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Methodology for Development of Condition-based Maintenance Program for Surface Drilling Equipment

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Abstract

Maintenance is the essential part of production process in today's industry. There are several philosophies (e.g. corrective maintenance and preventive maintenance) and concepts (e.g. overall equipment efficiency and reliability-centered maintenance) that are applied in industry. The challenge here is to choose the proper ones for the specific operation conditions and equipment. The solution to this challenge can be found through implementation of a reliability-centered maintenance (RCM). This concept implies application of combination of different maintenance policies. The author determines a condition-based maintenance (CBM) as one of the most challengeable policy among them. The development of CBM program needs an application of several complex tools. It is sometimes difficult to use these tools in combination with each other.

The main aim of the thesis is to set up a comprehensive methodology intended to develop the CBM program and ensure its continuous improvement. It is done by using the specific group of equipment (drilling equipment) as an object of case study in order to test and modify the constituents of the methodology. Methods used during the work with thesis are: interviewing, making observations, literature review, questioning, statistical and analytical methods.

The application resulted in identifying of the drilling equipment, which is mostly preferable for monitoring. Different techniques and approaches (e.g. reliability assessment tools) aiding in establishment of the complete CBM program are analyzed and adapted. The International and Norwegian standards related to condition monitoring are assessed according to their possibility of application. There are two aspects that are critical to success of the CBM program development: implementation of the program into the company overall maintenance strategy and availability of data sources (e.g. reliability data).

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Notations and Abbreviations

AHC	Active heave compensation
TPM	Total productive maintenance
CA	Criticality analysis
CBM	Condition-based maintenance
CM	Condition Monitoring
CMMS	Computerized maintenance management system
CS	Drawworks control system
DCS	Drillers control system
DNV	Det Norske Veritas
DP3	Dynamic positioning system (class 3 requirements)
ETTF	Estimated time-to-failure
FMEA	Failure mode and effect analysis
FMECA	Failure mode, effect and criticality analysis
FMMA	Failure mode and maintenance analysis
FMSA	Failure mode and symptom analysis
GMC	Generic maintenance concepts
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
KPI	Key performance indicator
MODU	Mobile offshore drilling unit
MRU	Motion Reference Unit
MS	Mechanical System
MTBF	Mean time between failures
MTTF	Mean time to failure
MTTR	Mean time to repair
NCS	Norwegian Continental Shelf
NOK	Norwegian krone
Norsok	Norwegian standard
NOV	National Oilwell Varco
O&G	Oil and gas
OBM	Opportunity-based maintenance
OEAD	Operation earnings after depreciation
OEE	Overall equipment effectiveness
OREDA	Offshore reliability data
PMS	Power Management System
Q&D	Quick & Dirty decision charts
RBD	Reliability block diagram
RBI	Reliability-based inspection
RCA	Root-cause analysis
RCFA	Root-cause failure analysis
RCM	Reliability-centered maintenance
RPM	Revolutions per minute
VSDS	Variable speed drive system

Terms and Definitions

availability
is the ability of an item to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval, assuming that the required external resources are provided (ISO 14224 2006)

benchmarks
determine the performance of the organization in key areas and can then be used for comparison, usually external, against organizations in the same or similar industry, or against organizations in different industries that have similar business processes (ISO 14224 2006)

best-in-class companies
is the companies with the highest performance level in a particular segment of the industry and are used as criteria for comparison (Faller 2008)

Boolean algebra
is a mathematical system using deductive approach and operating with values zero and one (false and true) (Gregg 1998)

common-cause failure
is a failure of different items resulting from the same direct cause, occurring within a relatively short time, where these failures are not consequences of another (lead to the common mode failure) (ISO 14224 2006)

common-mode failure
occurs when multiple components break down with equal error of individual outputs (Voas et al. 1996)

condition monitoring
is a tool to determine the health or condition of the equipment by monitoring parameters reflecting the mechanical state of the machine (Markeset 2011)

condition-based maintenance
is the maintenance policy where the system is monitored by a set of sensors which allow to track its state and decide whether a maintenance action is needed or not (Tobon-Mejia et al. 2010)

corrective maintenance

is a maintenance to be carried out after fault recognition and intended to put an item into a state in which it can perform a required function

dead line
is a part of drilling line between crown block and derrick leg (Skaugen 2011)

earning power
is a benchmark that shows the ability of the organization to create profit from performing its operations (Investopedia 2012)

equipment subunit
is an assembly of items that provides a specific function that is required for the equipment unit within the main boundary to achieve its intended performance (ISO 14224 2006)

equipment unit
is a specific equipment unit within an equipment class as defined by its boundary (e.g. one pump) (ISO 14224 2006)

estimated time to failure
an estimation of the period from the current point in time to the point in time where the monitored machine is deemed to be in the failed condition (ISO 13381 2003)

exponential distribution
is the continuous distribution that refers to the time between events described by a process when events happen continuously and independently at the same average rate (Sheldon M. Ross 2009)

failure cause
is circumstances associated with design, manufacture, installation, use and maintenance, which have led to a failure (ISO 14224 2006)

failure mode
is an effect by which a failure is observed on the failed item (ISO 14224 2006)

failure mode, effects and criticality analysis
is a process that adds an economic, financial, and/or safety component to FMEA to assist in maintenance management decisions (ISO 13381 2003)

failure modes effects analysis
is a pre-production design and development aid to try to determine the ways that a machine could fail and assess the associated effects that such failures (ISO 13381 2003)

failure modes and symptoms analysis
is a process that is based on FMECA and documents the symptoms produced by each mode and the most effective detection and monitoring techniques in order to develop and optimize a monitoring programme (ISO 13381 2003)

fast line
is the part of drilling line between drawworks and the crown block (Skaugen 2011)

frequency converter

changes an alternating current from one frequency to another, with or without a change in voltage or number of phases (McGraw-Hill 2002)

generic maintenance concept
is set of maintenance actions, strategies and maintenance details, which demonstrates a cost efficient maintenance method for a defined generic group of equipment functioning under similar frame and operating conditions (Norsok Z-008 2011)

key performance indicator
is used for managing an improvement on an ongoing basis, and for determining the progress towards a predetermined target (ISO 14224 2006)

maintainable item
is the item that constitutes a part, or an assembly of parts, that is normally the lowest level in the equipment hierarchy during maintenance (ISO 14224 2006)

maintenance concept
is a set of policies and activities planned and supported by decision structure (Pintelon & Puyvelde 2006b)

maintenance policy
represents a rule or a set of rules describing condition for the variety of maintenance activities (Pintelon & Puyvelde 2006b)

mathematical model
is combination of laws describing the system by using a mathematical concepts which includes both physical and statistical part (Bender 2000)

memory less property
is when just-maintained equipment has the same chance to fail as the new one (Walpole et al. 1998)

multiple failures
are the failures occurring simultaneously or within a very short time of each other (IEC 62502 2010)

opportunity-based maintenance
is maintenance of an item that is deferred or advanced in time when an unplanned opportunity becomes available (ISO 14224 2006)

overall equipment effectiveness
is intended to assess and indicates the efficiency of production (Pintelon & Puyvelde 2006b)

Pareto analysis
is aimed to identify the most critical systems, equipment and areas in plant (Andrews & Moss 2002)

precision maintenance
is the maintenance philosophy that in addition to condition-based maintenance is intended to find-root cause of failure and reduces the chance of problem to appear (Mobius Institute 2009)

preventive maintenance
is 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 (ISO 14224 2006)

reliability block diagram
is a tool to analyze the system availability and reliability by utilizing block diagrams in order to show network relationships (Andrews & Moss 2002).

reliability-centered maintenance
is identified as the methodology applied to create comprehensive overview of the equipment and also to realize the most convenient maintenance approach in order to achieve required availability, safety and production of the operation (IEC 60300-3 2011)

risk analysis
is the combination of initiating event, consequences of this event and uncertainty associated with both event and circumstances (Flage & Terje Aven 2009)

risk assessment
is a combination of risk analysis and risk evaluation, which is intended to compare risk against given acceptance criteria in order to determine the risk severity (Flage & Terje Aven 2009)

root-cause
is a root cause set of conditions and/or actions that occur at the beginning of a sequence of events that result in the initiation of a failure mode (ISO 13381 2003)

single point failure
is the failure that leads to loss of function of the whole system simultaneously (Abouamin et al. 2003)

symptom
is a perception, made by means of human observations and measurements (descriptors) which may indicate the presence of one or more faults with a certain probability (ISO 13379 2002)

1. Introduction

The main goal of this chapter is to introduce the current situation in the industry related to condition monitoring and discuss the importance of the problem investigation. Main objectives, deliverables, scope of work and limitations will be explained as well.

1.1 Background

According to Norsok Z-008 (Norsok Z-008 2011) there are three main criticality areas for oil and gas (O&G) industry: health and safety of the personnel, production and environment. The company wants to gain as much as possible profit with ensured safety and minimum environmental impact. Availability of the equipment is the core term for maintenance activities in the industry. The company is intended to ensure maximum performance of the equipment and its availability. The reason to that is the cost associated with operating of production or drilling rig. The daily rate makes about 1.4 mill NOK and 57.000 NOK per hour (Abouamin et al. 2003). Degradation of the critical equipment such as a top drive may result in thousands and sometimes millions loss in today's market. That is why growing number of companies apply modern maintenance philosophies (e.g. predictive and proactive) that were not relevant in the past.

New approaches bring new challenges. The main challenge here is the correct implementation. Sometimes a new method or methodology is not carefully introduced to the personnel and lose its value due to the fact that not all the benefits are understood and applied in the right way. Another challenge is the increased complexity of modern machines. More failure modes are introduced with more complex machine. It implies higher requirements for design review, analysis of failure cause and consequences (Abouamin et al. 2003). Generally O&G industry is conservative due to the high amount of resources involved in the process and high risks associated with it. In order to accept the new maintenance philosophy benefits and costs should be carefully investigated. The process may take long time and demand significant investments.

The risk analysis term is becoming more common in today's industry. People cannot assess the risk as it has been done in the past, considering probability of event and consequences only. Due to increased complexity and severity of consequences both for operations and equipment the human is no longer capable to perform risk assessment at the same confidence level as before. Maintenance planning and risk analysis have become very interrelated terms. In order to ensure the correct planning of maintenance activities, both significant amount of input reliability data and risk consideration are needed. Risk assessment is not only the tool; it is the way of thinking and acting. It is the philosophy that should be taken through designing, planning and operating.

Best-in-class companies start to invest in technologies to predict failure and get the comprehensive image of the machine state (Faller 2008). About 27% of the companies achieved over 10% of maintenance costs reduction (Faller 2008). On the other hand unnecessary maintenance or incorrectly chosen and applied maintenance philosophy is often the case. Companies are losing millions of NOK cause of wrong maintenance planning.

1.1.1 COSL Drilling Europe AS and COSLPioneer (mention about)

The current master thesis was written with the support from the drilling company called COSL Drilling Europe AS. COSL is a subsidiary to China Oilfield Service Limited. The company is located in Stavanger, Norway. COSL owns two accommodation rigs and three drilling rigs. The main mission of the company is: "to build and operate fit for purpose semi-submersible drilling units and provide world-class offshore drilling and well operations anywhere in the world". Accommodation rigs, COSLRigmar and COSLRival are operating on Norwegian Continental Shelf (NCS) and UK. The company owns four new almost identical mobile offshore drilling units (MODU) called COSLPioneer, COSLInovator, COSLPromoter and COSLProspector. The fourth rig, COSLProspector, is still under construction at Yantai CIMC Raffles. COSLPioneer was awarded a 5-year contract with Statoil and was put into operation in Mai 2011. COSLInovator and COSLPromoter are still at the stage of preparation for drilling activities.

COSLPioneer is designed to operate in water depths up to 750 meters and the North Sea/ Norwegian Sea and world – wide use in harsh environment. Eight line mooring system and six variable speed thrusters (DP3) maintain the constant location of the drilling rig. Main deck has a length equals to 81 meters, width to 65 m, and elevation above baseline to 36,85m. Pontoons length, width and height are respectively 104x16.25x9.75. COSLPioneer has recently started its operations and the base maintenance program was built up. The program has already included some condition monitoring activities, but there are still several areas of opportunity for predictive maintenance strategy. The essential and critical systems at the MODU are related to drilling. That is why the project is aimed at assessing the surface drilling equipment for possible condition monitoring. The main vendor of surface drilling equipment for COSLPioneer is National Oilwell Varco (NOV), the leader in providing mechanical components for offshore drilling rigs.

1.2 Problem Description

Let us start with a citation that describes the one of the main challenges related to maintenance planning in today's industry: "Knowing when a piece of equipment is going to fail is much more difficult than making it last long" (Fitch 2006). More companies start monitoring condition of their equipment both online or periodically than before. But decision to monitor every single machine is not the appropriate approach. First of all, not every machine can be monitored; secondly, condition monitoring needs resources to be raised. By unnecessary monitoring, companies increase maintenance costs significantly and lose profit.

The proactive way to do that is called reliability-centered maintenance (RCM). It implies the combination of maintenance strategies. By performing system analysis, machines are divided into different groups utilizing different maintenance approaches. For one group the periodical maintenance will be the best option, for another one condition monitoring (CM) is preferable. In order to fully implement RCM approach companies have to follow the specific methodology that is hard to find the comprehensive description of. One of the reasons could be that the RCM is a concept that is not often fully implemented as a part of maintenance strategy of the company. The difficulties associated with generalization of this approach could be another reason.

There are several ISO and Norsok standards that contribute to the process of establishing maintenance program, but very few of them show the application through examples. From the author's point of view one of the most challengeable parts of RCM is to establish the condition-based maintenance program (CBM). There are several tools that can assist in that process but not so many examples showing implementation of them in one comprehensive methodology aimed to establish CBM program and ensure continuous improvement of it.

Nowadays due to reliability databases and wide range of standards it is possible to get access to data and methods needed by engineer. The "bottleneck" here is not the data and methods itself, but the adaptation for specific systems, interpretation and decision-making based on results. In order to show us pros and cons of utilization of powerful reliability tools and data we should attempt to assess those in combination with each other, integrated into specific sequence of activities.

This can be summed up in the following issues:

1. What data and steps should be used in establishing condition-based maintenance program?
2. How to integrate different reliability methods together into one sequence?
3. What equipment is necessary to be monitored using CM techniques?
4. How to use the information on equipment condition in decision making?
5. How to ensure profitability of maintenance activities?

1.3 Main Goal of the Research

The aim of the thesis is to develop the methodology for planning and execution of condition-based maintenance (CBM) for surface drilling equipment. Achieving the main goal will contribute to:

1. Continuous optimization of maintenance strategy
2. Reduction of risk and costs associated with reliability of surface drilling equipment
3. Increase in productivity for the whole drilling rig
4. Reduction of corrective maintenance
5. Extension of lifetime, increase of reliability and performance of surface drilling equipment
6. Allocation of main bindings and interrelationships between equipment and failure mechanisms

1.4 The Scope of Work

The detailed description of activities and associated deadlines are provided in Attachment 1. Basic areas that the project is looking into are:

1. Modern surface drilling equipment and its role in operation
2. Commonly used maintenance practices in O&G industry
3. Criticality analysis and rough ranking methods
4. Common risk-analysis tools and RCM philosophy
5. Condition monitoring techniques and systems
6. Cost-benefits analysis of maintenance activities

1.5 Main Deliverables

The project is aimed to contribute to the engineering society and O&G industry, in particular, with following deliverables:

1. Methodology for development and continuous optimization of CBM program.
2. Surface drilling systems rough ranking criteria based on criticality evaluation.
3. Reliability assessment framework to decide about the type of surface drilling equipment to be assessed for CM.
4. Adaptation of reliability assessment tools for CBM program development process.
5. Methodology for deciding what parameters should be monitored
6. Method for diagnosing, prognostics and presenting of CM results.

1.6 Methods

It is important to choose the correct research method in order to collect the data needed or test the concept. There two basic types of research studies: qualitative and quantitative. Qualitative research operates with meanings and words suitable for description and understanding of input data. In quantitative research the data are received as quantitative measurements or counts and are suitable for statistical analysis (Wiersma & Jurs 2004).

The research method used during the project execution could be defined as a mixed method (Wiersma & Jurs 2004). It implies the use of both the qualitative and quantitative data methods. Qualitative method is used in order to understand and describe ideas of supervisors, experience of experts, project uncertainty and results. Quantitative method assists mostly in criticality evaluation and risk assessment part by translating results into values. Mixed method allows the research to gather information through interviewing, making observations, literature search, questionnaires, statistical and other methods from both paradigms.

The approach used in the research execution is developed by the author himself. Though the similar procedure is described by Alan Hevner in his book "Design Science in Information Systems Research" (Hevner et al. 2004). It includes the following main steps:

1. Problem definition
2. Development of the initial concept
3. Testing the solution on specific example
4. Evaluation of the testing results

5. Improving the concept based on previous step
6. Description of the pros and cons of the final solution

The reason the author has chosen this particular approach is the possibility for continuous improvement of the solution by using the data collected from new tests and experiments.

1.7 Delimitations, Limitations and Assumptions

This chapter provides the information about what the author doesn't plan to cover and assumptions needed for performing the research. Delimitations are the features of the project that determine the scope of work in proposed topic of the thesis (Cline & Clark 2000) . Limitations are special characteristics that reflect on the complexity of the research and application or interpretation of the final results (Cline & Clark 2000). Assumptions describe necessary conditions that are assumed to be correct in order to carry out the research.

Delimitations:

1. The research covers only the specific type of surface drilling equipment installed particularly on MODU COSLPioneer
2. All applied data is mostly related to Norwegian O&G industry.
3. The research is based on ISO, IEC and Norsok standards recommendations.
4. Amount of available literature and sources is limited by the university library and company archives.

Limitations:

1. Consequences will be mostly related to health, safety, environment and production and implies the complete loss of function.
2. Not all parts of the methodology are tested. Cause of limited amount of time the author decided to test, from his point of view, the essential steps of the methodology by applying it to the real case.
3. Almost all methods in the project are borrowed from publications and other sources. Some of the borrowed assessment tools are processed and changed by the author. It was done in order to fit existing methods to the project scope and features.
4. Only CBM strategy is considered. The thesis provides the description of main maintenance philosophies and lists its pros and cons. Although the research will look only at CM possibilities for surface drilling equipment. Other types of maintenance approaches will not be applied to the main case study.
5. Main CBM methodology will assist in choosing one of the most essential components and recommend it for condition monitoring. Depth of the component sublevel to be assessed is determined by the possibility and expediency of its maintenance.

Assumptions:

1. In order to simplify the methodology test, all the information related to the criticality analysis, maintenance history of equipment and system-components relations available internally at the company is assumed to be correct.

2. Reliability data collected from the OREDA database is assumed to be correct. It means that the author checked only those values that are calculated based on the input data, whereas the quality of input data is not checked. The reason is that the main focus of the thesis is on the methods and tools, and less consideration is given to the quality of used values.
3. Information from the experts from inside and outside COSL is assumed to be correct.

Thesis describes the uncertainty associated with the assumptions and consequences listed above. The project contains several assumptions and uncertainties that are described and explained in other parts of the report.

1.8 Thesis Outline

The whole report consists of six chapters. The first chapter called “introduction” presents the project with its main goals, results and background information. In the “theory” part the author describes surface drilling equipment on modern drilling rigs and main advantages and disadvantages associated with this equipment. Much attention will be given to general maintenance philosophies used nowadays and RCM in particular. Besides the theory chapter provides an overview of risk assessment process during the development of maintenance strategy. The analysis of costs associated with maintenance will be also considered and evaluated. One of the main focus areas in the theoretical part is the CM.

The description of CM concept and main techniques used for collecting, transferring and analyzing data are given as well as diagnosis and prognosis of the failure mode is provided. The third chapter of the report deals with (the case study) how the case study was carried out. Main methods of research and associated challenges are discussed and evaluated in this part. The next chapter presents the thesis results, which include main outcome and associated uncertainties. This part describes each step of final methodology for development of CBM program and outcome of its application. The main choices and modifications made during development of the final methodology will be explained.

The chapter five is aimed to provide a comprehensive analysis of achieved results. The CBM methodology is evaluated based on its advantages and disadvantages. In addition, possible improvements and new ideas related to RCM and CBM in particular are discussed and recommended. In the conclusion part the brief summary of the results is given. In addition the author gives an overview of possible future activities needed to develop the research and application areas.

2. Theory

This part gives an overview of work that has been already done related to maintenance strategy development and risk assessment. In addition to that, relevant international and Norwegian standards are considered. The chapter will start with description of commonly used modern surface drilling equipment and continue further with maintenance practices.

2.1 Modern Surface Drilling Equipment

2.1.1 Drilling Equipment Overview

In order to understand main challenges related to maintenance activities for drilling topside equipment the author decided to study this topic and create an overview. There are two books that contributed to this process:

1. "A Primer Of Oilwell Drilling" by Dr. Paul Bommer (Bommer 2008)
2. "A Primer Offshore Operations" by Ron Baker (Baker 1998)

According to A Primer Of Oilwell Drilling (Bommer 2008) there are four main types of drilling equipment for topside:

1. Derrick equipment
2. Hoisting equipment
3. Rotating equipment
4. Mud treatment and pumping equipment

2.1.1.1 Derrick

The steel beam tower is traditionally used as a derrick on MODU. The average height is around 60 meters. The derrick is located on the drill floor. The area on the drill floor or above may contain all the equipment related to handling, storing and operating the drill string. The pump floor is right below the drill floor. There one can find equipment for mixing, cleaning, pumping and storing of drilling mud (Gusman & Porozhskogo 2002). The wellhead and safety equipment (e.g. BOP) on fixed platforms are right below or on the pump floor. The derrick design for floating structures is almost the same except that the wellhead and the BOP are located on the seabed.

2.1.1.2 Hoisting equipment

Block and tackles coming from the derrick top are used to lift drill string and other equipment. The line runs up from the cable drum on the drill floor to the crown block down to the running block and up again, making totally from 4 to 6 times. Then the line runs to the dead anchor with force transducer that shows stretching on the line mud (Gusman & Porozhskogo 2002). The fastest moving part of the line called "fast line" is located between cable drum and crown block. The so-called "dead line" between crown block and dead anchor is not moving at all.

The hoisting equipment is capable to lift up to 300 ton. In this case the line in the block and the tackle must be capable to take a load of about 30 tons with 7 wheels in the traveling block (Baker 1998). The drilling string cannot itself take so much load, but BOP or large casing strings are able to.

The cable drum is often driven by an electrical motor, via reducing gears or V-belts, and a clutch. The clutch is designed to disconnect the drum and a motor while loading the load. During the loading operation, the powerful brakes are used and the potential energy is transformed to heat. In order to carry away the heat from the break the water is pumped through (Skaugen 2011). There are often two types of breaks used for hoisting system: mechanical and electromagnetic. In case of electromagnetic break, there is a dynamo that is able to produce the current when it is rotating. Approximately 90% of braking energy can be disposed of in big resistors.

The alternative way to carry away the current generated by brakes is heating the rotor and housing; and use water to cool the rotor. The breaking process is the result of magnetic field regulation created by the electromagnets in stator (see Appendix A). The electromagnetic brake can't provide the immediate and complete stop of lowering operation due to the fact that braking force is proportional to the rate of drum rotating. The mechanical brakes are often presented as calipers on both sides of the drum and are used for slow lowering rates. In this case the force applied to the breaking shoes is constant and independent of the drum rotating speed (Skaugen 2011).

The calipers can't provide so much breaking power as electromagnetic break can. Therefor both types of brakes are used. The main challenge for mechanical brake assembly is that the heat generated between calipers and drum is not so easy to be carried away and cooled rapidly from inside of the drum. Summarizing the information given above there are three main procedures for braking (Bommer 2008):

- Use only electromagnetic brake while lowering loads at high speed
- Use mechanical brake to carry out lowering loads at relatively low speeds
- Use only mechanical brake to keep the load at a fixed position

2.1.1.3 Equipment for Rotating and Handling Drill String

There are two types of equipment used to rotate the drill string: top drive and rotating table. The top drive is mainly the combination of motors coupled directly to the drill string. The rotating table is located at the same level as the drill floor and runs on rollers by the electric motor. The rotating table is seldom used in today's offshore industry, but it can be still be used to correct the direction and turn large strings of casing mud (Gusman & Porozhskogo 2002). That's why modern MODU have both top-drive and rotating table.

