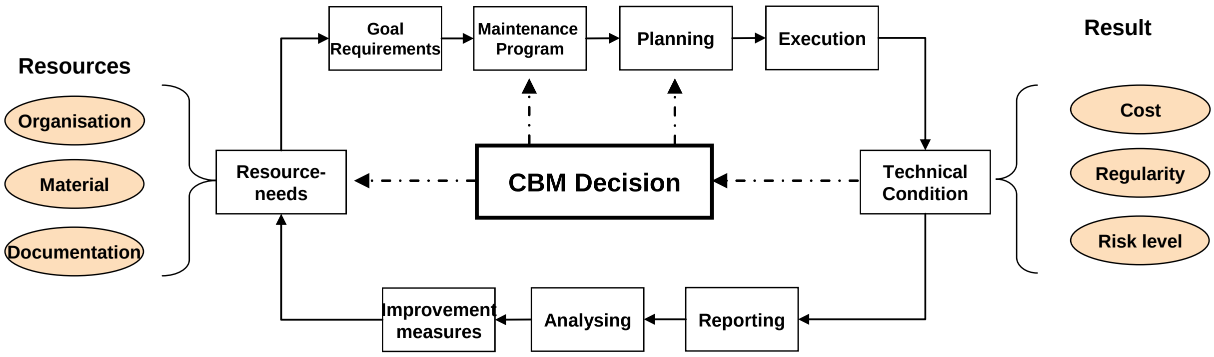

Figure 6-1. Modified maintenance management process (Based on figure 1-1, NPD, 1998)

A major challenge of a maintenance program combining CM, PM and CBM strategies are the *planning of maintenance activities*. Generally, CBM is said to improve scheduling of maintenance activities. But in most cases, the maintenance programs consist of different maintenance types, and thereby also different ways of handling the planning of maintenance actions. Combining static intervals with dynamic intervals creates challenges of the planning of maintenance tasks (Sethyia, 2005). Making sure that the maintenance activities are planned in such a way that it provides minimal downtime can be a complicated issue. The planning of maintenance activities therefore needs to be carefully considered. If an activity initiated by condition monitoring do not match the timing of a predetermined activity it may be necessary to see at the possibilities of moving the predetermined activities. Optimizing maintenance planning will be necessary for implementing CBM (Sethyia, 2005).

A *CMMS* system is an important tool for how to implement the planned activities. The traditional periodic maintenance actions are typically scheduled in a CMMS system in such a way that maintenance work orders are triggered by predetermined periodic intervals or by run-time based intervals. These maintenance actions are either calendar-based or run-time based, hence the frequency of maintenance intervals are defined. In CBM, maintenance actions are triggered by an alarm when there are indications of a failure. The efficiency of a maintenance program that includes CBM activities depends on the trigger levels and how these trigger levels are integrated in a CMMS. There should therefore be a clear connection between the CBM system and the CMMS. As illustrated in figure 2-7, chapter 2.5.2, CBM data will be analysed by the use of expert systems and manual evaluation. Figure 6-2 illustrates how a work order is triggered with the use of CBM. As mentioned will the monitored condition be analysed by a combination of expert systems and manual evaluation. The evaluation, which is done either automatically or manually, should then be decisive whether to trig a work order or not. The work orders should be predefined and be available in a database, so that when a decision is made or the alarm level is reached, the correct work order would be generated.