The top drive hangs from the traveling block and assists in pumping of mud into the top of dill string through the connection that is able to rotate freely (swivel). Through the flexible hose and standing pipe the mud pump is connected to the swivel. The average length of the drill pipe makes 10 meters (Skaugen 2011). At the beginning of operation all pipes are joined one by one to the string top, but later nearly every third joined (stand) is uncoupled and stored vertically on the drill floor (see Appendix A). It is done in order to reduce time needed to pulling the string out and setting it down again (tripping). The reason for tripping could be changing equipment, possible repairs, setting a new casing string or changing the drill bit/nozzle size (Baker 1998).

2.1.1.4 Mud Mixing and Treatment Equipment

Drilling mud is the liquid consisting of different components. Those components are mixed at the drilling rig and stored in the large tanks with capacity of hundred cubic meters. It is done by low pressure pumps. High pressure pumps are used for pumping mud down the drill string. In order to keep heavy small particles of mud in suspension and avoid their sinking down to the bottom storage tanks, the paddles are continuously rotated (Skaugen 2011). The returning mud flows to the shale shaker that removes drilling cuttings. During the vibration of slanted screen, gas bubbles inside the mud will disappear as well. Other small particles like oil and water that the returning mud may contain can be removed by secondary mud cleaning system (e.g. centrifuges, hydro cyclones and degassing units). There are still some types of contamination such as clay, small oil drops and very small solid particles that will be hard to remove because some of them are meant to be there.

The mud comes from the storage tank through the low pressure pump to the high pressure pump and then further to drill string. Usually it is so-called tri-axial piston pump having three single acting pistons (see Appendix A). They are driven by a common crankshaft, which transforms reciprocating movement of piston into rotation (Skaugen 2011). High-pressure pump outlet is connected to the pulse damper that is aimed to reduce the volume flow even more than it is done by three pistons with the phase displacement of 120 degrees (Bommer 2008). Pulse dumper is a special container between the high-pressure pump and the drill string that maintains the same pressure in mud with help of membrane based on a large volume of a compressed gas (e.g. nitrogen). The challenge here can be associated with possibility of solid particles in the mud to penetrate between the plunger and the liner. That can be avoided by utilizing proper pressure seals for each plunger.

2.1.2 Critical Surface Drilling Equipment

Based on maintenance historical data, industry determined what type of drilling equipment might be critical and bring serious consequences. Generally critical equipment can be defined as system's failure of which may lead to total stop of the operation, financial losses or serious safety issues (Faller 2008). In the last decade drilling industry went from manual operation of machinery to advanced autonomous systems controlled by the computer and operated by human-machine interface (Abouamin et al. 2003). Equipment modernization leads to the increased complexity of equipment, maintenance and operations. As the result of it the failure patterns change and come closer to the curve showed in Figure 1.

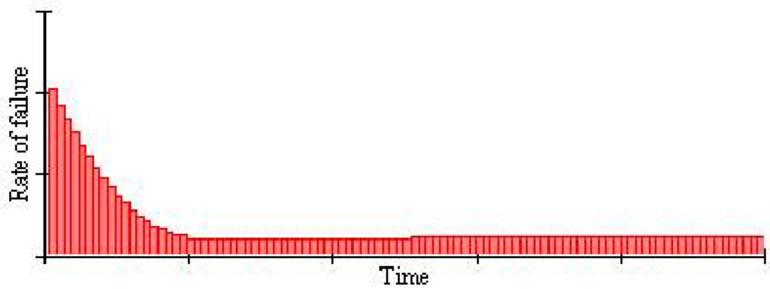


Figure 1: Wear Pattern (Holme 2006)

It implies that the modern drilling equipment has the highest probability of failure in the beginning of its operation. Based on that fact and features of today's remote offshore environment (some of the components don't have spare parts available on board) the following components were rated as the most critical ones (Faller 2008):

- Top drives
- Draw works
- Mud pumps
- Engines/motors
- Pipe handling system

By evaluating consequence of losing a top drive function we can conclude that the operation will stop completely and serious injuries may occur (cause of falling objects). At the same time maintenance history shows that this type of equipment is often served. There are several types of drawworks utilizing on the MODU, and active heave compensating is considered to be one of the most complex and critical operations.

If drawworks is not available, and not able to compensate for heave during drilling operation, it might lead to dramatic consequences both for production and safety of personnel. Loss of high pressure mud pumping may affect the well control and safety. The frequency of failure for this equipment is generally high. Diesel power generators are very critical for safety to maintain DP3. It may lead to loss of power for drilling operations. Fortunately the failure probability is not so high and other emergency equipment is available to perform diesel power generators function. Vertical pipe handling has the main function to handle critical equipment for drilling operation. The unavailability of this function may lead to danger of falling objects and total shutdown of drilling operation. Failure probability of this type of equipment is relatively high.

2.1.4 Active Heave Compensating Drawworks

The author decides to give a brief introduction to active heave compensation drawworks (AHC Draw works). It's done due to the fact that biggest part of the project research considers this type of equipment in particular. AHC drawworks contributes with following main functions: block hoisting, lowering, holding/stopping/parking and heave compensation. One of the biggest challenges for AHC is the variety of vendors providing different sub-systems (Abouamin et al. 2003).

The important feature of drawworkss hoisting sub-systems integration is that each vendor should consider the consequence of single point failure and the equipment importance. The single point failure in our case is the failure that leads to loss of function of the whole system simultaneously. The overall safety of AHC drawworks could be achieved if control signals, sensors, common signals, man-machine interface and etc. is evaluated both separately and as part of one complete system. It can be done by improving the cooperation between vendor and customer. The common active heave hoisting system has the following main subsystems (Abouamin et al. 2003):

- Driller's Control System (DCS)
- Drawworks Control System (CS)
- Mechanical System (MS)
- Variable Speed Drive System (VSDS)
- Vessel Power Management System (PMS)

In order to be able to control the speed of drum CS considers requested speed from the operator, signals from the Motion Reference Unit (MRU) (measure the vessel oscillation) and power getting from power generators. The result speed is used by VSDS to control the AC-motors (by using frequency converter) on Drawworks that contribute both with the hoisting power and dynamic brake.

As part of the VSDS one can find the resistor system that makes possible to regenerate power due to motor breaking. There is a hydraulic system for emergency braking, park braking and slow lowering operation. During the execution of this master thesis the author draws special attention to components effects of failure and global failure effects in particular. It is done in order to evaluate how the consequences of one failure affect the whole drilling operation. Three main categories of global failure effects categories for drawworks are determined (Abouamin et al. 2003):

1. Loss of control (when uncontrolled movement may lead to collision, safety hazard or dropped load)
2. Loss of heave compensation (when during the drawworks normal operations the heave compensating function is unavailable)
3. Shutdown (when unavailability of the AHC drawworks leads to the significant operations downtime)

2.2 Overview of Maintenance

The main objective of this chapter is to provide a description and pros and cons of common maintenance practices and consider in detail, according to author's point of view, the most relevant for the current research. In order to deal with various maintenance practices we should give the definition of this term according to ISO 14224:2006 (ISO 14224 2006):

"Combination of all technical and administrative actions, including supervisory actions, intended to retain an item in, or restore it to, a state in which it can perform a required function."

By carrying out the proper planned maintenance such issues as catastrophic failure, secondary damage, additional spare parts costs, unnecessary overtime and injury to stuff can be avoided (Mobius Institute 2009). As the result the uptime of the equipment may be increased and maintenance costs may be reduced. Maintenance costs are a wide topic and may cover various components of the total cost:

- Spare parts costs
- Overtime maintenance hours
- Loss of production
- Secondary damage to equipment (damage occurred as the result of primary failure)
- Energy consumption
- Etc.

Different types of companies have various ways to measure the success of the operations. In some cases keeping machine running is essential and failure of the equipment must be avoided in order to prevent huge casts associated with loss of production. In other cases, for instance, for supply vessels during the operations in the arctic, it is important to be prepared and be available for "operation windows" due to weather conditions. Maintenance planning varies according to the goals of the organization.

There are two definitions that one has to be aware of: maintenance policy and maintenance concept. Maintenance policy represents a rule or a set of rules describing condition for the variety of maintenance activities. Maintenance concept is a set of policies and activities planned and supported by decision structure (Pintelon & Puyvelde 2006b). There are four commonly used maintenance policies (Mobius Institute 2009):

- Breakdown maintenance
- Preventive maintenance
- Predictive maintenance
- Precision maintenance

2.2.1 Common Maintenance Policies

The first question that may contribute to better planning of maintenance is: "Why and how do machine fail?" The reason of failure could be everything from the design phase to maintenance program and working conditions. The understanding of potential sources and mechanisms of failure is the core precondition for improvement of equipment reliability.

2.2.1.1 Breakdown Maintenance

The main point of breakdown maintenance philosophy is that the machine is allowed to run until failure without preventive actions. This approach is cost-effective only for few types of components (e.g. light bulbs) and companies. It may be done in case if the repair costs exceed the costs of failure consequences. For most of the equipment related to offshore drilling industry this "Run-to-failure" philosophy may bring significant expenses. It may include secondary damage to the machine, additional spare-parts costs, overtime labor, production downtime and etc. There is no control involved in this maintenance approach that may significantly affect production and safety of operation.

One of the main advantages of the Breakdown maintenance is that no condition monitoring or preventive maintenance costs are involved. According to the characteristics of exponential distribution that is often used for statistical analysis of components failure, the just-maintained equipment has the same chance to fail as the new one (memory less property) (Walpole et al. 1998). The "run-to-failure" philosophy avoids over-maintenance. The number of disadvantages here exceeds advantages. Among them are: unplanned downtime, loss of production, reduced operations safety, high costs of repair, secondary equipment failure and lack of control.

2.2.1.2 Preventive Maintenance

Preventive maintenance may be called as: time based maintenance, calendar-based maintenance, planned maintenance and etc. (Barratt & Reed n.d.). The main point of this approach is to perform regular overhauls before the machine fails thus extending its lifetime. This philosophy is based on specifics periods between maintenance activities established according to the maintenance history and statistical analysis.

The important part of this type of maintenance and one of the most uncertain is the balance between overhaul costs and risks associated with equipment failure. The challenge here is the precise estimation of machines lifetime (Barratt & Reed n.d.). If it is overestimated and maintenance is planned to be performed too late, the component may fail. On the other hand if the lifetime is overestimated (maintenance is performed too early) the costs associated with overhaul activities and labor will be unnecessary high. The "bottleneck" of this approach is that it is assumed that the machine follows specific failure pattern showed in Figure 2 (Holme 2006).

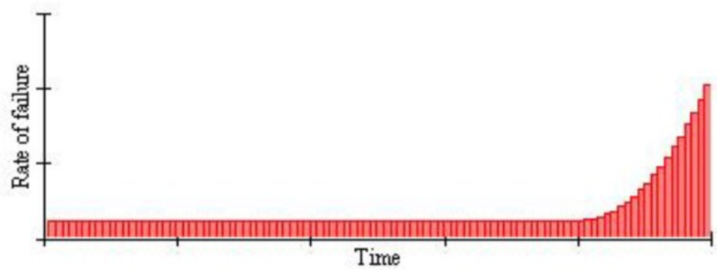


Figure 2: Wear Pattern (Holme 2006)

Based on the article (Holme 2006) very few components follow the curve presented in Figure 2. Most of the modern equipment as mentioned before has high failure probability at the beginning of its utilization (see Figure 1). It may happen due to improper maintenance, poor lubrication, incorrect parts being installed and etc. Thus, unnecessary performance of maintenance activities may often lead to higher risks of machine failure (Mobius Institute 2009).

The advantages of this approach in comparison with the previous one is that the failure is often prevented, few catastrophic failures occur and there is better control over spare parts and costs. The disadvantage with preventive maintenance is that machine is over-maintained, which may lead to even more breakdowns than without performing overhaul at all (Barratt & Reed n.d.).

2.2.1.3 Predictive Maintenance

Fortunately the machine is able to provide to us some symptoms before failing. It could be the increased vibration in some parts of the equipment, abnormal temperature level, too many metal particles in lubrication and changes in current. All of these and other signals may predict the imminent failure of the system and the maintenance activities could be planned according to this information. That is what the predictive maintenance approach is about: “Don’t fix it if it’s not going to break”. Ideally by utilizing this approach the lifetime of the machine supposed to increase and maintenance costs - to reduce. It could be done by using the opportunity-based maintenance which the author will talk about later. It implies that the maintenance and repair may be done at a time that suits current operation activities and schedules. But there are several “pitfalls” here.

First of all, not all of the machines can be and have to be monitored. Secondly, failure mechanisms and patterns are often uncertain and unavailable (SKF Aptitude Excange 2002). Thirdly, the expenses associated with monitoring equipment’s condition may be high. Installation of monitoring equipment and services intended to analyze results and recommend solutions add extra costs to the day-to-day maintenance activities. The author sees the main challenge of predictive maintenance in balancing between number of machines that are prioritized to be precisely monitored and total operational costs reduction due to increased availability and reduced costs of repair.

The core component of predictive maintenance or condition-based maintenance is the technologies that make monitoring possible. The report will describe in details the condition monitoring process later. It is important for now to keep in mind that correct chosen technology and monitoring frequency is the precondition to appropriate predictive maintenance strategy (Mobius Institute 2009). Some equipment requires to be monitored once a week, other continuously. It may depend on equipment criticality, severity of failure consequences, monitoring possibilities, costs associated with condition monitoring and etc. It is important to remember that the condition monitoring itself is just a tool to give us an early warning about of impending failure (SKF Aptitude Excange 2002). The decision has to be made and maintenance activities adjusted accordingly.

If we compare predictive maintenance to other types listed below, we may conclude about the main advantages and disadvantages of this philosophy (Mobius Institute 2009):

- Reduction of unplanned downtime
- Spare parts logistics costs reduction
- Longer machine lifetime
- Avoidance over-maintenance
- Lower risk for HMS related consequences
- Better quality performance and efficiency of operations.
- Increase in costs associated with additional instrumentation, services, systems and personnel
- Uncertainty related to diagnosis and prognosis of machine failure and consequences

2.2.1.4 Precision maintenance

Precision maintenance could be called as ”Proactive Maintenance”. One of the main differences between this approach and predictive maintenance is the intention to find root cause of failure and reduce the chance of problem to appear (M. Dunn 2008). Root-cause analysis (RCA) or Root-cause failure analysis (RCFA) is often considered as tool for investigating root cause of failure. It may imply the analysis of historical maintenance & condition monitoring records and performance of the specific test in order to identify main cause-effect relationships for the component (Mobius Institute 2009).

The whole point with the precision maintenance is to increase the reliability of the equipment. It could be done by performing a proper machine alignment and balancing in combination with right precautionary measures to avoid any preconditions leading to failure. Condition monitoring technologies will be still used but few problems will occur. One of the main challenges related to the precision maintenance philosophy is the implementation phase. It may take a significant amount of time before everyone in the whole companies’ structure will accept and understand the benefits and principals of this approach (M. Dunn 2008).

By summarizing main advantages of the precision maintenance we can identify the following. First of all the equipment reliability is intended to be improved and lifetime is extended. Secondly, risk of the secondary damage appears to be low. Thirdly, the reduction of total maintenance costs will take place as a result of increasing uptime assuming that the implementation process went well. On the other hand the costs associated with new instruments, services and training of personnel may add to the total expenses. In addition to that, time and resources needed to implement this philosophy may be a challenge.

2.2.2 Opportunity-Based Maintenance

The opportunity-based maintenance (OBM) is the extension of the breakdown maintenance philosophy and is a modern term and trend in the maintenance program development. Torgeir Brurok and Harald Sleire determined this approach with two words: agility and resilience (Wahl et al. 2008). This strategy is not included in the common maintenance practices but in spite of this, it has become well known in today's industry. The OBM basically consists of two parts: opportunities allocation and reaction according to them (Wahl et al. 2008).

During the operation plan execution unplanned events might occur and these situations could be considered as an opportunity to perform, for example, preventive maintenance tasks, various tests, information gathering and upgrading of the equipment. It may imply that in case of particular machine failure other systems may be exposed for unplanned preventive maintenance tasks (Samhouri 2009). The main advantage of this approach is to reduce the unplanned downtime.

One of the most essential parts of OBM execution is the selection of appropriate maintenance activities for possible equipment during unplanned shutdowns of the operation. There are several decision support tools that are able to contribute to this process. PROMPT for instance is able to define an opportunity of carrying out the preventive maintenance activity based on input information of planned activities (Dekker & Rijn 2003). The author sees the possibility to base the selection of preventive tasks during unplanned shutdowns on the condition monitoring parameters of the critical machinery.

The deviation of the components parameters from the baseline may be considered as a precondition of preventive maintenance during the unplanned stop of the operation, even though the deviation is not critical yet. All the information written above may be summarized in a single definition. Opportunity-based maintenance is the maintenance practice aimed to identify (collect, investigate, preplan and publish) and use the opportunity of carrying out the unscheduled maintenance activities during the unplanned loss of the main system function (Savic et al. 1995).

2.2.3 Maintenance Concepts

The first concept that is sometimes used in today's industry is the Quick & Dirty decision charts (Q&D). It represents a decision diagram with a set of questions related to equipment behavior, business conditions, maintenance capabilities, cost effectiveness and etc. The result of the Q&D is a recommendation of the most appropriate policy for the given system or installation (Pintelon & Puyvelde 2006b). The main advantage of this concept is rapidness and consistency. The con is lack of deep analysis.

The next concept that seems to be quite popular nowadays in O&G business environment is a Life Cycle Costing (LCC). This methodology has a goal to estimate and follow up the total cost of ownership from the beginning to the end. There are two basic ideas following this concept. The first one is the "iceberg" of equipment costs that points out that not only installation purchase costs are important, e.g. operational costs and maintenance costs play a significant role in creation of expenses (Blanchard 2004). The second idea called "Cost and life cycle" draws the attention to the fact that most of lifecycle costs may be determined during the design phase (Pintelon & Puyvelde 2006b). The pro here is the variety of available software that may assist in this concept application process. At the same time lots of data and resources are needed in order to get valuable results.

The third concept to be mentioned is called total productive maintenance (TPM) and originally came from Japan. It implies the total participation from all the hierarchical levels of the company & project and is aimed to maximize the overall equipment effectiveness (OEE) and develop the preventive maintenance program (Pintelon & Puyvelde 2006b). The application area of this concept is originally in the manufacturing industry. One of the main advantages here is a huge variety of tools and techniques used in TPM concept e.g. OEE, Pareto or ABC analysis, Fishbone diagrams and etc. Some of these techniques are applied in this project. The negative side of this concept is the time needed for its implementation.

2.2.3.1 Reliability-Centered Maintenance

This concept is already briefly discussed in parts of the report written above. Since the topic of this thesis is directly related to reliability-centered maintenance (RCM) and associated tools the author decides to study this question deeper. One of the easiest ways to get into this philosophy is to treat the equipment as human health. If body is exposed to unhealthy food, a lot of stress and little physical activities, the special signs like different physical and mental defects may occur. The human may take extra precautions like medicine or sports center visits once a month. One will be still sick from time to time. This is an example of preventive philosophy. We can find another type of people doing the same but periodically visiting their doctor and getting medicine to avoid sickness. That seems like predictive maintenance. The third group of people is aware of the processes taking place in their body very well and treats them in the right way. They eat healthy food, do exercises, meditate and are in a good mood. They may still attend the doctor as a part of a routine.

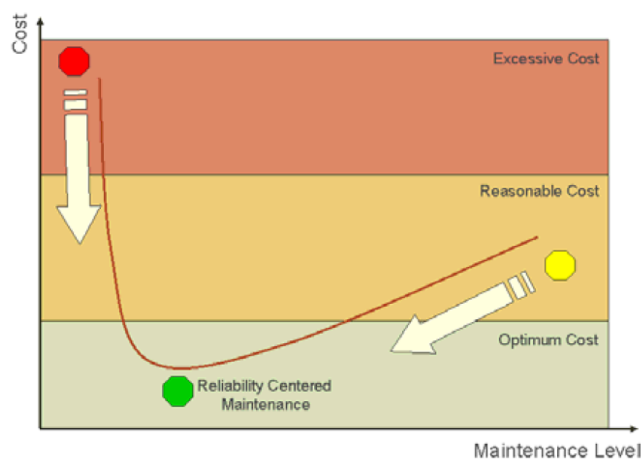


Figure 3: Operational Costs vs. Maintenance Costs (Holme 2006)

Generally speaking their health is very reliable. If man from one of these groups feels sick, the doctor will find root cause and give some recommendations in order to avoid it next time. This approach is very similar to precision maintenance. All of four listed practices above may be a part of RCM. Reliability centered maintenance could be identified as the methodology applied to create comprehensive overview (including all the failure modes, mechanisms, causes, consequences and root-causes) of the equipment and also to realize the most convenient maintenance approach in order to achieve required availability, safety and production of the operation (IEC 60300-3 2011). One of the main challenges for RCM is to find the balance between risks and costs as shown in Figure 3. The detailed RCM process is described in IEC 60300-3-11 ed 2.0 (see Figure 4).

There are four main phases of maintenance activity definition process. Initiation and Planning is aimed to determine need and extent of the study. RCM process will be not applied for all the tasks of the project (e.g. inspection that rather determined by RBI and RBD). Company itself decides the list of these tasks, for instance, in kick-off meetings. At this phase the primary system function will be evaluated according to the severity of consequences. The next phase called functional failure analysis has the goal to perform failure mode, effect and criticality analysis (FMECA). It will contribute to the RCM process by identifying a physical item that has failed with its failure modes, causes, consequences and failure mechanisms. The next step is to determine if the specific failure mode possesses an acceptable or unacceptable risk for the operation. It could be done by utilizing different methods e.g. risk matrix (see Figure 5).

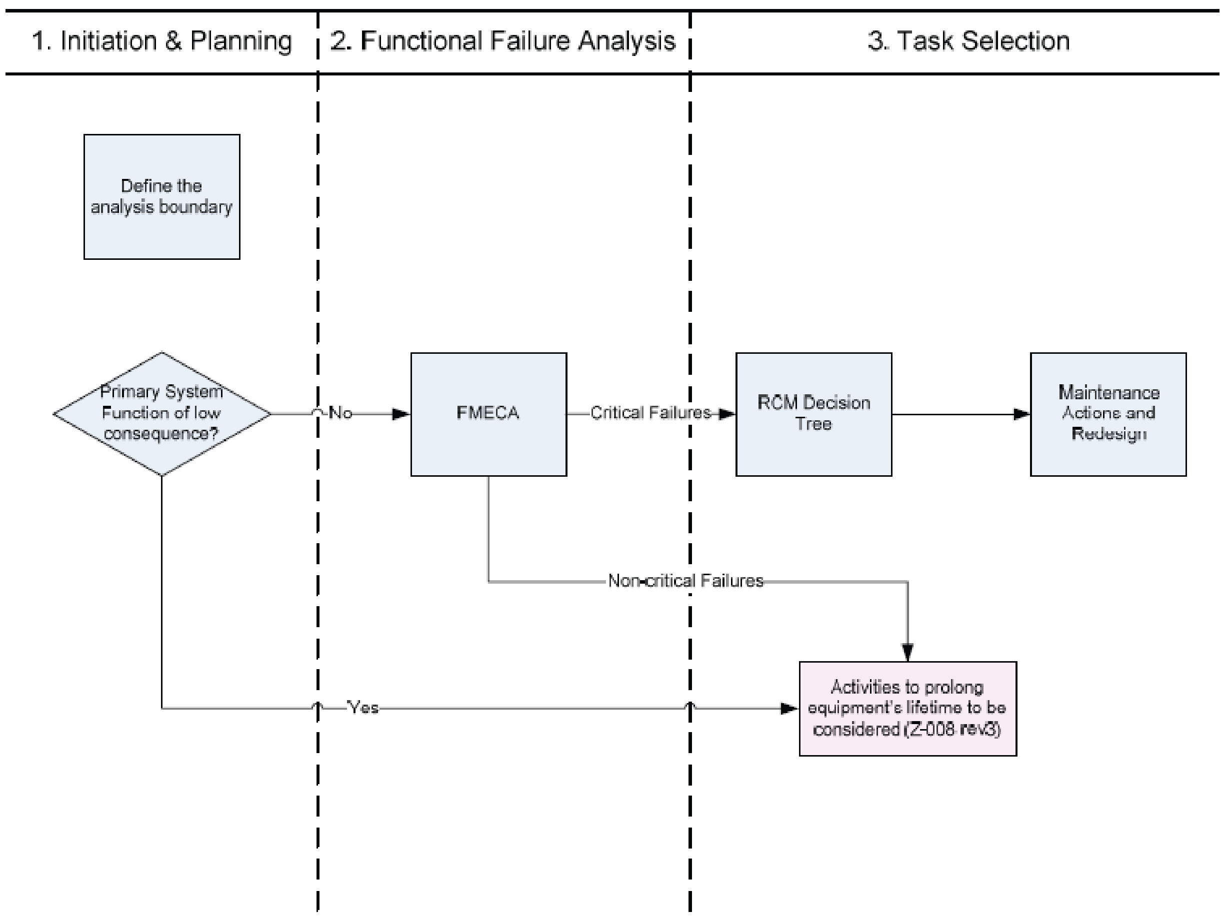


Figure 4: RCM Process (IEC 60300-3 2011)

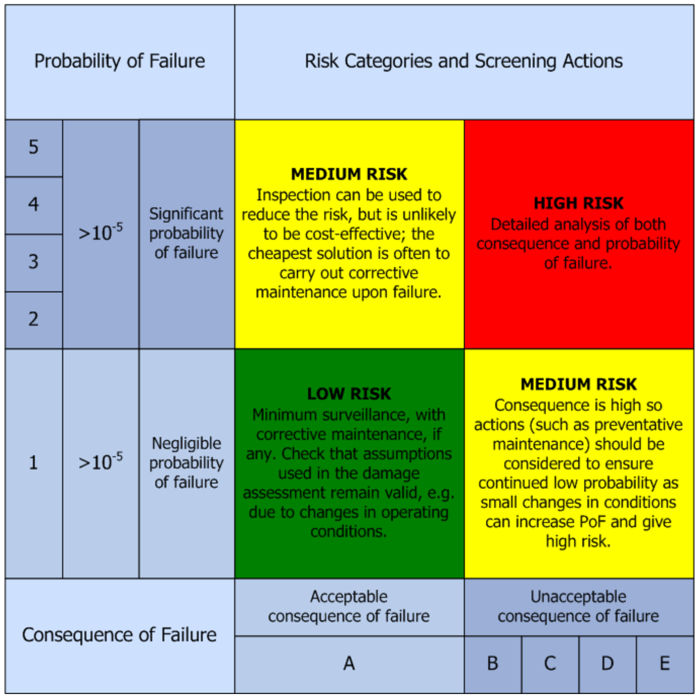


Figure 5: Risk Matrix (Det Norske Veritas 2010)

The third phase called "task selection" is intended to choose the most applicable maintenance strategy for the failure modes that contains unacceptable risk in order to reduce the likelihood and consequences of failure. The RCM decision logic is aimed to contribute to the process of maintenance actions selection (see Figure 6). If several maintenance approaches are applicable than cost-benefit analysis can be used to decide the most appropriate one. If the failure is not critical or primary system function has a low severity of consequences, the activities should be chosen according to Norsok Z-008 in order to prolong equipment lifetime (Norsok Z-008 2011).

The RCM philosophy is often mistakenly perceived at the same level as the FMECA. While FMECA is actually a risk assessment tool for reliability centered maintenance that selects equipment for the further process. It is important to remind that RCM in this project is only applied for drilling systems. For the containment equipment such strategy as risk based inspection (RBI) should be considered. It is also important to mention that both RBI and RCM are the parts of more general risk-based maintenance concept aiming at reducing risk of failure.

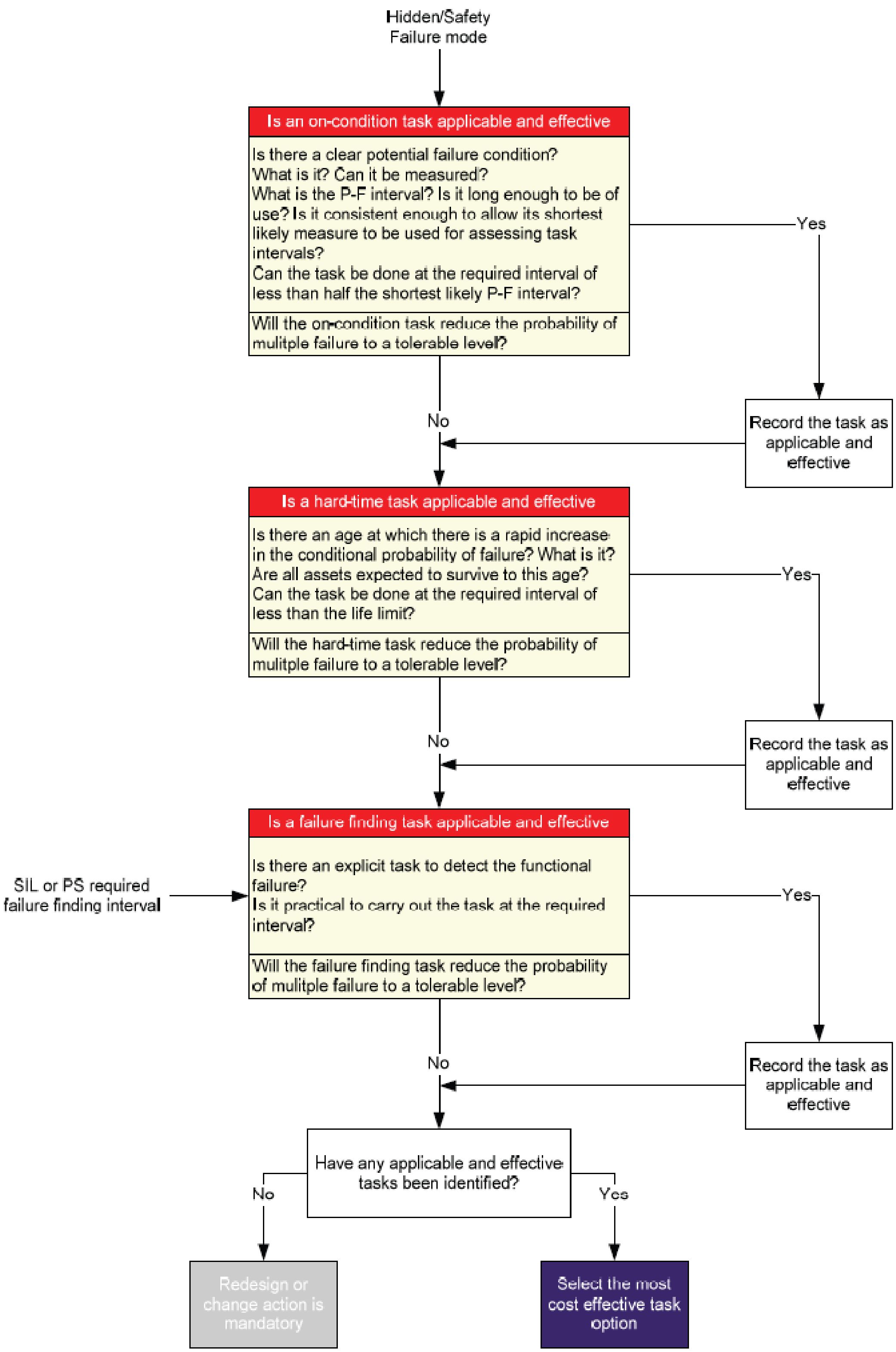


Figure 6: RCM Decision Logic (Det Norske Veritas 2010)

2.3 Maintenance Program

Maintenance program development is the essential process aimed to control all risks related to the equipment degradation (Norsok Z-008 2011). Maintenance program may include activities from different maintenance approaches like preventive activities, condition monitoring and etc. RCM methodology is commonly used for establishing maintenance program, but Norsok Z-008 applies detailed RCM methods in combination with the generic maintenance concepts (GMC). GMC is defined for the specific group of equipment with the similar characteristics and operating conditions (Norsok Z-008 2011). Different workflow for maintenance program development may be established for different maintenance philosophies. The workflow for development of preventive maintenance program is shown in Figure 7. We may observe that the whole logic consists of five main parts (Norsok Z-008 2011):

- Grouping and classification
- Risk Analysis
- Assignment of maintenance activities
- Cost/benefit analysis
- Establishing of maintenance program

In addition to the process shown above the framework to update the maintenance program is determined by Norsok Z-003 as well. COSL Drilling Europe AS has five steps working process for maintenance program development (Weidul 2011). At the first step all the data are collected including drawings, technical documents, historical data, questionnaires and etc. on the part of both vendor and engineering. The second step has a goal to establish a functional hierarchy and decide which systems will be recommended for the further analysis by carrying out the criticality analysis.

In case if the system is classified as a low critical one, the approved GMC should be selected if any. Otherwise the breakdown maintenance should be applied with no authority or company requirements applicable. The third step of the process is aimed to identify the risk level of the system including failure modes, mechanisms, maintenance type, safety and reliability. The next step is selection of maintenance method, establishing and scheduling activities, allocating resources and spare parts planning. The last step of maintenance program development for COSL Drilling Europe AS is to implement all findings into local computerized maintenance management system (CMMS). This process seems quite similar to the workflow that Norsok Z-008 recommends, but still has its own features e.g. implementation of results to computerized maintenance management system.

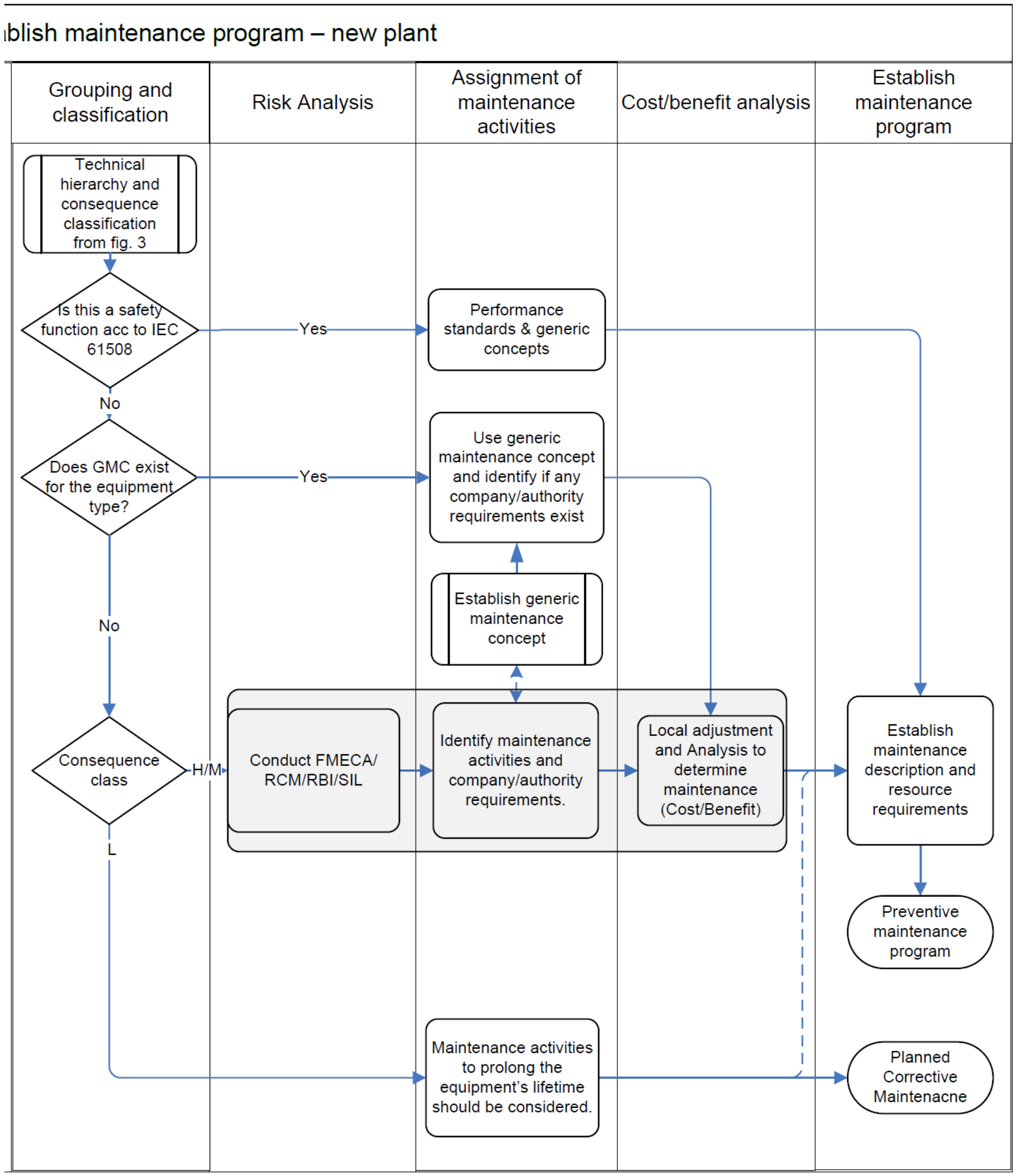


Figure 7: Preventive Maintenance Program Workflow (Norsok Z-008 2011)

2.4 Condition Monitoring

Condition monitoring (CM) is already mentioned above in connection with maintenance policy called predictive maintenance or condition-based maintenance. CM is a tool to determine the health or condition of the equipment by monitoring parameters reflecting the mechanical state of the machine (Markeset 2011). The first of the three total steps that CM consists of is aimed to measure parameters describing health of the equipment. The second one determines if the machine is in stable condition and estimate the speed of deterioration if it is a case (Mobius Institute 2009). The third one has a goal to communicate necessary information to the experts dealing with analysis and decision making. The last part is often underestimated in today's industry. As a result data collected by possibly expensive monitoring equipment is not applied to any further process and loose its value.

In order to get the comprehensive picture of the machines health one should be aware about to perform several tests and correlate the results. The single test may not tell us so much about the equipment condition. For instance, if we perform a lubrication analysis, the first observation gives us only the reference point. The wear process may be identified by performing test several times during the given period of time.

In addition to historical data, the information about the operating conditions should be available. The measured trend has to take into consideration the operating mode at that point in time when monitoring takes place. The increased vibration in bearing may be caused by machine's overrun (increased RPM). Several measurement parameters may contribute to more comprehensive picture about machines degradation mechanisms. For example, measuring both temperature and vibration may contribute to more accurate estimation of bearing's failure mode. Some monitoring technologies can identify the situation that may give rise to the problem, while the problem is itself not a case yet. For example, the fail consistency of lubrication oil may be the mistake coming from the vendor and not necessary machine degradation. But it can lead to the failure of the equipment after some time.

Another issue about CM is how successful implementation can be measured. We will discuss this topic deeply in "cost-effect analysis" part. For now all we need to know what the main effect of CM utilization is. If the information about the condition is gathered and assessed early the unplanned downtime spend on finding the cause, fixing secondary damage, spare parts and resources will be reduced. As a result the availability and reliability will be increased. The indicators of these two parameters of successful CM program implementation are mean time to repair (MTTR) and mean time between failures (MTBF).

2.4.1 Condition Monitoring Implementation Process

It is necessary to start with overview of general CM program implementation procedure. It will lead through the main steps of program development and introduce particular techniques to be studied in detail. It is important to remember that this process should happen continuously. It implies the review of the whole CM approach and alters it according to the current conditions. For example, the monitoring technique that had a high price in the past may be more available now (Hitchcock & Corporation 2005). Trip and alarm values need the reevaluation as well, due to e.g. modifications of the machine and its aging. Procedures related to CM program design, implementation, management and review should be developed based on ISO CM standards.

ISO 17359:2011(E) "Condition monitoring and diagnostics of machines" proposes the following procedure (ISO 17359 2011):

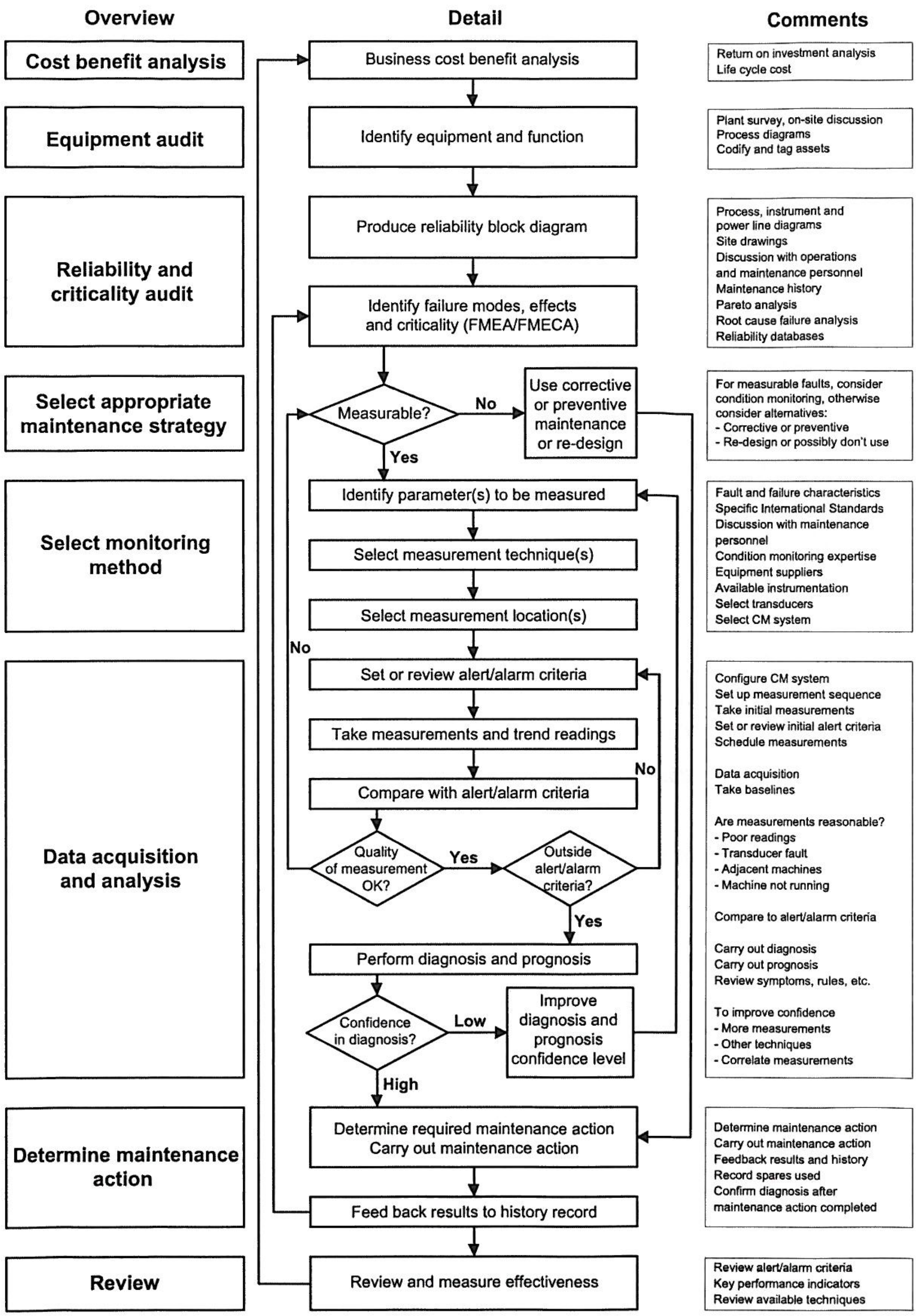


Figure 8: Condition Monitoring Procedure Flowchart (ISO 17359 2011)

2.4.2 Cost-Benefit Analysis

All the stages showed above have to be carried out effectively in order to ensure the proper measurement of effectiveness of their maintenance (Mills 2007). Cost benefit analysis and feasibility study contributes to establishing of measures aimed to determine the CM program successful implementation and effectiveness (ISO 17359 2011). Those measures are called key performance indicators (KPI). In ISO 14224:2006 a variety of benchmarks and KPI's are available (see Appendix B). It is important to distinguish between these two terms. KPI is intended for tracking the progress and manage improvements on a continuous basis.

A benchmark is an infrequent event to compare the performance of the company against other organizations involved in the similar process (ISO 14224 2006). Examples of KPI's could be: mean time between failures (MTBF), mean time to repair (MTTR), operational availability, technical availability, preventive maintenance man-hours ratio and etc. Benchmarks may include (ISO 17359 2011): life-cycle cost, cost of lost production, warranty and insurance, consequential damage, return on investment and etc.

The company called Karsten Moholt AS is located in Bergen and have a condition monitoring service as one of the business areas. In order to show the benefits of the CM to their customers they use the following approach. The first step is to identify what mindset the customer has: reduce maintenance costs or produce the product more efficiently. Then the customer supposed to look at the plant and estimate the ideal, technical production time. Planned production time could be found out by subtracting the planned downtime. The customer may determine the gross operating time by estimating unplanned downtime (Equipment failure + set-up and adjustments) that will represent the availability factor. The speed factor may include idling & minor stoppages and speed reduction. The subtracting of speed loses from gross operating time will give us net operating time. The final valuable operating time will exclude all the quality losses such as defects in process & rework and start-up losses which represent the quality factor. Based on the three factors listed above the final overall equipment efficiency (OEE) may be calculated by using the following formula (Pintelon & Puyvelde 2006b):

$$OEE = A * P * Q$$

where A is availability factor $= \frac{Actual\ production\ time}{Planned\ production\ time}$

P is a speed factor (performance) $= \frac{Actual\ run\ rate}{Planned\ run\ rate}$

Q is a quality factor $= \frac{Good\ product}{Total\ product}$

A typical plant has OEE equal 60% while the best in class companies has 85% of overall equipment efficiency value (Pintelon & Puyvelde 2006b). The sketch of OEE approach may be shown by Figure 9.

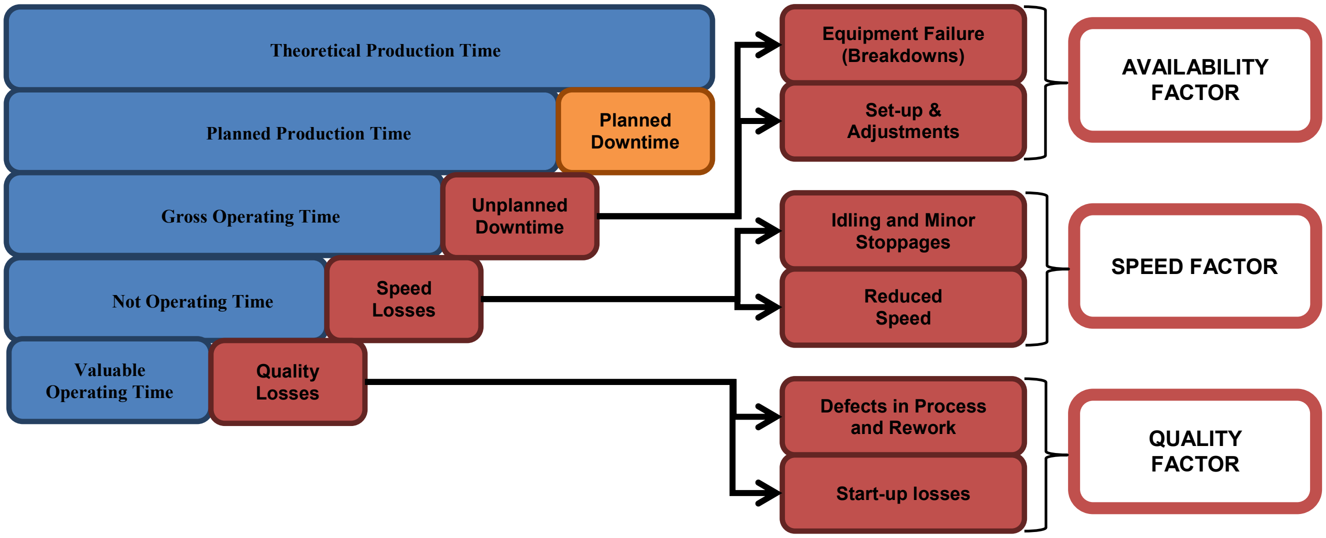


Figure 9: OEE Approach (Karsten Moholt 2008)

In the Figure below (Figure 10) one can see the particular KPI's and benchmarks that Karsten Moholt AS use to show the profitability of the CM. The final benchmark that all others contribute is called earning power. Investopedia, the popular online portal about investment analysis, define the earning power as an ability of the organization to create profit from performing its operations (Investopedia 2012).