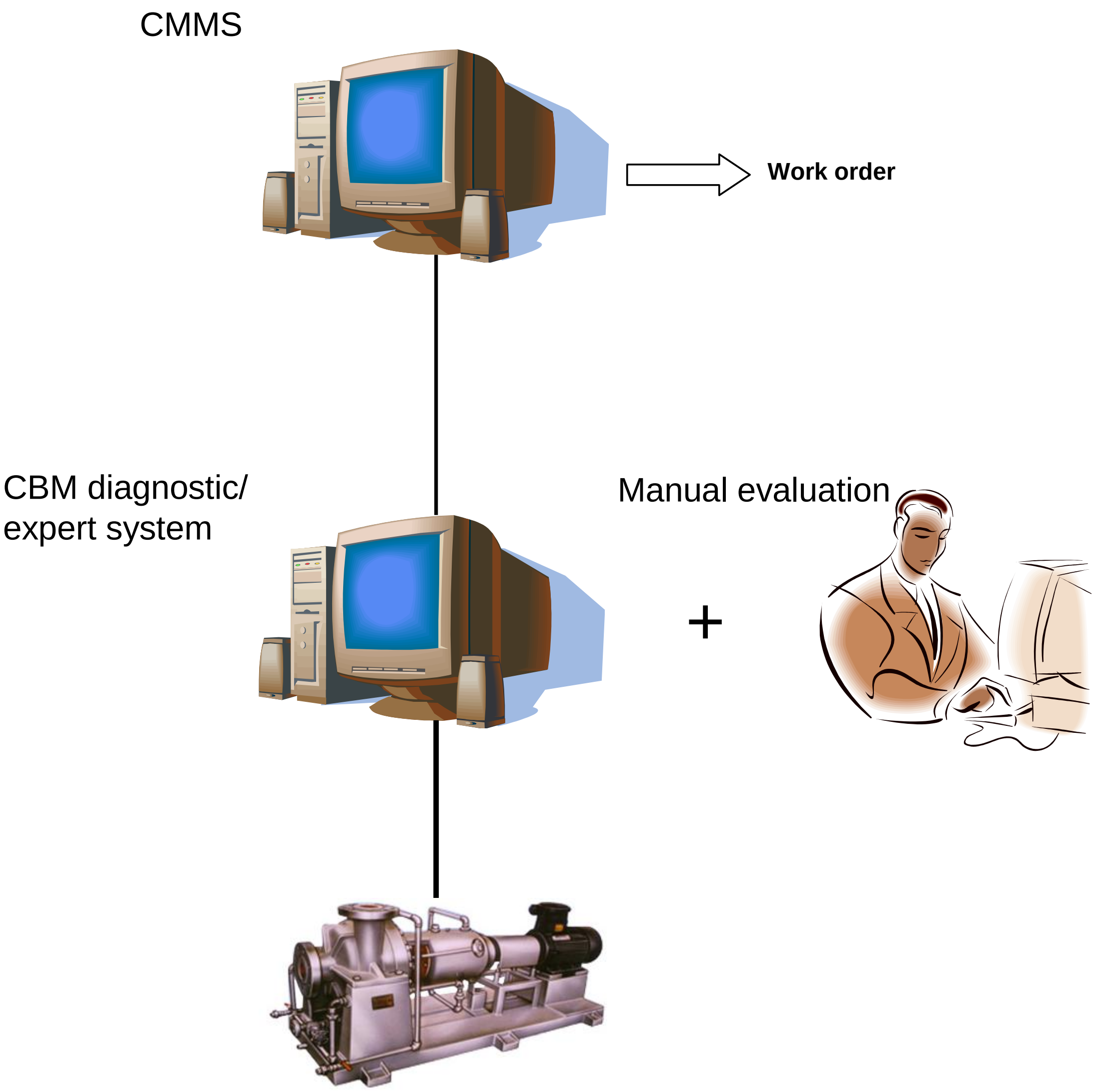

Figure 6-2. Implementing CBM in a CMMS.

In depth knowledge about the equipment is an important factor for performing CBM. In order to prevent failures from occurring, you have to know the equipments failure modes and effects. *Vendor involvement* is an important factor when implementing CBM. The experience of the vendor when it comes to deliver standardised equipment, spares, and services will be important for the maintenance function during the life time of the equipment (Aker, 2009). Although the operator will always have the main responsibility for maintaining their own equipment, the vendors may play an important support role in order to share their expertise. High degree of condition-based maintenance often requires a competent service partner. A huge drawback with vendor involvement is that the vendor will function both as a technical advisor as well as being a service provider and supplier for spare parts. The customer therefore has to be critical with regards to the recommendations from the vendor. Although a vendor should provide thoroughly justified recommendations, it may not always be the case. The service agreement therefore needs to clearly define both the service providers and the service receptors needs and expectations.

7. Discussion and concluding remarks

CBM offers many opportunities and advantages that other maintenance types may not provide. But introducing CBM with all the new technology and new ways of working will also generate challenges. The primary focus of this thesis has been to develop a methodology to ensure a qualified and documented selection of equipment suitable for CBM. Time and resource consuming analyses such as RCM has traditionally been used as a tool for selecting the appropriate maintenance type. But the results from this methodology have to influence the detailed design, and should therefore be performed at an early stage of the project. A simplified process is therefore suggested in order to define the suitability for CBM.

In order to develop the methodology, challenges and opportunities with CBM as well as criteria for selecting CBM have been discussed. Chapter 3, which describes the *challenges and opportunities* with CBM, targets a balanced view of CBM. A decision should be based on a well-considered evaluation, and it is therefore important that the decision makers are competent and are aware of the advantages and disadvantages with CBM. The *criteria* described in chapter 4 include those that are considered most important when introducing CBM. The criteria described are basic criteria and additional criteria may be added if needed. Some organization may have special requirements for CBM and these should then be added to the methodology.

The methodology consists of 7 stages: data collection, criticality screening, equipment categorization, technical feasibility evaluation, cost-benefit evaluation, input to design and input to maintenance program development. One of the most critical steps in the methodology is data collection. Having enough information available to support the decisions is crucial for assuring a qualified and well documented selection process. The methodology would be based on a combination of available data and engineering judgement. Although engineering judgement may provide good decisions, lack of significant data would probably reduce the quality of the methodology. It may therefore be smart to give some extra attention to this step in the methodology.