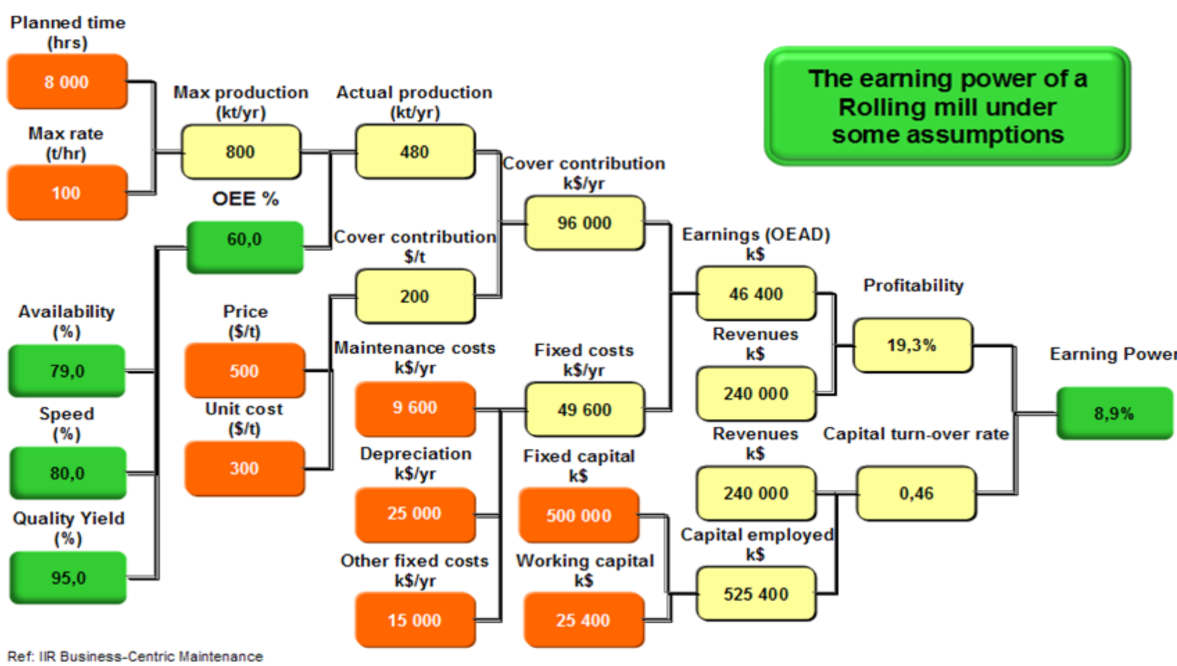


Figure 10: Maintenance KPI's Interdependences (Karsten Moholt 2008)

As we see from the figure the change of one of the parameters will cause, in a varying degree, alteration in earning power. This diagram is not a general solution and has to be customized in each particular case. Using this example Karsten Moholt AS shows the reaction of earning power on caring out different activities related to maintenance optimization. If we reduce maintenance costs by 73 % and spend 2.600 thousand dollars per year, operation earnings after depreciation (OEAD) will be equal:

$$OEAD = Cover\ contribution\ (96000k) - Fixed\ costs\ (42600k = 49600k - 7000k)$$
$$= 53400k\$$$

As a result:

$$Profitability = \frac{Earnings}{Revenues} = \frac{53400k}{240000k} = 22.25\%$$

$$Earning\ power = Profitability * Capital\ turn - over\ rate = 22.25\% * 0.46 = 10.2\%$$

As we see from calculations cutting maintenance costs may lead to increased earning power. The challenge here is how long the particular level of profitability could be maintained. As a result of reduced maintenance, equipment lifetime may become shorter and may cause dramatic machine failure consequences. In perspective the availability of the components will be reduced and cause the decrease of earning power.

In order to increase the earning power the company may sell the product at a higher price (515$ instead of 500$). In this case we may observe the increase in the earning power by 1.3%:

$$Cover\ contribution\ per\ hour = Price - Unit\ cost = 515\$ - 300\$ = 215\$$$

$$Cover\ contribution\ per\ year = Cover\ contribution\ per\ hour * Actual\ production$$
$$= 215\$ * 480kh = 103200k\$$$

$$OEAD = Cover\ contribution - Fixed\ costs = 103200k\$ - 49600k\$ = 53600k\$$$

$$Profitability = \frac{OEAD}{Revenues} = \frac{53600k}{240000k} = 22.23\%$$

$$Earning\ power = Profitability * Capital\ turn - over\ rate = 22.23\% * 0.46 = 10.2\%$$

The same result as in previous case but caused by change of another parameter. The challenge for this case is the market reaction on price increase. The current costumers might refuse to purchase a product with such a price level. At the same time in order to increase a price, additional expenses related to quality improvement or additional marketing might take place.

The third option that company might have is the introduction of CM. It can lead to maintenance costs increase and availability improvement. By investing 1000k$ the company may obtain availability equal to 83.9% (instead of 79%) and speed factor equal to 81.6% (instead of 80%). Calculations showed below will prove that in this case earning power will increase by approximately the same level as it happened in other examples:

$$OEE = Availability * Speed * Quality\ yield = 83.9\% * 81.6\% * 95\% = 65\%$$

$$Actual\ production\ per\ year = Max\ production\ per\ year * OEE = 800\ {}^{kt}/_{yr} * 65\% = 520.3\ {}^{kt}/_{yr}$$

$$Cover\ contribution\ per\ year = 520.3\ {}^{kt}/_{yr} * 200\ {}^{\$}/_{t} = 104062\ {}^{k\$}/_{yr}$$

$$Earnings\ (OEAD) = Cover\ contribution - Fixed\ costs = 104062\ {}^{k\$}/_{yr} - 49600\ {}^{k\$}/_{yr} = 54462k\$$$

$$Profitability = \frac{OEAD}{Revenues} = \frac{54462k\$}{240000k\$} = 22.69\%$$

$$Earning\ power = Profitability * Capital\ turn - over\ rate = 22.69\% * 0.46 = 10.4\%$$

The third example shows the significant contribution from implementing the CM in day-to-day operations and what benefits it brings. The final table where all the results are compared is shown below:

Table 1: Earning Power Improvement Options (Karsten Moholt 2008)

Variable	Original	OEE Improvement	Price Increase	Maintenance Cost Reduction
Availability, %	79%	83.9%	79%	79%
Speed, %	80%	81.6%	80%	80%
OEE, %	60%	65% (+5%)	60%	60%
Price ($/t)	500$	500$	515$ (+3%)	500$
Maintenance Cost (k$/yr)	9,600k$	10,400k$	9,600k$	2,600k$ (-73%)
Profitability, %	19.3%	20.6%	21.7%	22.2%
Earning Power, %	8.9%	10.2%	10.2%	10.2%

The main advantage of the Karsten Moholt's approach is that the calculations are based on "real numbers". All of the values included in the diagram are the result of the real case and don't deal with abstract concepts. The disadvantage is that the method is limited to the particular case and number of benchmarks. And at the same time it doesn't cover the uncertainty related to CM influence on availability and other values.

2.4.3 Equipment Audit

At this stage the company is intended to carry out the plant survey and prepare overview of necessary systems, functions and sub-functions (ISO 17359 2011). It may imply the development of process diagrams and codifying & tagging of assets. In addition to that, maintenance and performance history should be mapped as well. Equipment function and sub-function should to include the information about what is the system & sub-systems intended to do and range of operating conditions (ISO 17359 2011). It is important to gather data about equipment interrelations and interdependences with other type of equipment. Control systems, power supplies and other systems required to comprehensive functioning have to be mapped as well (see example for drawworks in Figure 11).

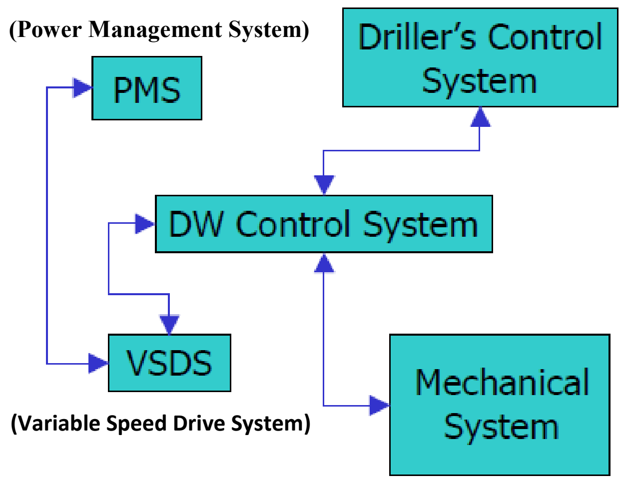


Figure 11: Drawworks System Overview (Abouamin et al. 2003)

2.4.4 Reliability and Criticality Audit

Before starting the description of different risk and reliability assessment tools, the author seems that it is important to clarify what the Risk term implies. The author uses the definition given by Terje Aven (T Aven 2008), a professor of risk analysis and risk management at the University of Stavanger. The risk is the combination of initiating event, consequences of this event and uncertainty associated with both event and circumstances. By using this approach risk can be equal to probability multiplied by consequences, where probability is one of the possible ways to describe uncertainty.

The goal of this stage is to prioritize equipment for further assessment by estimating the availability, reliability, maintainability and criticality. It is done by utilizing a variety of risk assessment tools like FMECA, fault tree analysis (FTA), event tree analysis (ETA) and etc. The first step that could be useful in this process is to produce a reliability block diagram. One can present what reliability effect (parallel or serious) the equipment has as well as the redundancy level and reliability & availability factors (ISO 17359 2011). It will significantly contribute to criticality analysis that is aimed to perform a rough ranking of the interested systems and sub-systems. The next step is intended for risk analysis which helps to prioritize final equipment to be monitored.

2.4.4.1 Reliability Block Diagram

Reliability block diagram (RBD) is a tool to analyze the system availability and reliability by utilizing block diagrams in order to show network relationships (Andrews & Moss 2002). One of the main goals of RBD is to present the logical interaction of failures for the system. The diagram consists of nodes which provide the component link points and blocks structure. There are two basic types of network structures: simple and complex. The main difference between them is that in the simple one the contribution of the components to the failure mode is considered only. It is useful to take into account physical arrangement of the components while constructing the RBD, but sometimes it's not applicable due to e.g. fail short of the resistors, even if they are physically in parallel. In the complex network, the structures cannot be reduced to the combination of parallel and serious sections (Andrews & Moss 2002).

Simple network structures include: series, parallel, combination of series and parallel, voting systems and stand-by systems. A parallel structure represents a redundancy of system components and is joined by multiple paths from start to end. While series represents a one continuous link and maintaining of all the components is necessary for sustaining system operations. Series/parallel combination consists of only series and parallel structures and is analyzed in several stages (Andrews & Moss 2002).

A voting logic represents the set number of sensors that may identify a trip condition. It implies that in k-out-of-n system, k number of components n registers the shutdown condition. Standby systems may represent systems that have an option to be kept in standby mode, but are normally operated continuously. Another type implies redundant components that will be utilized only in case of the primary components failure. In order to simplify complex network structures like e.g. bridge network, conditional probability approach and star & delta configurations should be used (Andrews & Moss 2002).

In case of bridge structure the conditional probability approach may divide the initial RBD into two with bridge component in functional and non-functional state. The second technique is intended to transform the initial delta configuration to the set of virtual blocks in star reliability structure, which is supposed to be equivalent to the primary one and can be interchanged (Andrews & Moss 2002).

The final approach is aimed to obtain the system reliability from RBD by using network failure modes. The first step of this method is to determine minimal path sets which are the minimum number of sets allowing machine to work. Then minimal path sets are transformed to minimal cut sets which represent the minimum number of failing components that cause the system failure. And the last part is to perform network quantification (Andrews & Moss 2002).

RBD is not just a drawing tool; a significant contribution comes from calculations. Right after the diagram and proper data are configured, such reliability values as failure rate, MTBF, availability and reliability can be calculated (Andrews & Moss 2002). The results will be changed due to block diagram rearrangement. In order to provide an overview what values can be calculated with help of RBD, some of them will be presented below:

1. System Conditional Failure Intensity at time t is the probability of components failure per unit time t, assumed that it is as good as new at the beginning until now (Henley & Kumamoto 1991).

$$\lambda_s(t) = \frac{\omega(t)}{1 - Q(t)}$$

Where: ω(t) = Failure Frequency at time t.

Q(t) = Unavailability at time t.

2. Expected Number of Failures in lifetime t (Henley & Kumamoto 1991).

$$W(t_1, t_2) = \int_{t_1}^{t_2} \omega(t)d(t)$$

Where: $W(t_1, t_2)$ = Expected Number of Failures given that the component was as good as new

at time zero.

ω(t) = Failure Frequency at time t (Unconditional Failure Intensity), Or System Failure

Frequency

3. Failure Frequency of a Cut Set: is the probability of components failure per unit time t, without assuming component as good as new at time zero (Henley & Kumamoto 1991).

$$\omega_{CutSet} = \sum_{j=1}^{n} \omega_j * \prod_{\substack{i=1 \\ i \neq j}}^{n} Q_i$$

Where: ω_{CutSet} = Failure frequency of the cut set

ω_j = Failure frequency of the jth event in the cut set

Q_i = Unavailability of the ith event in the cut set

n = Events in the cut set

4. System Failure Rate given the constant rate model (Henley & Kumamoto 1991).

$$\lambda(t) = \frac{1}{MTBF}$$

Where: $MTBF(Mean\ Time\ Between\ Failure) = MTTF + MTTR$

MTTF = mean time to failure

MTTR = mean time to repair

5. System Unavailability (Henley & Kumamoto 1991):

- Rare equation (is only focused on cut sets)

$$\omega_{sys} = \sum_{j=1}^{n} \omega_{CutSet_i}$$

Where: ω_{sys} = *System failure frequency*

ω_{CutSet_i} = *Failure frequency of cut set i*

n = Number of cut sets

- Esary-Proschan equation (this approach provides more precise results due to taking into account unavailability of cut sets)

$$\omega_{sys} = \sum_{j=1}^{n} \omega_{CutSet_i} * \prod_{\substack{i=1 \\ i \neq j}}^{n} (1 - Q_{CutSet_j})$$

Where: ω_{sys} = *System failure frequency*

ω_{CutSet_i} = *Failure frequency of cut set i*

n = Number of cut sets

Q_{CutSet_j} = *Unavailability of cut set j*

6. System Unreliability (Henley & Kumamoto 1991):

$$F(t) = 1 - e^{-(1-Q(t))}$$

Where: $Q(t)$ = Unavailability at time t

7. Fussel-Vesely Importance: indicates the component effect on the total system unavailability (Henley & Kumamoto 1991).

$$IMP_{FV} = \frac{\sum Q_{cutsets\ block}}{\sum Q_{all\ cutsets}}$$

Where: $Q_{cutsets\ block} = Unavailability\ of\ cut\ sets\ containing\ block$

$Q_{all\ cutsets} = Unavailability\ of\ all\ cut\ sets$

8. Birnbaum importance: shows how system is sensitive to changes in blocks unavailability (Henley & Kumamoto 1991).

$$IMP_{BB} = \frac{\sum Q_{cutsets\ block}}{\sum Q_{block}}$$

Where: $Q_{block} = Unavailability\ of\ block$

$Q_{cutsets\ block} = Unavailability\ of\ cut\ sets\ containing\ block$

2.4.4.2 Criticality Analysis

The main goal of performing the criticality analysis (CA) is to priorities equipment/functions according to potential consequences for business performance. It could be used for the further process in developing of condition monitoring program (ISO 17359 2011). As it is mentioned above the CA is usually applied for functions and is used for assigning equipment to sub-functions prioritized during the process. Norsok Z-008 also recommends other areas of application: establishing of PM program; preparation and optimization of GMCs; evaluations of design; work orders prioritization and evaluation of spare parts (Norsok Z-008 2011).

The rough ranking of equipment/functions methodology can be based on following parameters: redundancy level, safety and environmental impact, failure rates, production impact, life cycle costs and etc. Norsok Z-008 uses only few of them. The process of criticality analysis (consequence classification according to Z-008) is well shown in Figure 12. The important feature of CA is that only total loss of function is considered.

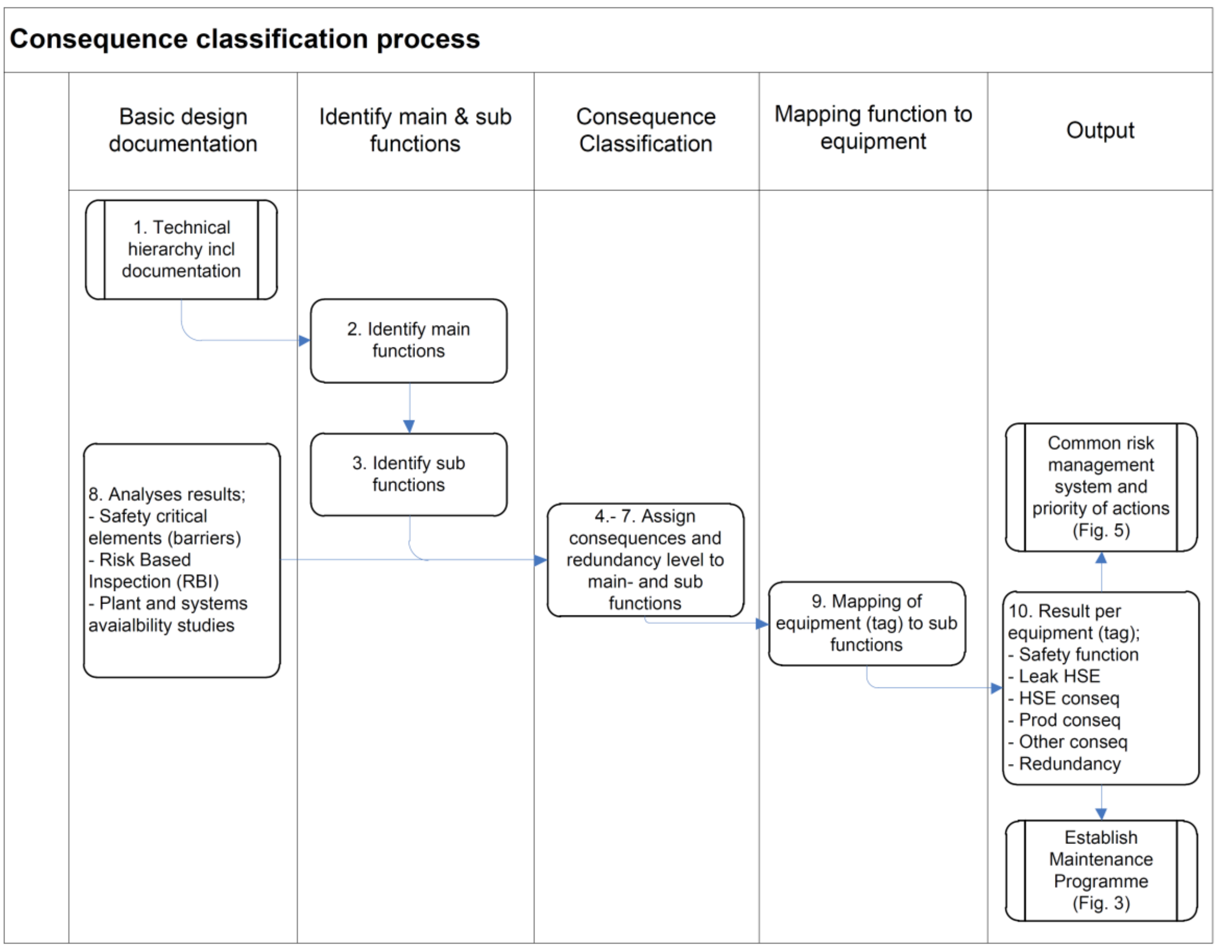


Figure 12: Consequence Classification Process (Norsok Z-008 2011)

COSL Drilling Europe AS bases its criticality evaluation on one proposed by Z-008, but includes in addition the probability of failure and effect on system itself and installation as a whole (see Figure 14). The consequence assessment is based on criticality matrix presented at Z-

008 but customized according to the COSL features (see Figure 13). The first step is to define all main & sub-functions that have to be included in further analysis. Then the process of assigning the consequence criticality both to main & sub-functions is carried out. This is usually done by experts during discussions. Most critical sub-functions are assigned to equipment and is ready for the further process steps.

One of the highest uncertain values in criticality evaluation method provided by COSL is the probability of failure, which is decided during the discussions. Despite the fact that CA is only a rough ranking tool, some deviations in results may occur because of unreliable data used to perform this stage. Another challenge is to get the single criticality value assigned to each sub-function/equipment in order to perform ranking. Norsok Z-008 selects the highest criticality value among all types of consequences and is limited to 1, 2 and 3.

Criticality Matrix COSL

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

Figure 13: Criticality matrix (Weidul 2011)

Installation:	Pioneer	COSL Pioneer
System:	301	DERRICK STRUCTURE

			Revision date	
3S	**Main Function Criticality Evaluation**		A0	03.03.3009
	PIONEER-30101	**DERRICK**		

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

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

	Effect on system	Effect on installation	S	P	O	H
Does not work	MF shut down or unavailable. Derrick is bolted. 25% of derrick inspected each year, i.e. complete derrick inspected every 4 years. Cladding most common failure.	Critical for safety and drilling downtime. Danger of falling objects. Support for drilling equipment. No immediate effect on oil spill. Low probability of failure.	3	3	1	N

Data source: Kamfer 04.03.2009

Figure 14: Criticality evaluation example (Weidul 2011)

Smith and Mobley in their book called "Rules of thumb for maintenance and reliability engineers" derive one criticality number assigned to equipment based on several criticality parameters (Smith & R. K. Mobley 2008). Those criticality parameters are chosen by the company according to their main mission and goals. The example in the book introduces the six of them: safety, environment, quality, throughput, customer service, operating cost (Smith & R. K. Mobley 2008). Both safety and environment issues have the maximum value equal to 40, while all others can score a maximum value of 10. In order to get the final relative risk number (criticality number), which rank equipment according to the impact on the business performance, probability should be included in calculations. The probability/frequency number varies from 10 (failure occur daily) to 1 (failures occurs less frequently than 1 in 10 years). There are two simple calculations that may contribute to rough ranking of the equipment (sub-functions) according to criticality (Smith & R. K. Mobley 2008):

$$TC = S + E + Q + T + CS + OC$$

$$RR = TC * F/P$$

where, TC – Total consequence

S – Consequences related to safety

E – Consequences related to environment

Q – Consequences related to quality

T – Consequences related to throughput

CS – Consequences related to customer service

OC – Consequences related to operating cost

F/P – Failure/frequency number

RR – Relative risk number (criticality number)

The main advantage of this approach is that the result is presented by a single number, which could be used as criteria to rank the equipment. The challenge of this approach is to be aware of what the value is based on and various assumptions which are made to evaluate failure consequences and probability. The second challenge is that the criticality number is valid only for equipment evaluated by the same method.

2.4.4.3 Failure mode, effects, and criticality analysis

Failure mode, effects, and criticality analysis (FMECA) is the most fundamental and well recognized tool in reliability analysis due to its simplicity of understanding and qualitative nature (Smith & R. K. Mobley 2008). The FMECA process was originally utilized by the US military since 1949 (Pintelon & Puyvelde 2006c). This tool was used to classify failures according to their influence on mission success and safety. FMECA as a common tool for risk analysis can be used in different forms: FMEA (failure mode and effect analysis), FMMA (failure mode and maintenance analysis), FMSA (failure mode and symptom analysis) and etc. The distinctive feature of this approach is that the analysis should start at the most reasonably possible detailed level (Thompson 1999). In order to present a general definition of failure mode, effects, and criticality analysis we have to identify common features. Identification of all potential failure modes of the system is one of the features. It gives the description of what is wrong and what we need to prevent or fix (Smith & R. K. Mobley 2008).

Failure cause provides a reason for failure modes occurrence. If the failure mode occurs, failure effect is responsible for describing the consequences. Criticality evaluation can be carried out in different forms. One of these forms is the risk priority number (RPN) that implies the combination of severity, likelihood of failure mode to occur and ability to detect this failure mode. All the processes related to FMECA are aimed to identify the core systems and equipment for which the required maintenance actions should be especially considered and evaluated (Thompson 1999). This risk assessment tool could be used both to find shortcomings and identify opportunities for design optimization. There are four application areas where FMECA could be useful: system, design, process and service (Abouamin et al. 2003). These four areas are closely related with the product development phases from concept to operations.

The proper performed analysis is supposed to determine the most critical equipment and remove from further assessment of secondary or non-critical components. FMECA may include data gathered from other risk assessment tools applied such as: fault tree analysis, event tree analysis, root cause analysis, criticality analysis, reliability block diagrams, Markov method and etc. The last tool is capable to find a probability over the time period by analyzing time dependent behavior (Wardt et al. 2011). Summarizing the information presented above we can conclude with following objectives for FMECA (IEC 60812 2006):

- Identification and evaluation of undesired events and their effects & causes evoked by each failure mode within defined system boundaries
- Classification of equipment based on criticality or priority for consideration of each failure mode

- Ranking of failure modes according to predefined relevant characteristics (e.g. RPN)
- Development of design improvement plan considering prioritized failure modes
- Contribution to the development of maintenance strategy by implementing mitigation measures for identified failure mode

The author decided to describe such form of FMECA as FMSA due to the direct relevance for current master thesis. International standard ISO 13379:2002 provides a comprehensive overview of this tool. FMSA is actually a modified FMECA focusing primary on the symptoms as a result of identified failure modes. The main aim of such modification is to assist with the selection of monitoring technique. The proper defined monitoring approach may contribute with better detection rate of the failure mode (ISO 13379 2002). The following steps are recommended for this process (ISO 13379 2002):

- listing relevant components
- Identifying possible failure modes
- listing the effect of each failure modes
- finding the causes for failure modes
- determining the symptoms produced by the failure modes
- using the monitoring priority number to rank the failure modes
- choosing the monitoring technique and estimating the frequency of monitoring
- choosing the correlation technique and estimating the frequency of monitoring

The variety of terms involved in FMSA process points to the importance of their definitions clarification. The core term in this reliability assesment tool is a symptom. It is defined as a perception made by observations and measurements in order to indicate one or several faults (ISO 13379 2002). This term stays very close to "failure mechanism" defined as the process or combination of processes that contribute to failure (ISO 14224 2006). Symptoms could be expressed in different forms: by time (e.g. 1 hour, slow), by type of development and degree of change (e.g. increase, stability, <10, etc.), by descriptor (e.g. pressure, temperature, harmonics, etc.), by location (e.g. bearing #5, high pressure body), by operating conditions (e.g. 2 hours after start-up, at 100% capacity) (ISO 13379 2002). The comprehensive example of the symptom could be that the temperature of bearing #4 is 15 degrees above baseline in 70% machine capacity. A failure mode has the goal to define the way failure could be observed and can produce the measurable symptoms for diagnosis and prognosis (Thompson 1999). An example of a failure mode could be: low output, internal leakage, abnormal instrument reading and etc. Failure can be expressed in terms of the name of the machine and its component. It may include type of degradation and severity if needed (ISO 13379 2002). An example of the failure could be: wear of bearing #1 in Drawworks electric motor #2. Failure modes, mechanisms (symptoms), causes and effects could have some areas of overlap due to different focus of analysis. ISO 13379:2002 points, however, that special attention should be paid to avoid duplication in the same line of all terms listed above.

One of the most significant tools FMSA possesses is the monitoring priority number (MPN) (ISO 13379 2002). It is the value that makes possible to rank all the failure modes according to monitoring possibility and suitability. MPN can be found by multiplication of four main parameters assigned to each failure mode:

$$MPN = DET * SEV * DGN * PGN$$

where, DET – probability of detection rating ranges from 1 (remote probability) to 5 (certain probability)

SEV – severity of failure ranges from 1 (negligible) to 4 (significant)

DGN – diagnosis confidence rating ranges from 1 (low) to 5 (high)

PGN – prognosis confidence rating ranges from 1 (low) to 5 (high)

High value of the MPN is supposed to mean that the primary monitoring techniques is the best option for detection, diagnosis and prognosis of the particular failure mode. However, the low MPN doesn't necessary mean that monitoring is useless (ISO 13379 2002). First of all it implies that the low level of detection, diagnosis and prognosis is expected by using given monitoring technique. The main advantage of FMSA is the applicability for CM implementation process that can contribute to ranking of the most preferable equipment to monitoring. See example of the FMSA sheet in the Figure 15 shown below.

Item	Part No Name Issue	Function or process	Failure Mode	Effect of failure	Cause of failure	Failure Symptoms	Primary Technique	Frequency of monitoring	Primary MPN					Correlation Techniques	Frequency of monitoring	Correlation MPN				
									DET	SEV	DGN	PGN	MPN			DET	SEV	DGN	PGN	MP

Figure 15: Failure Mode & Symptoms Analysis (ISO 13379 2002)

Failure mode, effect and criticality analysis has several benefits. One of them is the identification of safety and product liability problem areas and assistance in the maintenance program development (IEC 60812 2006). The information gathered by this assessment tool can be utilized in combination with finance information for determining financial risks, feasibility and return on investment (ROI) (Wardt et al. 2011). At the same time performing FMECA can contribute to redesign or design modifications. If during the analysis process it appears that the risk can't be mitigated, it is possible to reduce the severity of consequences. FMECA provides the model aimed to contribute to the evaluation of probability or rate of failure occurrence. There are number of qualitative limitations of this risk assessment tool such as bias, uncertainty in predicting the failure modes and deficiencies related to inability of accounting for complex system dependences and common mode failures. Individual features of assessment team members may distort the analysis (Wardt et al. 2011).

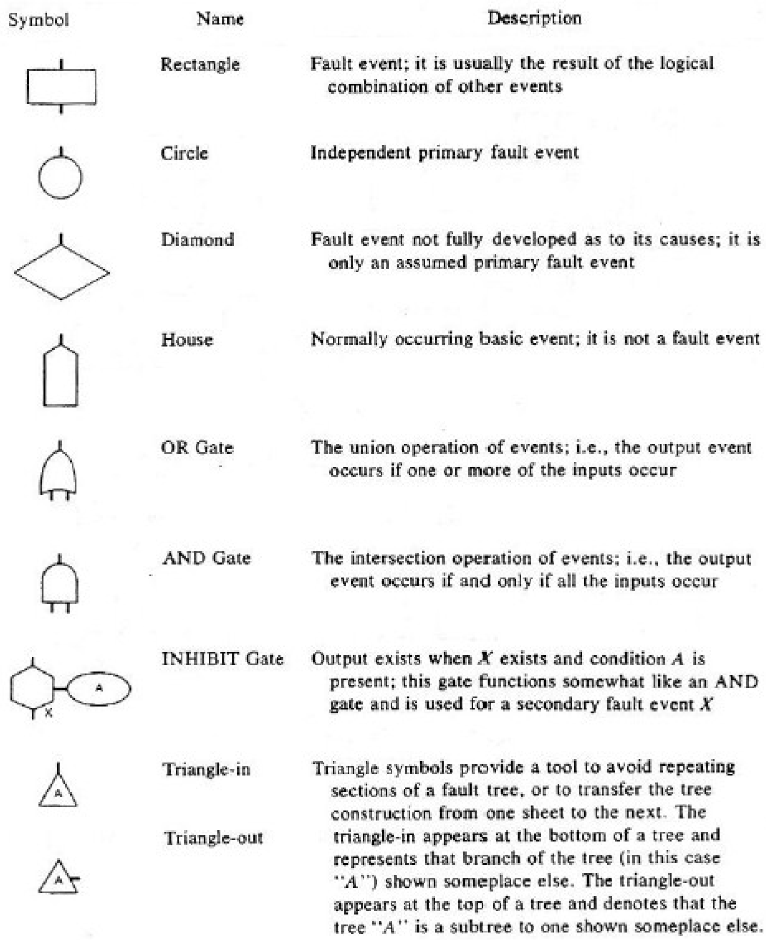
2.4.4.4 Fault Tree Analysis

Fault tree analysis (FTA) is a typical "top down" deductive approach for reliability and safety analysis. It is the graphical analytical method of dependability analysis (IEC 61025 2006). FTA starts with the definition of the top-event and breaks into several lower level failures, events and consequences which can lead to the main failure mode (Thompson 1999). The FTA structure makes it possible to understand the relationship between events through the sequence of failures. The analysis can be qualitative or quantitative according to its current application area. The quantitative part of FTA implies the calculation of top failure mode & low-level events probabilities and determination of contribution from each failure event (Thompson 1999). In case of unavailability of failure frequency, qualitative approach can be used and introduce the descriptive probability of occurrence (e.g. very probable, remote probability). In other words this tool indicates a single or a group of components at the, as low as reasonable, hierarchical level that contributes mostly to the top failure mode. The FTA utilizes traditional Boolean logic functions and symbols in order to present the fault tree graphically (see Figure 16). This method can be described by following sequence (Pintelon & Puyvelde 2006c):

- System definition (functions, components, interrelations)
- Top event or failure mode definition
- FT construction starting from the top event
- Probability estimation

The application area of FTA is first of all systems with several interdependent sub-systems (IEC 61025 2006). The most common application examples of this reliability assessment tool are the design of: aviation industry, nuclear power plant, industrial processes, communication systems and etc. Fault tree analysis could be used in combination with other reliability analysis tools such as FMECA, ETA, Markov analysis and RBD. For instance the result of FTA can be utilized as the input data source for FMECA providing the main cause of failure mode and single point failure investigation.

The main advantage of FTA is the possibility for simplification of the process through computerization. This approach indicates the most critical components presenting them visually and makes it possible to evaluate hardware and human faults. In addition to that, multiple failures and failure scenarios could be considered and evaluated. The limitation of this approach is the large amount of data needed to provide a sufficient basis for performing this complex analysis.



Symbol	Name	Description
	Rectangle	Fault event; it is usually the result of the logical combination of other events
	Circle	Independent primary fault event
	Diamond	Fault event not fully developed as to its causes; it is only an assumed primary fault event
	House	Normally occurring basic event; it is not a fault event
	OR Gate	The union operation of events; i.e., the output event occurs if one or more of the inputs occur
	AND Gate	The intersection operation of events; i.e., the output event occurs if and only if all the inputs occur
	INHIBIT Gate	Output exists when *X* exists and condition *A* is present; this gate functions somewhat like an AND gate and is used for a secondary fault event *X*
	Triangle-in	Triangle symbols provide a tool to avoid repeating sections of a fault tree, or to transfer the tree construction from one sheet to the next. The triangle-in appears at the bottom of a tree and represents that branch of the tree (in this case "*A*") shown someplace else. The triangle-out appears at the top of a tree and denotes that the tree "*A*" is a subtree to one shown someplace else.
	Triangle-out	

Figure 16: Fault Trees Commonly Used Symbols (Ragheb 2010)

2.4.4.5 Event Tree Analysis and Decision Tree Analysis

Event Tree Analysis (ETA) and Decision Tree Analysis (DTA) are two techniques that are quiet related to each other but have a significant difference. DTA is process where the quality of the tree depends almost only on skills of the analyst, while in ETA the expert aids to the process with the existing elements of the tree.

Event tree analysis (ETA) is the graphical inductive method to develop the consequence scenarios of the initiating event by using the binary logic and mitigating factors (Pintelon & Puyvelde 2006c). Binary logic makes it possible to identify and assess the probability of the possible outcomes. Graphical representation of ETA can vary according to the symbols' identifies and labels that are used. In 62502 IEC: 2010 commonly used representations are given (see Figure 17).

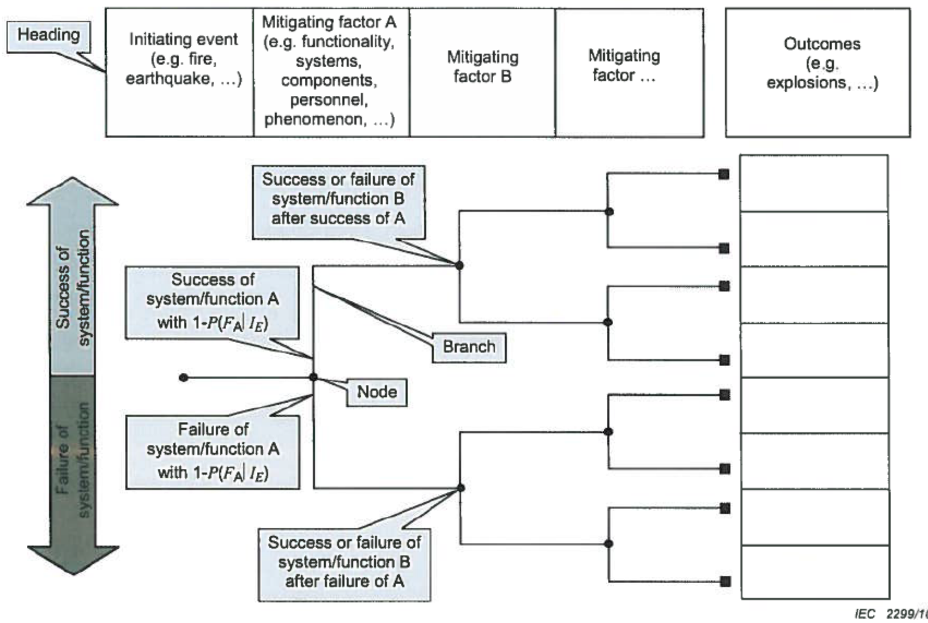


Figure 17: Frequently Used Graphical Representation (IEC 62502 2010)

The main question that is asked during the ETA process is: "What happens if …?". This implies the continuous checking of the outcome in case of a component/barrier has or has not failed (Pintelon & Puyvelde 2006c). The construction of the event tree starts with definition of the relevant system or activity boundaries. The second step is aimed to determine initiating events or categories of the events that might bring serious consequences e.g. human error, equipment failure and process disturbance. In order to find out what conditions will affect the sequence and outcome of the initiating event we have to identify mitigation factors e.g. safety systems, alarms, barriers, procedures and emergency responses (IEC 62502 2010). By using these factors we can define various accident scenarios and perform quantitative analysis based on the event tree structure. All the outcomes can be grouped and analyzed according to destruction of the system, loss of life, environmental impact and etc.

The findings from ETA can be used in different ways. First of all results can be utilized as a decision-making basis and contribute to the most preferable technical and organizational solution (IEC 62502 2010). It may include barriers evaluation, changing of maintenance procedures or modification of primary system design. ETA can be used in combination with other risk analysis techniques e.g. FMECA and FTA. By utilizing FTA and ETA together, the frequency of the initiating event and conditional probabilities of failure or success of mitigation factors can be calculated (see Figure 18). Using this approach such weaknesses of ETA as unnoticed common cause failures can be avoided.

The main advantage of the event tree analysis is the applicability to all types of the systems and intuitive understanding of visualized structure. It provides the sequence of events and identifies potential single point failure that may be used in a sensitivity analysis (how the outcome changes due to change in features of the mitigation factors) (IEC 62502 2010). One of the main limitations in ETA is the difficulties related to determination of the initiating events and operating scenarios lists. Frequency of failures may involve a certain degree of uncertainty that will impact the final quantitative findings. The risk to overlook hidden system dependences should be also considered (IEC 62502 2010).

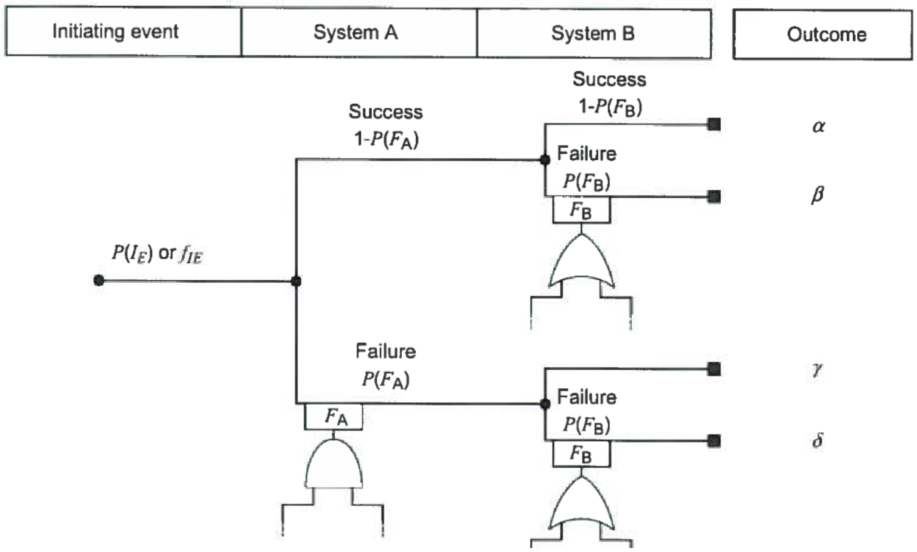


Figure 18: Fault Tree Linking (IEC 62502 2010)

There is another method called Condition-based FTA (CFTA) that utilizes CM to recalculate the failure rate of the top event by using updated values of the sub-events and components. Conditions of critical components will be monitored and analyzed. And the results will be used in updating of the top event reliability value (Shalev & Tiran 2007).

DTA is the binary tree model where the value of the output can be predicted by using predictor variables (Faller 2008). One of the main application areas for decision trees is the patterns recognition. It implies that the CM data is used to model the value of the outcome continually with help of predictor values through an iterative process (Faller 2008). It may utilize the machine-learning technology to build predictive models that could be used in prognosis and diagnosis of failure modes.

2.4.4.6 Root Cause Analysis

Root cause analysis (RCA) is a class of the problem-solving methods aiding with identifying the event sequence that resulted in functional failure of the component, equipment or system. It is done by simply “asking the repetitive why” in order to find hidden causes (Faller 2008). As mentioned above RCA plays the significant role in developing Precision Maintenance (Proactive Maintenance) by helping to reduce the chance of failure occurrence. It could appear that there are several correctable root causes that contribute to the failure e.g. poor management and wrong tools (Pintelon & Puyvelde 2006c). RCA is not a specifically defined methodology. RCA can imply different tools and processes but there are some common principles to be applied (Pintelon & Puyvelde 2006c):

- The goal of RCA is to find and correct the root-cause rather than the symptom.
- There often exists several root causes

- RCA should be systematically performed and be based on background and statistical knowledge.

The root cause of each problem contributed to the basic failure mode (casual factor) is often assessed after defining this mode and casual factors (Pintelon & Puyvelde 2006c). If we consider the bearing failure as the main problem, the increase of bearing temperature is the casual factor, while lubrication starvation refers to the root causes (Faller 2008). RCA should be the continuous process and take into account the dependency on operating conditions. For instance, bearing temperature could be increased due to the increased RPM.

2.4.4.7 Pareto Analysis

Pareto Analysis is simple technique in comparison with reliability assessment tools named above. The main goal of this method is to identify the most critical systems, equipment and areas in plant (Andrews & Moss 2002). The approach aims to choose the most critical systems among the other critical systems. The example of steps included in the procedure is shown below (Andrews & Moss 2002):

- Identification of equipment population within the system
- Definition of the boundaries (what failures are included in the analysis) of each system
- Counting of downtime outages for each system in a specified period
- Presentation of results e.g. as a histogram
- Choosing the predefined number of systems contributing mostly to plant downtime

Predefined number of areas where the greatest reliability improvements may be achieved is decided by the company by using the cost-benefit approach. For example, 20% of systems contribute to 80% of plant downtime. Nowadays several big companies utilize "Top-ten" analysis based on Pareto approach with other performance indicators in order to reduce plant downtime (Andrews & Moss 2002).

2.4.5 Monitoring Methods

After performing a ranking of the critical equipment we are able to decide what is the most applicable maintenance strategy in given conditions. If the condition-based maintenance is chosen we proceed further with selecting a proper monitoring method including parameters to be measured, measurement techniques and locations. Parameters should be decided based on the reliability and criticality audit described above. Measured parameters can be both a simple instantaneous measure and averaged values over the time period (ISO 17359 2011). For instance, current and voltage simple measurements are not enough to predict the failure mode, while it could be done with spectral and phase measurements (ISO 17359 2011). Monitoring interval should be chosen based on the type of fault, degradation time (lead time to failure) and parameters rate of change (ISO 17359 2011). It could be also influenced by operation conditions and economic issues.

2.4.5.1 Measurement Techniques

The best result of utilizing CM techniques could be achieved by integrating the output from several technologies into one report (Mobius Institute 2009). In order to select the best technology or the set of technologies for all the plant equipment several issues must be considered: reliability requirement, process importance, redundancy, accessibility and failure consequences (Mobius Institute 2009). All this issues should be transformed into a finance equivalent to support decision-making process.

There are six technologies typically used in CM:

- Airborne Ultrasonic
- Infrared Thermography
- Electric Motor Analysis
- Oil Analysis
- Wear Particle Analysis
- Vibration Analysis

Different monitoring technologies aid in asking the right question to machine and getting an answer. It is not necessary to study technologies at the physicist level. It is a brief overview that can provide relevant information for the expert to choose the best technology for the given situation. Some of the technologies may detect the existing problem, while others are able to identify conditions that may create a problem in the near future. In some cases when alarm levels cannot be determined so easily, the trends reflecting deviation from a primary condition have to be assessed.

Vibration analysis is applicable for all rotating machines e.g. fans pumps, motors, turbines and compressors. The level and the pattern of the vibration may indicate the components condition. By using electronic instruments to perform the vibration analysis we can study the patterns and even diagnose the type & location of the problem. There are several typical faults that can be detected by vibration analysis, in particular, bearing problems, imbalance, misalignment, looseness, soft foot, electrical faults, eccentric rotors, belt and coupling problems, gear mesh and broken rotor bars (Markeset 2011).

The vibration data is provided by the special sensor or sensor connector mounted on a bearing housing. Data could be collected periodically (e.g. once a month) or continuously. Due to that the machine vibrates up and down (vertically), side-to-side (horizontally), and end-to-end (axially), data should be collected from different locations and directions (Mobius Institute 2009). In some cases, specifically for the high critical machines, sensors are preinstalled and all the data could be collected from junction boxes. Turbines and generators have often protection systems that will shut down the machine if the critical predefined vibration level is reached. There is a commonly used sequence for performing the vibration analysis: detecting the problem, identifying the severity, determine the root cause and checking if the problem is solved after the repairs (Mobius Institute 2009).

Rotating equipment as well as other plant assets produces high frequency sounds. These sounds can be analyzed and used in identification of the potential problems. The airborne ultrasound is excellent for finding air leaks. This technology provides good evidence in finding bearing problems, lubrication problems, detecting electrical faults and finding steam leaks in steam traps (Mobius Institute 2009). The technology uses ultrasonic sensors (>20,000Hz) and demodulates the signal to the frequency range within the hearing range (20Hz-20,000Hz) (Higgins & R. Mobley 2002). One of the main challenges considering this technology is that the measurements appear to be too directional that may create situations when the sources of sounds can be missed. The volume of the sounds depends significantly on the distance to the source. One more limitation of this technology is related to the vacuum through which sound cannot go. Headphones which are used together with ultrasound instrument can be a very effective way to search for leaks and detect faults in a noisy environment (Mobius Institute 2009). In addition to that the result can be measured and displayed in decibel by waveform and spectra.

Infrared thermography makes it possible to study the emitted energy by utilizing a thermal infrared imaging system. This technology can be applied both for rotating and non-moving equipment such as electrical panels, boilers, transformers, insulators and switchgear (Mobius Institute 2009). It can identify e.g. steam leaks, increased wear and electrical arcing. By using the electromagnetic energy sensors radiated energy can be detected and translated into the temperature.

There are two types of devices utilizing this technology: spot radiometers and infrared cameras. The firs one is designed for detecting the radiation in a small particular area, where area size depends on the distance from the target (Higgins & R. Mobley 2002). The actual measurement can be affected by the air flow, surface type and other factors. Infrared cameras detect the heat (radiated electromagnetic energy), calculate the temperature and may take the picture in order to compare it with the thermographic image. In most cases it is more useful to have the relative temperature measurements than the absolute ones (Mobius Institute 2009).

Electric motor testing is aimed to test one of the main equipment components in most plants. As stated above mechanical problems can be identified by three technologies described before: ultrasonic, infrared thermography and vibration analysis (Higgins & R. Mobley 2002). At the same time two categories of the electric motor tests exist: static (offline) and dynamic (online). Offline test is usually performed once a year or during the motor shutdowns. It can be used as the quality assurance test for the just-received motors in order to check the primary condition of the equipment and set the base-line. If a problem with a motor occurs, the insulation integrity should be tested. Insulation can be compromised by e.g. contamination issues, overload and voltage problems (Higgins & R. Mobley 2002).