The coarse criticality screening includes three criticality issues; safety and environment, production and economy. Not all three factors are equally relevant for CBM. Those factors that are most relevant with regard to CBM are production and economy. Criticality with regards to safety and environment would usually require periodic testing and CBM would in a number of cases not be the best solution. If a piece of equipment is regarded as critical with regards to safety or environment, one should therefore be aware of the fact that CBM may not solve the problem.

Equipment categorization is the third step in the methodology and focus in categorizing equipment with similar functions and failure modes. The categorization should be appropriate for the intended use and would therefore vary from project to project. In order to categorize the equipment one should have thorough knowledge of the functions and the failure modes. In order to decide how to categorize the equipment engineering judgement should be used as decision method, but the decision should also be supported by available data such as FMECA.

The technical feasibility stage will be highly dependent on data provided by FMECA. Information regarding the failure mode characteristics is essential when considering CBM. Although experts may provide such information based on experience, they would probably not be able to provide a complete picture. It is assumed that these analyses are provided by the vendor. The methodology may be performed without these analyses, but then the quality would probably be reduced. Performing these analyses on their own has however been regarded as too demanding for the engineering contractor.

Important input data regarding the P-F intervals is also needed. For some random failures, without any clear indications of failure, it would be difficult to actually determine the P-F intervals. It is very difficult to gather data that can tell us something about the P-F interval in the context of this thesis. P-F intervals would therefore be a big uncertainty factor for the specification methodology.

A potential bottleneck for the proposed methodology is the cost-benefit evaluation. The effectiveness of a cost-benefit evaluation will be highly dependent on available information. In order to be effective in an engineering context, a cost-benefit evaluation should include minimal calculations and should be as uncomplicated as possible. The potential complexity of performing all calculations in a cost-benefit analysis will lead to higher requirements with regards to time and resources. In this methodology it is desirable to perform a simplified evaluation. In order to perform a simplified and still satisfactory cost-benefit evaluation, some input information should be available. Such information may not be that easy to obtain. But as explained in chapter 5.5, some cost estimations may be provided by the different involved parties. However, the entire methodology for this study is mainly based on qualitative engineering judgement. The best solution in this phase of a project would probably therefore be to perform a coarse and mainly qualitative cost-benefit evaluation. Although a quantitative assessment is preferable, a qualitative assessment is regarded as sufficient in this context.

The cost-savings taken into account in the cost-benefit evaluation do not include qualitative benefits such as increased plant life, improved safety, reduced personnel risk and improved plant design. These benefits are not that easy to quantify. Although improved safety, for example, can be reflected by cost savings due to avoided major accidents, this would be a far-fetched approach. The best solution will probably be that these benefits are evaluated qualitatively in addition to a quantitative approach.

There have been made many assumptions regarding support from the vendor in this thesis. It is important to clarify that the vendors may not always are able to provide all the support that is required in this methodology. Although increased support from the vendor may be needed, the vendor will also have some limitations. In order to make use of this methodology it is therefore recommended to make sure that the needed data and service can be provided by the vendor. As discussed in chapter 6, one should also be aware of the fact that the vendor is a technical advisor as well as a service provider and spare part supplier. The recommendations from the vendor should be thoroughly justified in order to assure that the vendor does not have any hidden motives.

The timing of the methodology has also been discussed in this thesis. It has been recommended that the methodology should be performed late enough to *obtain* enough input data, and soon enough to *provide* input to design and procurement. Although this way of defining the timing may seem a bit diffuse, it is recommended to use this definition as guidance for where in the process it should be performed. The timing is actually one of the most important factors when dealing with this methodology. One of the main reasons for developing this methodology is to provide important information regarding CBM candidates to influence the design and procurement. And it is therefore important that the methodology is executed in due time. In addition to the importance of gathering enough data and provide input to design and procurement, time and resources will be important factors influencing the timing.

Developing a condition based maintenance program will cause some challenges. One of the most central issues is how the CBM work process will influence the development of a maintenance program. The maintenance program will be the same, except from the planning and trigging of the different PM tasks. From the work process it can be observed that the process of observing, analysing and deciding is not a fully automated process. Although some of the condition data may be analysed by diagnostic/expert systems, some of the data will also be analysed manually. Combining analyses done automatically and manually in order to trigger work orders at the right time would cause challenges. It is therefore recommended that implementation issues also are considered before CBM is introduced.

CBM offers many advantages versus the traditional maintenance types. But this maintenance type will also introduce new challenges. Considering introducing CBM, one should therefore be critical and making sure that decisions are well considered. This thesis has been focusing on identifying some of these challenges and criteria for justifying CBM. The methodology suggested in this thesis reflects important issues that have to be considered when selecting equipment suitable for CBM. However, the methodology should be tested on some practical cases in order to verify the usefulness. It is suggested that cost-benefit evaluation should be a subject for further investigation. Developing an effective cost-benefit model for selecting CBM would make the selection process more effective. In order to justify the use of CBM, there is a need for collecting relevant evaluation data in form of best practice. Further investigation of best practice should help improving a methodology for selecting equipment suitable for CBM.

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