On-line test implies testing while the motor is in operation. It shows the current and voltage spectra. The data gathered from the test is treated at the same way as during the vibration analysis. The current spectrum may show us probable issues with e.g. rotor bars, uneven air gap or a bowed motor. The voltage spectrum can indicate potential problems in windings. Generally on-line tests are less destructive then off-line and don't require stops.

Rotating equipment can perform their function by using correct lubrication only. If the lubricant is contaminated or incorrect composition is used, increased wear of equipment could take place. Lubricant is quite expensive and balancing the costs and benefits is significantly important. The oil test is made to indicate the following (Higgins & R. Mobley 2002):

- The ability of the lubricant to perform its function

- The contaminants such as water or dirt
- Metals and other elements that may cause the early wear of the machine

Samples are used to be collected periodically or some tests could be performed continuously. There are several types of oil test and related measures shown in Figure 19.

Test	Measures...
Oil Bath 40c and 100c	Viscosity
R. D. E. Spectroscopy	Elemental Concentrations
FT – IR (Infrared)	Degradation, contamination, additive depletion
Total Acid	Acid Levels
Total Base	Base Levels
Water Crackle Karl Fisher	 Concentrations to 200ppm Concentrations to 10ppm
Particle Count	NAS & ISO Cleanliness

Figure 19: Oil Tests (Mobius Institute 2009)

Oil analysis has its limitations and one of them is the inability to detect the onset of abnormal wear (particles bigger than 10 microns). In addition to that it is impossible to detect the source of wear and no information regarding the machine condition can be provided (Mobius Institute 2009). Oil analysis may contribute with providing information about oil condition, but not the machine condition.

Ferrography is a type of wear particle analysis which performs the lubricated machine condition analysis by examining particles (size, concentration, shape and composition) in the lubricant (Mobius Institute 2009). It can aid in early identification of the abnormal wear-related conditions and in some cases (e.g. slowly rotating machine) even earlier than vibration analysis. There are typically six types of the wear particles: abrasive wear, adhesive wear, corrosive wear, cutting wear, fatigue wear and sliding wear. The cause of abrasive wear is the interaction between hard particles (e.g. dirt and wear metals) and internal components (Higgins & R. Mobley 2002). Filtration as a mitigation measure can reduce this type of wear.

Adhesive wear is generated by the interaction between two metal surfaces which leads to removing particles away from the components. In order to avoid this type of wear the correct volume of the lubricant, proper viscosity grade and no contamination (e.g. air and gas bubbles) should be a case. Corrosive wear is the chemical process which is able to remove particles from the surface of the component. This chemical reaction can be caused by acidic oxidation or random electrical current.

Corrosive wear can be reduced by avoiding contact with water and combustion products (Mobius Institute 2009). Cutting wear is the result of that an abrasive particle has imbedded itself in a soft surface in case of imbalance and misalignment. This type of wear can be avoided by the proper filtration and maintenance. Fatigue wear occurs in case of cracks development of the component that allows particles to be removed. Sliding wear is the result of equipment overload and stress. Abnormal heat during the operations can be the reason of the lubricant degradation and result in metal-to-metal sliding.

2.4.5.2 Condition Monitoring System Design

Nowadays critical equipment has often preinstalled instrumentation related to e.g. temperature, speed, torque and current. These data sources may be used to identify the equipment condition and predict possible deviations. For instance, the motor torque/pressure ratio can be increased as a result of wear in the pump (Holme 2006). The other way to assess the equipment condition is to log operating parameters and trace the trend over time. Adding this to the physical models and historical data, the comprehensive picture of the equipment condition can be created. The obtained CM data can be used for updating and modifying the permanent physical model and improving the quality of equipment design, expenses and spare-parts control (Holme 2006). CM system usually consists of three main parts: local logging unit, data processing, storage cluster and web server for reporting and distribution (Holme 2006).

Local logging unit can be both the part of the machine control and stand-alone unit. At this stage the simple pre-processing like averaging, max/min logging and rates of change calculation can be done. The local buffer can contain pre-processed data until communication channels (e.g. satellite links and high-speed fiber links) are able to transfer it further to service center (Holme 2006). Service center is in charge of storing operational data into databases and process them according to the predefined mathematical models. It is done to make data available for further analysis process. There are typically two types of the analysis: automated and manual one.

Automated analysis presented through web-based reports is able to make a majority of conclusions such as estimated component wear and component lifetime (Holme 2006). Manual analysis will be first carried out by the service operator in order to detect any breakdowns and unnatural behavior. In case of defects, equipment experts will perform the investigation and possibly modify the CM system. The data obtained from the analysis can be used by equipment owners and users to perform other type of studies e.g. investment analysis and asset optimization (Holme 2006). Equipment developers in the turn will utilize result of the analysis to e.g. develop or modify equipment design.

2.4.6 Data Acquisition and Analysis

The commonly used practice for data acquisition is to compare measurements to given trends and baselines. As stated in the previous chapter the collection of data may happen both online and offline (periodically). For this purpose the computer-based systems may be used in order to aid in management of data acquisition process & its routes, measurements trending and recording (ISO 17359 2011). Quality of measurements should be also assessed. Poor mounting of transducers & their faults, cable faults, incorrect range of measurements and poor planned sampling rate may affect the measurements' quality.

2.4.6.1 Diagnosis

There are two main approaches to be used for diagnosing a machine condition (ISO 13379 2002):

- Numerical methods (by using neural networks, pattern recognition, statistical analysis and etc. to develop through the learning process its own way to diagnose the machine)
- Knowledge-based methods (by utilizing existing fault & operating models and similar cases that took place early)

A good example of the first approach could be a "fault/symptoms approach" that require only basic knowledge of the mechanical systems and processes (ISO 13379 2002). This method is based on evaluation of relationships between faults & symptoms and includes the sequence of four main steps. The anomaly qualification as the first step is aimed to check the correctness of data used to detect the condition deviation and establish groups of symptoms (macro-symptoms).

The next step has a goal to develop fault hypotheses based on macro-symptoms. Confirmation of fault hypothesis step includes the process of reduction & reordering of the fault hypothesis list and evaluation of the necessary symptoms (required to accept the fault hypothesis) and reinforcement once (to reinforce the expectation of a fault) (ISO 13379 2002). The last part of this approach is aimed to review and put together all the previous steps.

The second approach called "Casual Tree Modeling" has something similar to fault tree analysis, but in contrast to FTA, it is used in the diagnostic sense to indicate the relationships between failure modes. Failure modes are initiated by root cause and correspond to each other through influence factors and initiation criteria (Isermann 2011). It implies that failure modes can have an influence on the other failure modes, possibly initiate them or don't have any effect at all (see the Figure 20).

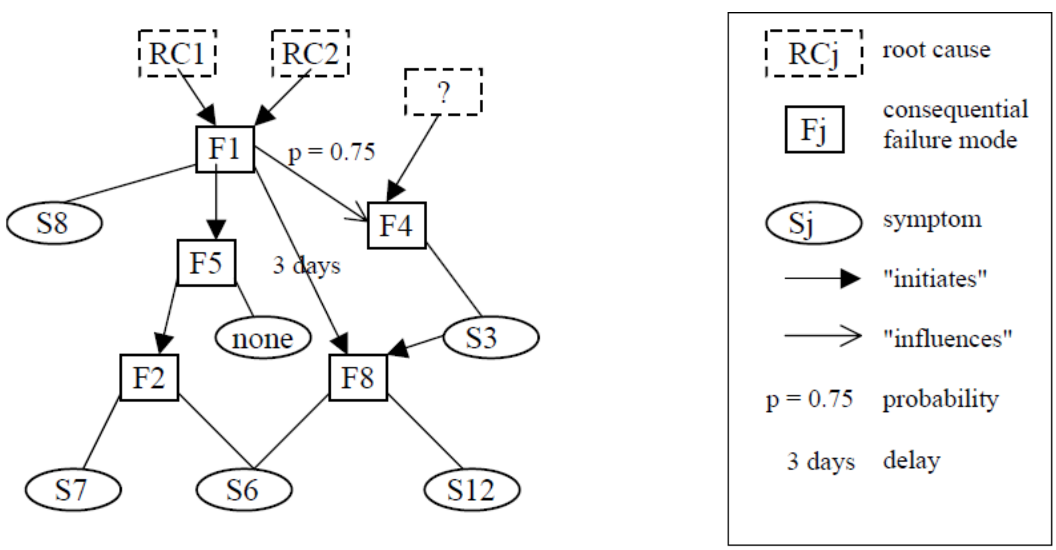


Figure 20: Example of Casual Tree Modeling (ISO 13379 2002)

2.4.6.2 Prognosis

Prognosis is a process of time-to-failure estimation and risk of one or several future failure modes occurrence (ISO 13381 2003). The prognosis approach presented by ISO 13381:2003 covers four main steps:

- Trip set point definition
- Current severity identification
- Parameter behavior and expected deterioration rate estimation
- Estimated Time-To-Failure (ETTF) prediction

The biggest effect of prognosis can be achieved by using predefined age related and progressive deterioration characteristics of failure modes such as: deterioration rates; future failure modes initiating criteria; relationships between current failure modes and future ones; detection capabilities for current and future failure modes; operation conditions and maintenance actions effect (ISO 13381 2003).

In order to identify failure mode and effect on future fault, the symptoms or influence factors are used. Vibration (symptom) due to the bearing failure (current failure mode) may be the initiator of the seal failure (future failure mode) which, fails faster than bearings (Tobon-Mejia et al. 2010). Without taking into account this feature, the priority of the seal failure might be underestimated and together with the current failure mode may result into the serious consequences e.g. impeller failure in the pump.

Three limits could be used to react to equipment condition deviation: alarm, trip limit and failure set point (Tobon-Mejia et al. 2010). The failure occurs when a parameter (e.g. vibration, temperature, pressure) reaches the predefined set point. Machine is supposed to shut down before failure occurs when the value of parameter increases to the level of the trip set point, which might be defined by the equipment technical documentation or standards. Alarm limit is usually less than trip value and is determined based on the following (ISO 13381 2003):

- Prognosis confidence level
- Requirements for future production
- Delivery lead time for spare parts
- Planning lead time required for maintenance
- Planning activities needed to fix the fault
- Extrapolation and projection of trend

Extrapolation and projection are two different approaches having the same goal - to predict the behavior of parameter value in the future. Projection reconstructs the curve by estimating future data based on the mathematical model and historical data, while extrapolation takes into account only the current data & rate and basically prolongs the curve.

In order to display all the data of a single system simultaneously e.g., bearing temperature and viscosity, the multiple parameter analysis is needed (ISO 13381 2003). In this case independent reference value (e.g. time) is assigned to one of the axis and percent of life usage - to another one. Life usage varies from 0% when the machine is in perfect condition to 100% indicates it is in broken condition. One parameter or a combination of them can be both symptoms for the current failure mode and initiation criteria for the future one (see Figure 21). It requires a deep understanding of interdependences of failure modes and their initiating criteria generated historically and statistically (ISO 13381 2003).

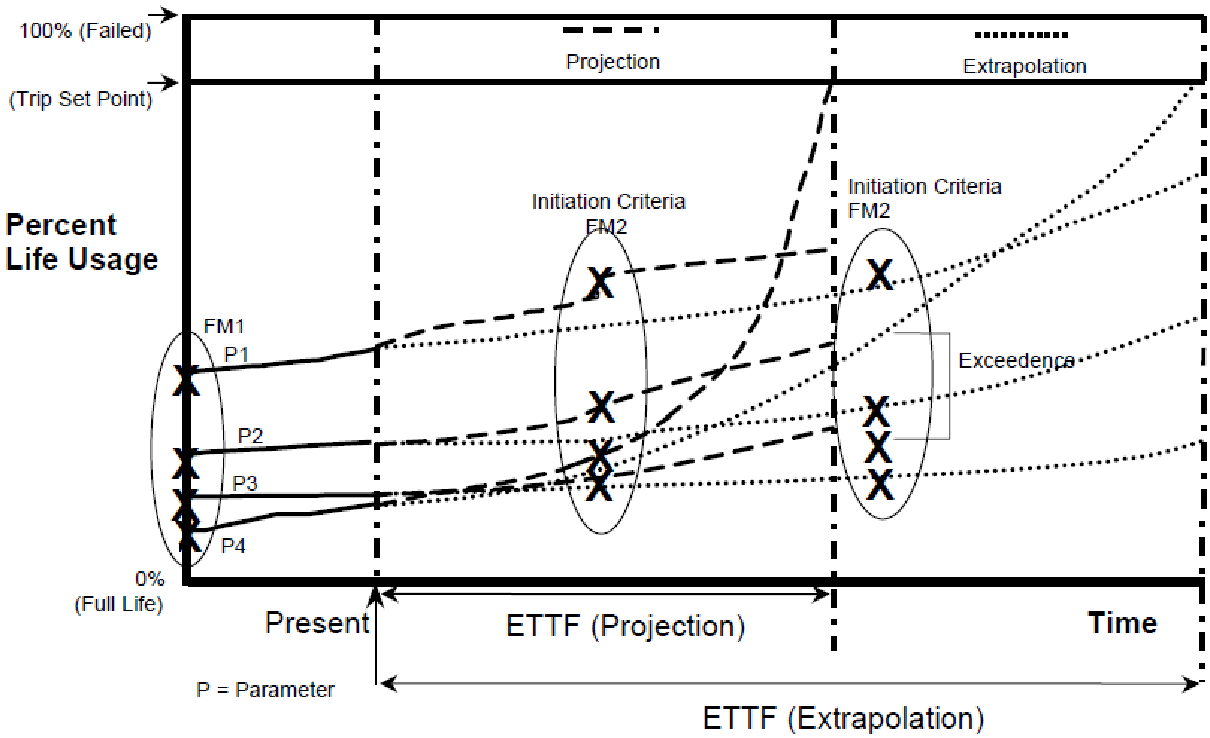


Figure 21: Initiating Prognosis - Projection vs. Extrapolation (ISO 13381 2003)

In order to perform a proper prognosis, such reliability assessment tools as FMECA, casual FTA and RCA should be used to provide the source data on failure modes and inter-dependences. After the failure mode is detected, one of the main tasks will be to estimate time to failure. It could be done by applying e.g. monitoring data, operational data, previous cases and test data (ISO 13381 2003). The process can be atomized by applying the mathematical model that will include the data listed above and update itself in case of new data coming.

2.4.7 Future of Condition Monitoring

There are several CM trends that are still under development, test or implementation phase. The first one is the integration of several monitoring technologies together in one approach and presentation to the operator as a holistic picture of the machine condition. It can contribute to the decision-making process by providing necessary input for decision model and accordingly integrate process management and CM into each other. CM role in the improvement of control over maintenance activities and overall process optimization increases (S. Dunn 2009). Possible online monitoring together with Internet provides the capability for immediate identification of failure mode and communication of it to the interested parties located even far from the equipment location.

Online technologies are becoming cheaper and more available for utilization. “Smart sensor” technologies, for instance, are able to do preprocessing of raw data on-board before forwarding them to the more complex analysis. In addition, this type of sensors are able to carry out self-assessment for failure and condition deviation (S. Dunn 2009). CM services, in many cases, have become a mandatory part of the contract offered from the equipment vendor side.

3. Case Study Description

In this part the main research methods and equipment used to achieve the final result of the thesis are described. Feedback related to the applied research methodology and main advantages and disadvantages is presented as well. Chapter starts with the research strategy description and continues further with the main tools and approaches used to accomplish this strategic objectives.

3.1 Research Strategy

The strategy for caring out the research is briefly described in the introduction part. There were five main steps followed by the author:

- Problem definition
- Development of the initial concept
- Testing the solution on a specific example
- Evaluation of the testing results
- Improving the concept based on previous steps
- Description of the pros and cons of the final solution

At the beginning of the research together with supervisors both from COSL Drilling Europe AS and University of Stavanger the goals and scope of work were defined. The plan of main activities and milestones was developed and approved.

The research started from studying of the equipment group that is suggested by COSL as candidates for condition monitoring. Significant amount of time was used for brief understanding of the drilling equipment functions and features. It was done mainly through books and additional clarifications were obtained with the help of experts in COSL. The last step of equipment studying was a visit to a similar MODU COSLInnovator, where leader of the maintenance department demonstrated the relevant equipment and associated challenges. This stage is considered to be necessary due to the importance of understanding deterioration mechanisms, the reason of initiation and it contributes significantly to reliability assessment part.

The next part of the research is aimed to study the existing practices of CBM programs implementation for drilling equipment in today's offshore industry. Based on articles and relevant references, a list of most frequently CM exposed equipment was determined and evaluated. Significant attention was given to reasons for choosing particular equipment and results of CBM program implementation. At this stage the author drew attention to different tools applied for choosing the right equipment for monitoring and prioritized monitoring techniques. The result of this step was the establishment of the draft concept of CBM program development methodology.

The further research process implied testing of the methodology and modifying it according to the results of the test. The specific group of equipment (drilling equipment) was chosen to evaluate reliability, applicability and necessity of the concept steps. Some of the steps were prioritized by the author to be deeper investigated than the others. For example, it the specific reliability assessment framework consisting of several tools and techniques was developed. This part of methodology was prioritized due to the complexity of this step and significance of its contribution to the final result. Main steps of the CBM methodology were applied for drilling equipment on topside of COSLPioneer.

Most of the tools and techniques were borrowed from international and Norwegian standards, though some of them were modified by the author in order to adapt them for particular use. The important part of testing was studying of existing standards in condition monitoring. The author attempted to assess different approaches given in ISO and Norsok standards and concluded with several pros and cons.

Input data for testing the concept was received from several sources. The biggest contribution was gained from consultations with experts. The COSLInnovator rig manager gave a brief overview of the drilling equipment functions, failure modes and criticality. Maintenance engineer presented the existing maintenance program applied in COSL and its main challenges. During the work on the thesis, the trip to CM service provider Karsten Moholdt in Bergen was organized. Almost all the main CM techniques together with diagnosis and prognosis were explained and demonstrated there. The result of this trip was comprehensive understanding of the CM services provided by this particular company and examples of successful and not so successful implementation process. An additional reason for this trip was to find possible “pitfalls” in CM process and come up with necessary mitigation measures.

Another important source of information was an OREDA database, which is aimed to collect and exchange reliability data among the companies participating in this project. The access to the database was provided by Statoil as one of the project participant and the company that orders services from the COSL. Thus, maintenance history, failure rates and etc. were successfully extracted and applied in risk assessment part of the overall methodology. COSL Drilling Europe has its own computerized maintenance management system (CMMS) called STAR IPS. Main data about criticality, maintenance history and systems composition for drilling equipment on COSLPioneer was taken from this system.

The results of the methods used in steps of the methodology were checked by comparing them with the results received from experts based on the interviews. That has been performed both for criticality analysis and reliability assessment part. The interviewing process implied presentation of available input data, used for results calculation, to the maintenance personnel of COSL and asking for their own opinion and evaluation. Then the calculated results were compared with the expert’s evaluation and assessed according to their accuracy and reliability.

Main software tools used during the concept development process were as follows: Microsoft Word, Microsoft Excel, Microsoft Project, Microsoft Visio and STAR IPS (CMMS). MS Excel was used in order to calculate results related to criticality and reliability studies. MS Project contributed with planning and following the main project activities. MS Visio was used to develop main frameworks and block diagrams for the concept. STAR IPS provided data for the specific drilling equipment installed on MODU COSLPioneer.

Based on the results of the concept test, main modifications, changes and recommendations were applied & described for the CBM program development methodology. The next step implied the determination of the main strengths and weaknesses of the final concept and each step in particular. It was done to limit the application area of the methodology in order to provide the most reliable results for particular cases.

Both qualitative and quantitative methods were used during the work on the thesis. There are two main reasons to that:

- Limited technical information (e.g. reliability and financial data)
- Several possibilities for receiving and assessing the valuable information.

This approach gave a possibility to look beyond the numbers and describe what different values imply and what degree of uncertainty they possess. It is important to mention that the thesis status was periodically reported and evaluated by the supervisors. The table 2 given below summarizes all the main steps author went through in order to obtain the final result.

The research strategy used during the project has its own advantages and disadvantages. The idea to establish the brief concept of the required CBM development methodology and correct it during the further testing was very helpful for the start phase of the master thesis. It gave the starting and referencing point for the whole process. Another positive feature of the strategy the author chose was using the relative values provided by the experts through the interviews for the ranking purposes. It helped to save time for calculations and searching process.

The advantage of testing the concept in order to find possibilities for improvement and modifications gave necessary details on applicability of different assessment tools. One of research strategy disadvantages was a significant amount of time used for studying the company processes and drilling equipment. This part of the project could be limited to those equipment groups that are most critical according to the given criticality evaluation. The scope of the project could be reduced to, for example, reliability assessment framework only and its testing with several equipment groups.

Table 2: The Main Steps of Case Study

Steps	Tools & Methods	Results
Definition of project goals & scope and planning of the activities	• Meeting with supervisors • MS Project	• Plan of the activities and milestones
Studying drilling systems and maintenance approach generally and on COSLPioneer in particular	• Scientific books and articles • Conversations with experts • Practical experience	• Drilling systems basic understanding • Overview of existence practices
Establishment of CBM development methodology concept	• MS Visio • ISO and Norsok Standards • Conversation with supervisors	• Draft concept of CBM development methodology presented as a sequence of steps and activities • ISO and Norsok pros and cons
Testing the concept and evaluation of the results	• MS Excel • MS Visio • Interviewing of the experts • OREDA • STAR IPS	• Necessary modifications and improvement of the particular steps of the methodology
Concept improvement and modification	• MS Visio • MS Excel • Conversations with experts	• Final concept of CBM development methodology
Assessment of the final concept	• MS Excel • Feedback from the experts and supervisors	• Concepts pros and cons and application area limitations

4. Case Study Results

A draft and a final concept of CBM development methodology and outcome of its application are presented in this chapter. All the parts of the concept are described and evaluated according to the contribution to the final result. All the main modifications of applied methods will be discussed as well.

4.1 CBM Development Methodology (First Version)

As stated above, at the beginning of the project the draft concept is established and each step is described. It represented the on-going process consisting of several steps, which imply specific techniques and tools. The steps in the draft concept were inspired by the philosophy of CBM (Markeset 2011) and CM procedure flowchart from ISO 17359:2011 (ISO 17359 2011). The sequence of steps is shown in a flowchart presented below in Figure 22. The first step called "data collection" implies gathering of equipment/system technical documentation and drawings. Documents related to safety and reliability were collected as well.

By identification of critical functions the author suggests to establish a clear hierarchy of functions and break the systems/equipment into components. After doing it a special algorithm is intended to rank all the sub-functions of the systems according to their criticality. The particular equipment/system is assigned to the most critical functions at the next stage. The part called risk assessment includes actually reliability assessment tools by which ranking of the most critical failure modes is carried out.

In order to assess the success of CBM program implementation, the main KPIs should be established and followed. Identification of the current state is necessary to define further deviations of the state. "Degradation mechanisms" part is essential in choosing the right maintenance strategy and aids significantly in diagnosis and prognosis approaches development. After this step the set of parameters and their interdependences influencing the failure mechanisms of the equipment/system should be selected.

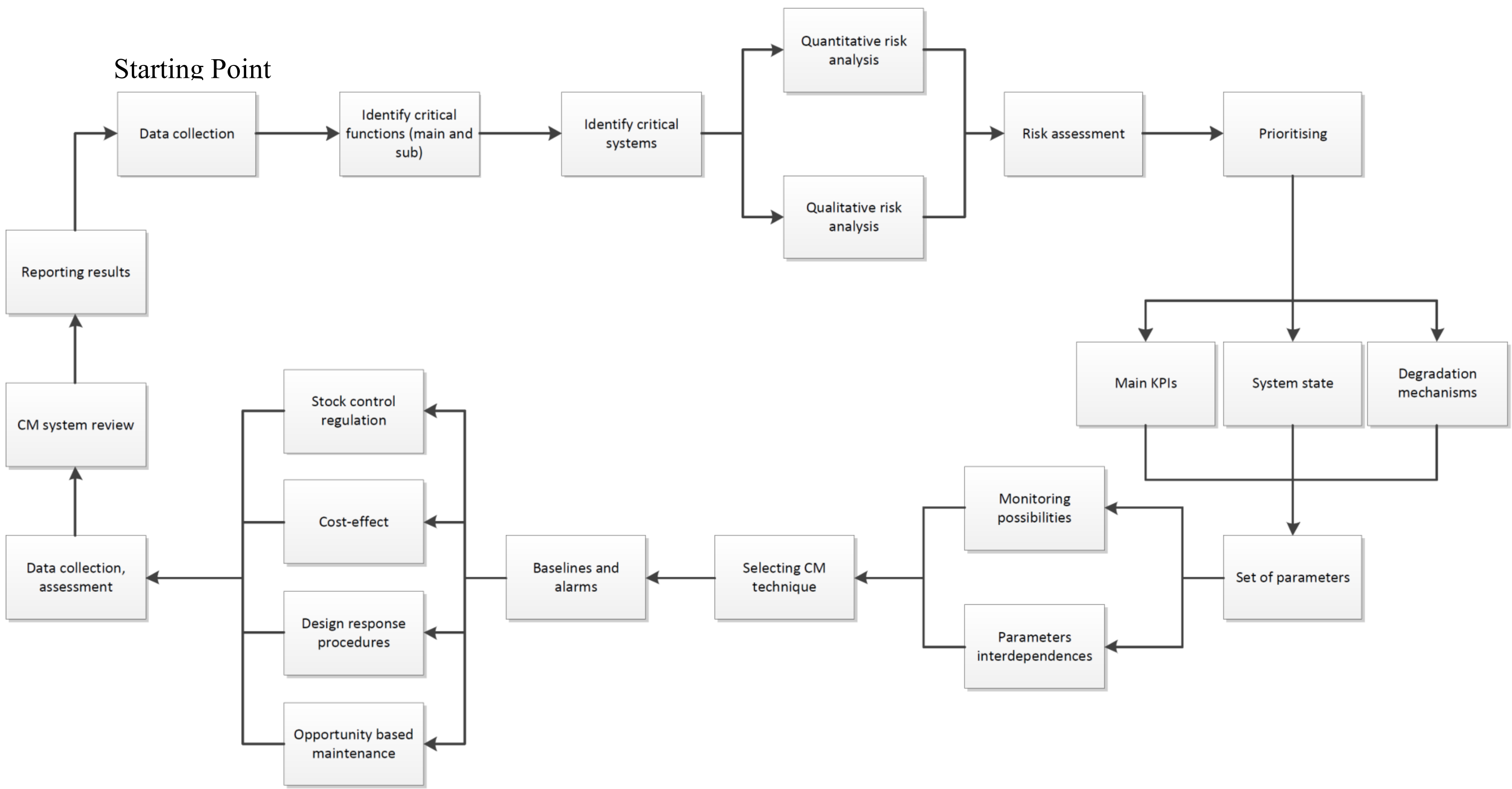


Figure 22: Draft Concept of CBM Development Methodology

Based on the set of parameters chosen to be monitored, design of CM system including sensors, processing systems and etc. should be determined. Baselines and alarm levels should be established right after CM technique is chosen. It gives an idea of how much time we have for getting spare-parts delivered. It contributes significantly to the stock control regulation strategy. The cost-benefit analysis in the flowchart shown above is aimed to establish the clear relationship between the CBM implementation and its effect on the earning power of the company. It is done in order to measure the performance and control the effectiveness of the project execution.

The actions related to the response on CM parameters deviation should be formalized and included into guidelines and procedures. The opportunity-based maintenance is included into a flowchart in order to provide the logic of choosing the equipment to maintain during the unplanned stops. The last significant part of the draft concept is the establishment of continuous CBM program updating by reviewing main technical conditions, costs, available technology and etc.

4.2 CBM Development Methodology (Final Version)

The final version of the CBM development methodology came as a result of applying the draft version of the concept to drilling equipment on MODU COSLPioneer. Due to the time and data limitation not all of the steps are tested. The author chooses, from his point of view, the most significant one. The final flowchart is presented below in Figure 23 and Appendix I.

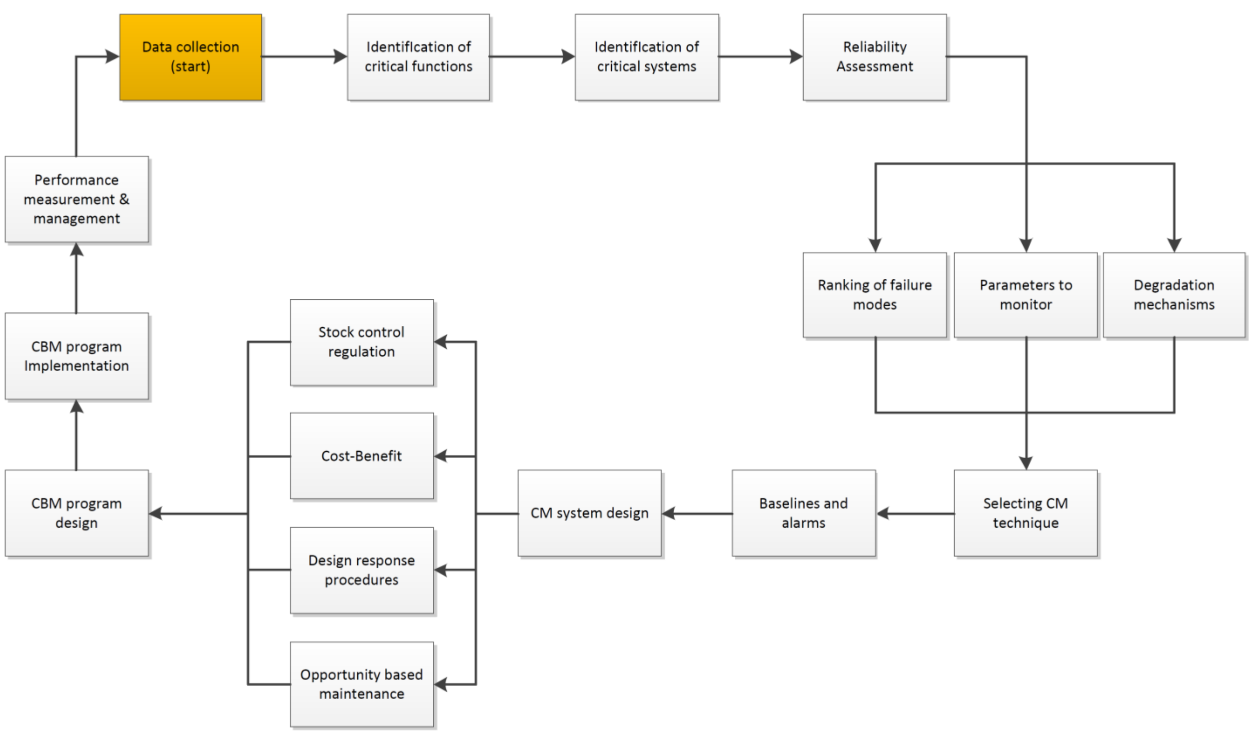


Figure 23: The Final Concept for CBM Development Methodology

4.2.1 Data Collection

At the beginning of the CBM program development all data necessary for the further process should be collected. Ideally this part includes collecting data needed for all the steps in the methodology like technical information, drawings, reliability data, maintenance reports and etc. Another goal of this step is to create a comprehensive overview of equipment to be tested and maintenance approach used in the particular company where the CBM is supposed to be developed. This process is very important in order to establish the solid base for the future development.

4.2.2 Identification of Critical Functions and Systems

In order to rank all the functions and sub-functions related to drilling equipment on MODU COSLPioneer the author decided to establish a single relative criticality number. It compares criticality of one function to another and concludes about which one should be prioritized. It can be done by using MS Excel and simple formulae. The guidelines presented further are just one of the possible ways to do it.

The input data for ranking can be picked up from the criticality evaluation that has already been done for all the functions related to drilling equipment. It is based on recommendations from Norsok Z-008 (Norsok Z-008 2011). The main variables presented in criticality analysis used by COSL as follows: severity of consequences, failure probability, capacity, number of parallel units and redundancy grade. An example of the criticality evaluation sheet is shown in Figure 14. The next step is to put the necessary data into the excel sheet and arrange it according to the type of function and system it belongs to. The example of this arrangement is presented below in Figure 24.

№	Type of function	Function tittle	Safety	Production	Oil spill	Capacity*	Probability of failure		
332		**BOP Control System**	Consequences**				High	Medium	Low
33201	MF	Hydraulic Power Unit (HPU)	2	3	1	100%	Low		
33209	MF	Accumulator Bottle Rack Assy Surface	2	2	1	100%	Low		
33202	MF	BOP/Diverter Control Unit/Panel	3	3	3	100%	Low		
	SF-IND	Local Indication	1	1	1	100%	Low		
33203	MF	BOP Fluid Recovery System (FRS)	1	1	3	100%	Low		
33204	MF	BOP Remote Operated Control Panels	3	3	3	100%	Low		
33205	MF	BOP Control Pod Hose and Reels	2	3	1	200%	Low		
33401	MF	Diverter With Control System	2	2	3	100%	Low		
33208	MF	BOP Acoustic System ACS 433	3	3	3	100%	Low		
33206	MF	BOP Control Pods	2	3	1	200%	Low		
	SF-Control	Regulating	2	3	1	200%	Low		
33109	MF	Flexjoint, Kick out Subs and Flex-loops	3	3	3	100%	Low		
33207	MF	Other Hydraulic Valves and other Equipment	2	3	1	100%	Low		

Figure 24: Example of Table for Criticality Ranking

The "capacity" term used in the table above implies a total value which is calculated by adding single capacities of all units performing the same function. Consequences are presented by numbers ranged from one to three where three is the highest severity grade of consequence. COSL developed a specific risk matrix (see Figure 13) in order to define what different criticalities imply for different type of consequences. For example, the highest severity of consequences related to safety implies potential for serious personnel injuries and fire.

The next step of functions ranking based on criticality is to assign the "risk group" to each of them. The "risk group" is the term introduced by the author himself and is aimed to perform separation of the most critical functions from the less critical ones. It is done by applying the modified criticality matrix to determine consequence severity degree. The matrix is created based on the one presented in Norsok Z-008 and discussions with the experts. It was decided to assign a "high risk group" to all the functions having 3 as severity degree for at least one of consequence types. It was done in order to ensure that high critical functions will be always prioritized over medium and low ones during the ranking process.

Table 3: Criticality Matrix

Probability \ Consequences*	1	2	3
Low	**LR**	**LR**	**HR**
Medium	**LR**	**MR**	**HR**
High	**MR**	**MR**	**HR**

*consequences imply maximum value among three types of consequences (safety, production, oil spill)

After the rough ranking the single relative criticality value can be calculated using the following formula:

$$CV = R_{co} * \frac{1}{6} + R_{ca} * \frac{1}{2}$$

where, R_{co} is a risk related to consequences

Ra is a redundancy number

$\frac{1}{6}$, $\frac{1}{2}$ is weight given to R_{co} and Ra based on its maximum values and on assumption that CV corresponds to 100%

The formula shown above is inspired by the relative risk number presented by Smith and Mobley in their book named "Rules of thumb for maintenance and reliability engineers" and described in chapter 2.4.4.2 of the thesis. Values "1/6" and "1/2" are introduced in order to balance the contribution between R_{co} and Ra to the final relative criticality value. The weights are decided based on maximum values of risk related to consequences and redundancy number:

$$maxR_{co} = T_{co} * P_f = 3 * 1$$

$$maxRa = \frac{1}{Ca} * P_f = \frac{1}{1}$$

where, P_f is a probability of failure that has a maximum value equal to 1 (100%)

T_{co} is total consequences that has a maximum value equal to 3

Ca is a capacity that has a minimum value equal to 1 (100%)

In order to balance contribution between R_{co} and Ra, the author suggests to set them equal to each other and define a maximum value of the total risk (CV) as 1 (100%):

$$CV = R_{co} * X + R_{ca} * Y = 3 * X + 1 * Y = 1$$

$$3 * X = 1 * Y;\ X = \frac{1}{3}Y$$

$$3 * \frac{1}{3}Y + 1 * Y = 2 * Y = 1;\ Y = \frac{1}{2}; X = \frac{1}{6}$$

Where X and Y are the weights assigned to R_{co} and Ra and are aimed to balance their contribution to the final risk result (CV).

The risk related to consequences (R_{co}) is suggested to be calculated as a general risk approach, which is equal to consequences multiplied by probability of failure:

$$R_{co} = T_{co} * P_f$$

where, T_{co} is total consequences
P_f is a probability of failure : low (0.15), medium (0.55), high (0.9)

Probability of failure is not given as a numerical value in the available criticality evaluation, where probability is only called as high, medium and low. In order to simplify calculations the author decided to assign relative values to the probability without reflecting a failure frequency but only ranking three possible probabilities among within one particular case.

The total consequences may be calculated by following way:

$$T_{co} = S * w_s + P * w_p + O * w_o$$

where S corresponds to consequences related to safety
P corresponds to consequences related to production
O corresponds to consequences related to oil spill
w_s, w_p, w_o correspond to weight given to S, P and O based on the company strategy

The weights presented in the formula given above may vary according to changes in the organization strategy and its priorities. It is done in order to introduce flexibility in prioritizing on particular type of consequences. In some companies, for example, the attention is given to consequences related to health and safety. It can result into increase of parameter "w_s". The important thing to remember here is that the sum of weights should be always equal to 100% due to their probabilistic nature. After several conversations with the experts from COSL, the author decided to have equal weights (1/3) for all of the consequence types.

The redundancy number is aimed to demonstrate a risk associated with the limited capacity of function performance. The higher is the number, lower is the redundancy. The formula makes it possible to reduce the redundancy number due to increase in capacity of function performance and decrease in failure probability.

Redundancy number:

$$R_{ca} = \frac{1}{Ca} * P_f$$

where, Ca is a capacity

P_f is a probability of failure: low (0.15), medium (0.55), high (0.9)

The capacity here implies a total value which is calculated by adding single capacities of all units performing the same function. If, for example, there are three units with single capacities equal to 50% the capacity used in the formula will make 150%.

After calculation of the final criticality value we rank the sub-functions within the risk group (shown by the color) from the most critical (1) to less critical as shown in table 4. The sub-function that has a priority one in the "high risk group" is the first candidate for the further process. After all the sub-functions from the "red group" are processed, "medium risk group" (yellow color) is the next to be processed.

Table 4 Example on Final Criticality Ranking

Ranking in each risk group
4
3
7
2
1
4
6
5
2
6
3
4
1
2
2
1

In order to check the reliability of method for criticality ranking, the author asked four experts from the COSL Drilling Europe to manually evaluate a set of equipment related to subsea systems (see Appendix C). They were asked to assign a ranking value between 1 (min. critical) and 10 (max. critical) for each function presented in a specific table. Experts were suggested to base the assessment on information given in the table and/or their own perception of criticality for each particular function. In order to compare the results achieved by people and computer, the author decided to perform a statistical test called a least-squares test. This test indicates the linear correlation of the data (Pintelon & Puyvelde 2006a). The following formula was used:

$$r = \frac{S_{xy}}{S_x * S_y}$$

where, r is a correlation coefficient

S_{xy} is a covariance and S_x, S_y the variances

$$S_{xy} = \frac{1}{n} * \sum_{i=1}^{n} (x_i - \bar{x}) * (y_i - \bar{y})$$

$$S_x = \frac{1}{n} * \sum_{i=1}^{n} (x_i - \bar{x})^2$$

where, n is the number of functions evaluated

x_i is the criticality value for function i

$\bar{x}$ is the expectation of criticality value

Covariance (S_{xy}) is a measure to show how two variables change together (Pintelon & Puyvelde 2006a). The correlation coefficient together with covariance shows the reliability of results obtained by the computer. The calculations results showed that $r = 0.5$, $S_{xy} = 0.6$ that indicates a positive relationship between manual and automatic evaluation of criticality value.

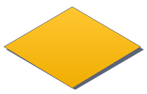
The test result of criticality ranking methodology demonstrated the sub-functions with assigned equipment to be assessed further for condition monitoring possibilities. Sub-functions with the highest ranking are as follows:

- Telescopic joint 50 Ft. Stroke
- Tensioner ring assembly
- Heave compensating drawworks
- Storing/High pressure unit
- Top drive
- HP Mud pumping

4.2.3 Reliability Assessment

The next step of the assessment deals with reliability. The function that has the highest rank according to the previous step is to be assessed further by utilizing main reliability tools. The main goal of this step is to prepare necessary information (e.g. most critical failure mode, parameters to be monitored, degradation mechanisms) to select the CM technique for the equipment units performing the particular function. In order to do that, the author decided to prepare the reliability assessment framework consisting of blocks connected to each other and contributing to the final result (see figure 25). Blocks used in the framework below are described in ISO 5807:1985 (ISO 5807 1985) and presented in table 5.

Table 5: Main Elements of Flowchart

	It is a unit for performing one or several operations to process the data.		This unit converts input data into a suitable form for further processing.
	In our case it represents the solution and result of the whole process.		This block represents the databases applied
	It is a block that is in charge for sub-process contributing to the main one.		
	This element represents the beginning of the whole logic.		

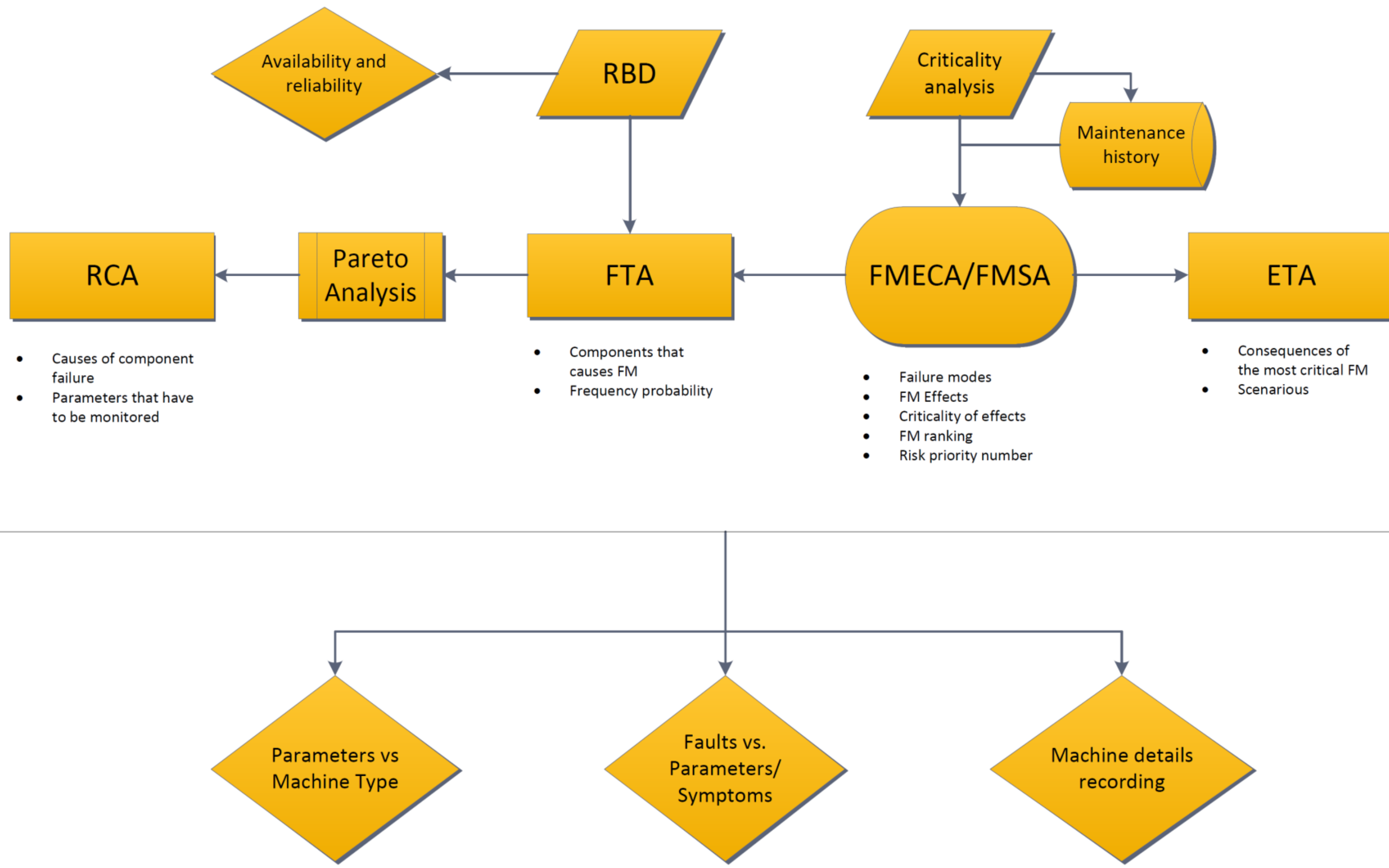


Figure 25: Reliability Assessment Framework

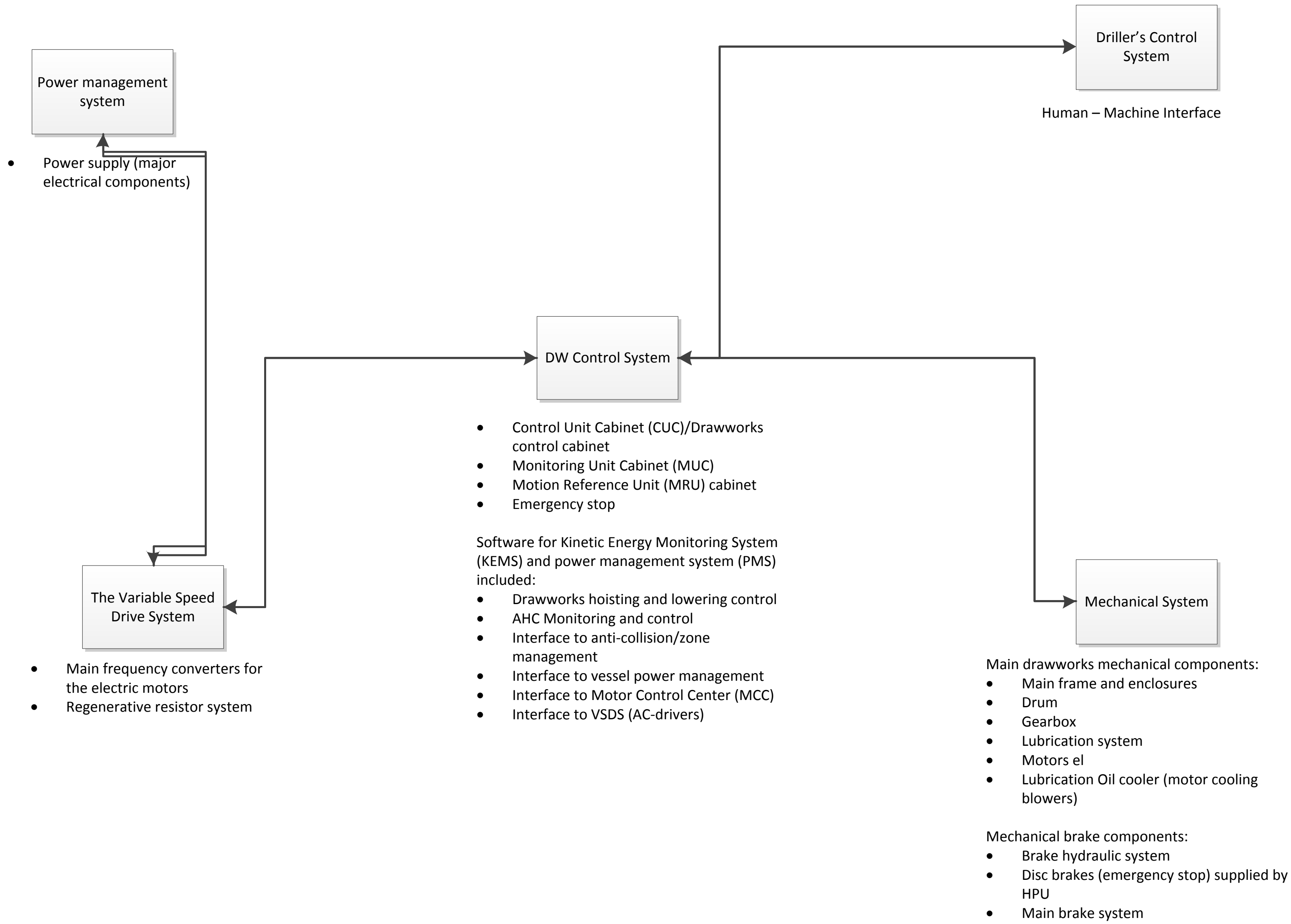


Figure 26: Simple Block Diagram for AHC Drawworks

The logic presented in Figure 25 is based on several reference sources, but the main contribution came from the lecture notes in condition monitoring by Tore Markeset, professor of Faculty of Science and Technology at the University of Stavanger (Markeset 2011). There is one essential task mentioned in the theoretical part chapter 2.4.3 that should be done before turning to the framework shown in Figure 25. The function performed by equipment unit must be carefully studied and presented, for example, by a simple block diagram. It may include interaction between main systems and their components.

The author made the block diagram based on the article from the proceedings of Offshore Technology Conference 2003 (Abouamin et al. 2003) and consultancy with rig manager on COSL Innovator and maintenance supervisor specialized in electrical equipment. The main components of the diagram are: equipment systems aiding in performing function; equipment units belonging to each of the systems; interrelations between all the blocks. The final version of the diagram that was used as a starting point and background knowledge during the reliability assessment is presented in Figure 26.

4.2.3.1 Failure Mode and Symptom Analysis

The starting point of logic in Figure 26 is the FMECA/FMSA. These two reliability assessment tools are described in chapter 2.4.4.3 of the thesis. The author chooses the FMSA due to applicability of this technique to CM. The main outcome of this part of analysis is the failure mode's prioritizing according to its importance to monitor for the further assessment. It is done by using the ranking criteria called monitoring priority number (MPN). The FMSA sheet was modified with focus on the establishment of MPN for each equipment unit failure. "Causes" and "effects" where removed by the author from the table recommended by the ISO 13379: 2002 (ISO 13379 2002). It was done due to the fact that these two important fields of analysis will be assessed further by utilizing other reliability assessment tools. The author includes the following information in the modified FMSA sheet as shown in table 6.

Table 6: FMSA Sheet

Function	Code	Sub-Functions	Failure modes	Symptoms	Failure mechanisms (ISO 14224)	Failure modes (ISO 14224)	DET	SEV	DGN	PGN	MPN

The "function" represents what the equipment is actually used for in order to ensure the whole process is taking place. The code makes it simpler to identify the type of function (e.g. main, sub-function alarm, sub-function) and what system it refers to. In the sub-functions field the brief description of what it relates to is given (e.g. regulating, safety critical equipment and lubrication oil pumps with redundancy). In failure modes the author recommends to write the failure of equipment units performing the function (e.g. motor blower skid failure and drum failure). By using this approach, the result of the analysis will provide MPN for the failure of the particular equipment unit.

In the symptoms' part all necessary perceptions based on human observations and measurements indicating a fault are presented (ISO 13379 2002). These symptoms don't have to be standardized but could be taken from technical documentation supplied with the equipment by vendor (e.g. blower fan works at one high speed). The goal of this part is to collect vendor information for the specific equipment unit and use it further for determining MPN. Failure mechanisms column includes the standardized terms according to ISO 14224:2006 annex B (ISO 14224 2006). Failure mechanisms are defined as the process (e.g. physical and chemical) that results into failure (ISO 14224 2006). Terms “symptom” and “failure mechanism” can be quite close to each other. Based on the information described in chapter 2.4.4.3 the author concludes that failure mechanism is the part of the symptom or can be a symptom itself. Standard failure modes can be found in the ISO 14224:2006 annex B as well.

It is important to remember that methods and tools presented in the standards should be considered as a recommendation and could be changed and modified for each specific case. Both standard failure modes and mechanisms were discussed with experts from the COSL and changed/modified according to the features and specifications of the particular equipment. Probability of detection rate (DET), severity of failure rating (SEV), diagnosis confidence rate (DGN) and prognosis confidence rate (PGN) are well described in chapter 2.4.4.3. All the rate types’ provided above are multiplied thus making the final monitoring priority number. The author determines the value of these four rate types based on discussions with people of different specific backgrounds according to recommendations given in the proceedings of offshore technology conference (Abouamin et al. 2003).

Three COSL employees were invited to participate in this part of assessment: a maintenance supervisor, a maintenance engineer and a rig manager. The maintenance supervisor contributed to the process with providing maintenance history of the particular equipment. The maintenance engineer made assessment based on knowledge of components structure and vulnerability. Rig Managers participation was necessary to evaluate the severity of the failure and diagnosis possibility. The important contribution came from the history of maintenance actions available in COSL’s CMMS STAR IPS and OREDA database. The most frequent failures where assessed and studied for the possible causes. As the FMSA result the priority of equipment to be monitored within the AHC Drawworks system was established. The first four places where assigned to:

- Drum failure
- Gearbox failure
- Electrical motors failure
- Motor blower skid failure

The author decided to choose electrical motor for the further assessment. There are three main reasons to that: lots of available information; already mounted instrumentation; several systems among other equipment groups that have el. motor as sub-equipment. It actually demonstrates that after carrying out the FMSA version presented above, the assessment of results is needed to choose the first failure mode to start with.

4.2.3.2 Fault Tree Analysis

The next step of the sequence could be both event tree analysis (ETA) and fault tree analysis (FTA). The decision to proceed with FTA was based on the degree of contribution to the final result from this assessment tool. It leads us closer to the set of parameters to be monitored. FTA was built by using the Boolean logical symbols presented in chapter 2.4.4.4 of the current thesis.

The first step in the building up of the fault tree was creating overview of all maintainable items as part of the el. motor. This information was taken from the NS-EN ISO 14224: 2006 (ISO 14224 2006). This standard describes the main subunits and interaction between them as shown in Figure 27. It is important to distinguish between equipment unit (electric motors) and subunits (electric motor). The main difference here is that subunits are assembly of items that delivers a particular function in order to let the equipment unit within the main boundary achieve the required performance (ISO 14224 2006).

For example, the subunit of electric motors (equipment unit) called electric motor includes the following maintainable items: stator, rotor, excitation and etc. The maintainable items should be assessed according to their contribution to the top event (failure mode). In order to do that the author decided to use the Birnbaums importance measure, which is described in chapter 2.4.4.1 where the highest value will correspond to the most important subunit among electric motor, control & monitoring, lubrication system, cooling system and miscellaneous.

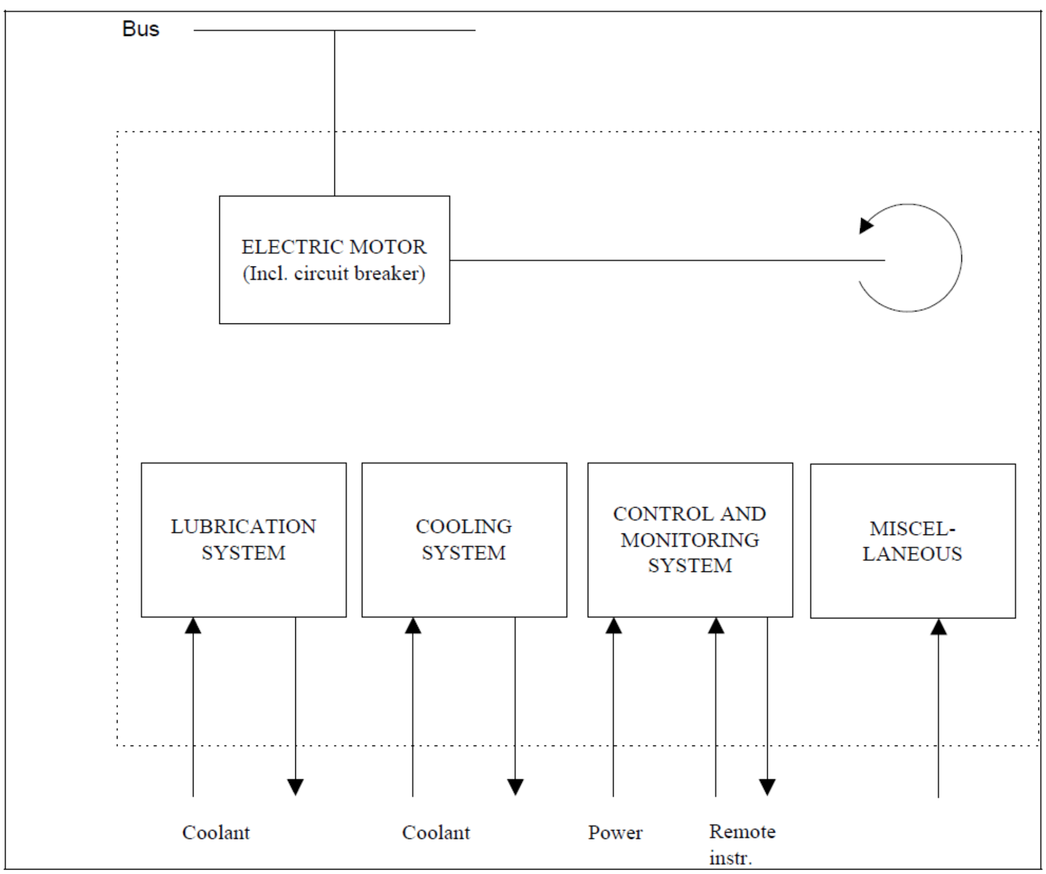


Figure 27: Boundary Definition - Electric Motors (ISO 14224 2006)

The table used for calculating the Birnbaums importance measure is shown in Appendix D. The general methodology to decide which subunit has to be assessed further can be described by the following steps:

1. Find the unavailability of the subunits for revealed failures by applying the following formula (Andrews & Moss 2002):

$$Q(H) = \frac{MTTR}{MTTR + MTBF}$$

where, MTTR is corrective maintenance repair time (average) in hours
MTBF is mean time between failures operating time in years
MTTR, MTBF values can be picked up from the reliability database like OREDA

2. Another formula could be used for this purpose but only in case of short time period (Andrews & Moss 2002):

$$Q(H) = \frac{MTTR}{MTTR + MTBF} * (1 - e^{-(MTTR+MTTF)t})$$

3. The equation describing Birnbaum's importance measure is presented in chapter 2.4.4.1. This formula was modified to the following (Andrews & Moss 2002):

$$G_i(q) = Q(1_i, q) - Q(0_i, q)$$

where, $G_i(q)$ is the criticality function for the component i
$Q(1_i, q)$ is the probability of the system failure given that the subunit i is in failure condition
$Q(0_i, q)$ is the probability of the system failure given that the subunit i is in working condition

The author sticks to the following approach:

$$G_a(q) = Q(1_a, q) - Q(0_a, q) = 1 - 0 - \big(1 - (1 - q_b)(1 - q_c)(1 - q_d)(1 - q_e)\big)$$
$$= (1 - q_b)(1 - q_c)(1 - q_d)(1 - q_e)$$

where, $Q(1_a, q)$ is equal to (1-0) due to the assumption that the failure in a single subunit leads to the failure mode of the equipment unit (serious structure)

4. The result of applying the approach presented above should be subtracted from 1. This measure is necessary to perform due to the difficulty of assessing the maximum importance measure when most of the values are equal to something like 0.999543.
5. The smallest value after performing the inversion at the previous stage will indicate the most critical subunit for the specific equipment unit

For testing of the methodology presented above, values for MTTR and MTBF were picked up from OREDA. Based on the authors expectations the calculation results showed that the electric motor (subunit) is the most critical for electric motors (equipment unit) failure. It is recommended to apply Birnbaum's importance measure for maintainable items as well (items included in subunit), but due to lack of reliability data and the limited time, the author decided to skip it.

After choosing the subunit for FTA, the fault tree should be built up. The process of fault tree development should be based on the technical drawings and reliability data received from vendor. The author used several sources for this purpose. During this process simple block diagram presented in Figure 26 and Drawworks technical documentation were used. In addition, the significant contribution was given from the maintenance supervisor for electrical equipment in COSL.

Some standard with description of typical equipment failures and causes like ISO 14224:2006 or ISO 17359:2011 where applied in order to achieve the final fault tree for further analysis (see Figure 28). In order to simplify the process the author assumed the series structure that implies that the failure of one component leads to the top failure event. This assumption is not critical due to the application area of the current fault tree. The main purpose for this particular case is to show the relationship between the maintainable items, its components and the main subunit failure (electric motor). In case of having the sufficient amount of time this analysis should be carried out by using additional reliability data for the subunit (e.g. reliability block diagram and frequencies of failure). Then FTA can present the precise component that has the highest criticality in comparison with others. It means that the ranking of maintainable units referring to subunit will be possible.

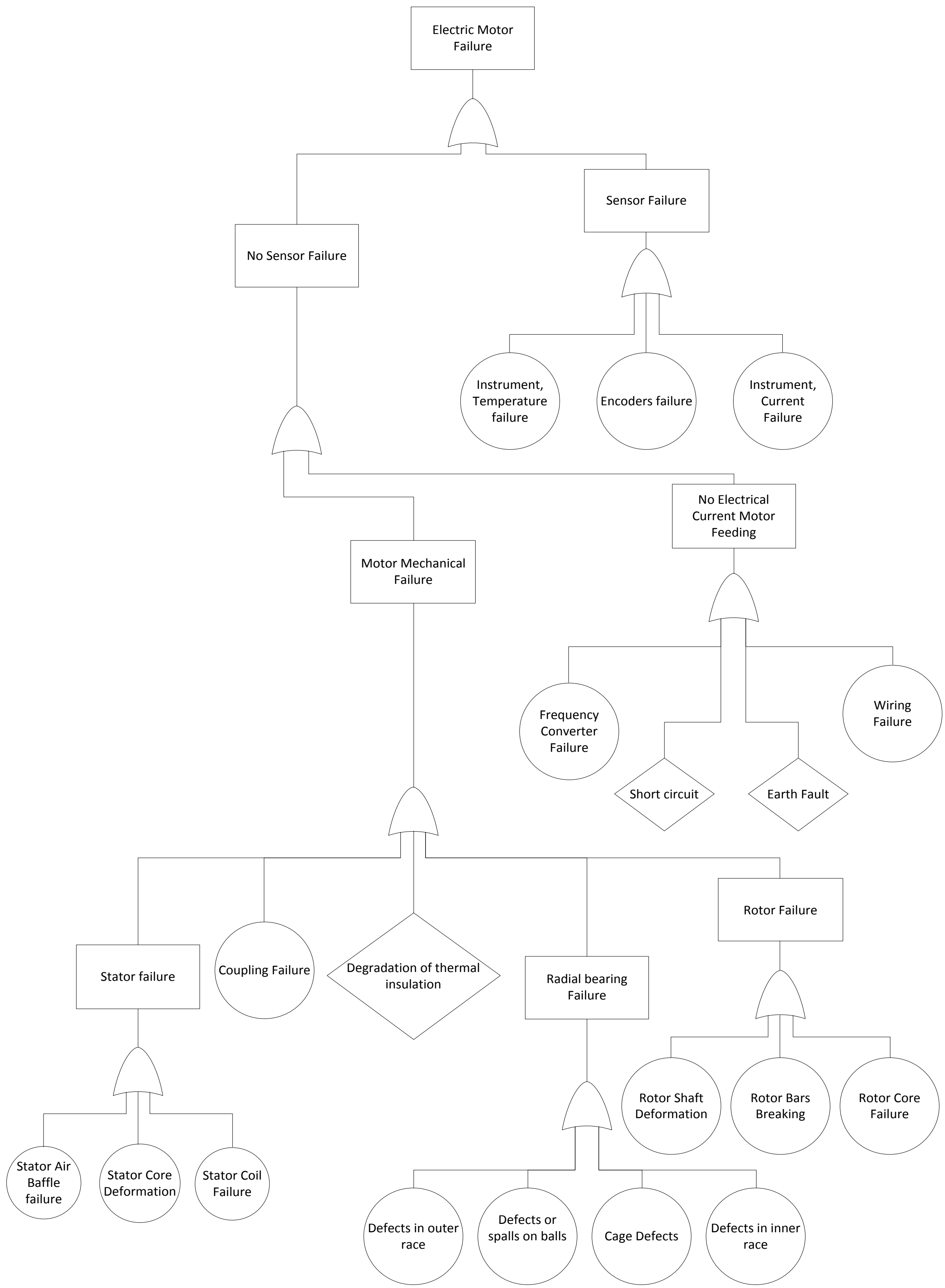


Figure 28: Fault Tree for Electric Motor (subunit)

After the final ranking of the maintainable units according to their criticality, the priority for the further assessment (e.g. root cause analysis) can be decided. The author chooses to assess all the maintainable items simultaneously. It can be possible only if of the subunit (e.g. electric motor) consists of few components. By doing this the Pareto analysis described in chapter 2.4.4.7 of the current thesis is not needed. It's only applicable for maintainable items that are ranked.

4.2.3.3 Root-cause Analysis

The next step is called root-cause analysis (RCA). As stated in chapter 2.4.4.6, RCA is not a precisely specified methodology, but its goal is to find the correct root-cause of failure. The primary idea of this methodology is to analyze the failure of each component of maintainable item (e.g. radial bearing cage defect and rotor bars breaking) and find a root-cause for the failure.

Due to the time limitation the author decided to carry out this process by finding the root-cause for all failures of a single maintainable item simultaneously (e.g. radial bearing failure and rotor failure). In order to present the result of RCA it is recommended to make a table consisting of maintainable items or components of items that might fail, failure modes and possible root causes. Table 7 was made with the help of OREDA database, OREDA handbook (SINTEF Technology 2009) and technical documentation provided by COSL.

Table 7: Example of Root-Cause Analysis Sheet

Components	**Noise**	**Overheating**	**Other**	**Minor in-service problem**	**Structural deficiency**
Radial Bearing	0.78		0.78		
Thrust bearing					
Stator		0.78			0.78
Excitation					
Wiring				0.78	0.78
Rotor					
Caupling					
	Mechanical failure	**Electrical failure**	**Mechanical failure**	**Control Failure**	**Electrical failure**
		Instrument failure	**Wear**	**Electrical Failure**	**Short circuiting**
				Instrument failure	

The table presented above consists of four main parts. The first column presents different maintainable items of the subunit (electric motor). The head-row shows various failure modes of the components and the bottom-rows represent root-causes. "Root-cause" term according to the definition presented in chapter 2.4.4.6 stays close to failure mechanism. Both of these terms are acceptable for using in a particular case, for example, OREDA handbook 2009 applies the term failure mechanism instead.

The connection between root-causes and maintainable items can be shown by different colors. The logic of using the RCA sheet can be the following: "If the rotor is overheated, the electrical failure can be a possible root cause to that". The discussion about how deep RCA should be carried out is provided in the next part of the thesis. The complete table as a result of root-cause analysis is presented in attachment.

4.2.3.4 Event Tree Analysis

The event tree analysis (ETA) was the last tool evaluated by the author as a part of reliability assessment framework. The event tree analysis logic is well defined and can be carried out using the recommendations given in chapter 2.4.4.5. The necessary data for performing this type of analysis can be obtained from the barrier evaluation (if available), technical documentation (e.g. shutdown sequence) and through the discussion with the equipment experts. ETA within the applied CBM development methodology can be used for several purposes. The first one is the possibility to find the interdependences between failures and parameters to monitor the same or different maintainable items.

For example, in case of all four electrical motors' failure, lifting operation & heave compensation will not be possible and calipers (mechanical brakes) will be activated. If calipers cannot perform their function, the handbrake may be used and etc. It shows how the severity of scenarios depends on relation degree between items. Secondly, ETA contributes significantly to diagnosis and prognosis by providing the foundation for different current failure modes and initiating criteria for the future one. Through utilizing both FTA and ETA together, the common-cause failures can be easily identified and used in the diagnosis process.

One of the biggest contributions from ETA to be used in Risk and Reliability Assessment is the failure scenarios and its probabilities, by which all the failures will be evaluated together based on a specific model. The testing of event tree analysis was not completely performed by the author due to the time limitation. The evaluation is given, based on interviewing maintenance personnel at COSL, in the next part of the thesis.

4.2.3.5 Results

The main result of the reliability assessment framework can be presented by three documents. The first one is intended to show all the equipment unit failures (in our case failure modes) by CM parameters. The example of presenting this information is given in ISO 17359:2011 and shown in Figure 29.

Parameter	Machine type								
	Electric motor	Steam turbine	Aero gas turbine	Industrial gas turbine	Pump	Com-pressor	Electric generator	Reciprocating internal combustion engine	Fan
Temperature	•	•	•	•	•	•	•	•	•
Pressure		•	•	•	•	•		•	•
Pressure (head)					•				
Pressure ratio			•	•		•			
Pressure (vacuum)		•			•				
Air flow			•	•		•		•	•
Fuel flow			•	•				•	
Fluid flow		•			•	•			
Current	•						•		
Voltage	•						•		

Figure 29: CM Parameters vs. Machine Type (ISO 17359 2011)

The difference here is that the author recommends putting equipment unit instead of machine type, since the results of the assessment refer to the one function and its failure modes (failures of equipment unit). The current thesis evaluates only a single failure mode with the highest MPN (monitoring priority number). This decision was based on limitation of data, time and specific goals of the project.

Though creation of the table presented above contributes significantly to choosing the correct CM techniques for the main function chosen for reliability assessment. The second part of the final result is another table aimed to show the maintainable items failure against CM parameters. This part is intended to present type of failure to be detected by different methods. The table 8 was created by using the outcomes both from RCA and ETA.

As it follows from the table the biggest contribution in diagnosing of equipment failure (functions failure mode) comes from monitoring temperature, vibration and current. In order to choose a final set of parameters to be monitored, instrumentation that is already installed should be assessed.

Table 8: Faults vs. CM Parameters

Faults:	Current	Voltage	Resistance	Partial discharge	Power	Torque	Speed	Vibration	Temperature	Axial flux	Oil Debris
Rotor Windings	■				■	■	■	■	■	■	
Stator windings	■							■	■	■	
Eccentric rotor	■							■		■	
Bearing Failure	■					■		■	■		■
Insulation deterioration	■	■	■	■							
Loss of input power phase	■	■						■		■	
Unbalance								■			
Misalignment/clearence failure								■	■		
Circuit Breaker Failure			■								

In our case temperature sensors both for winding & bearing, amperemeter and encoders (measure speed) are installed. Based on this information and discussion with the maintenance engineer from COSL the final list of parameters to be monitored is the following:

- Temperature on motor windings and bearing
- Vibration on bearings (both driving end and non-driving end)
- Current to be measured through the frequency converter
- Speed (e.g. can indicate that the speed of motor is uneven)

The third important document that should be prepared before proceeding further with CBM program development is the recording of typical information for equipment units chosen to be monitored. This document may include at least three parts: equipment unit details (e.g. type, speed range and rated speed); measurements (e.g. instrument type, location and value); other type of information like historical maintenance data. The example of form created for recording this type of information is shown in Appendix F.

4.2.4 Selecting Condition Monitoring Technique

After selecting a necessary set of parameters to be monitor, the monitoring techniques should be selected. The first step in this process is to assess information of already installed instrumentation on the equipment subunit. In our case temperature sensors, speed encoders and current measures are already there. The only technique necessary to be implemented is a vibration measurement. In chapter 2.4.5.1 of the thesis several measurement techniques are well described. The main task for vibration measurement is to define measurement points and frequency of monitoring.

During the visit to Karsten Moholdt AS (the CM department) different monitoring approaches (e.g. online, periodical and conditional) were reviewed and evaluated. The choice should be based on deterioration mechanism and criticality of the equipment unit. In case of el.

motor subunit the author chooses the continuous monitoring due to the high criticality of equipment and possibility of the secondary damage. Accelerometer is chosen as the appropriate sensor to identify the vibration due to its frequency range (1 to 20000HZ), low cost and longtime stability (Markeset 2011). The measurement points are chosen according to the el. motors bearing location. There is no need for many points in order to be able to detect the problem, but several measurement points should be used to find a root-cause for trouble shooting.

Together with employees from Karsten Moholt the main points for vibration analysis were established for the whole Drawworks system (see Figure 30). Eight accelerometers (two for each motor) are recommended for el. motors. All other parameters (speed, temperature and current) are decided to be monitored continuously as well, due to relative simplicity of values comparison and failure modes identification.

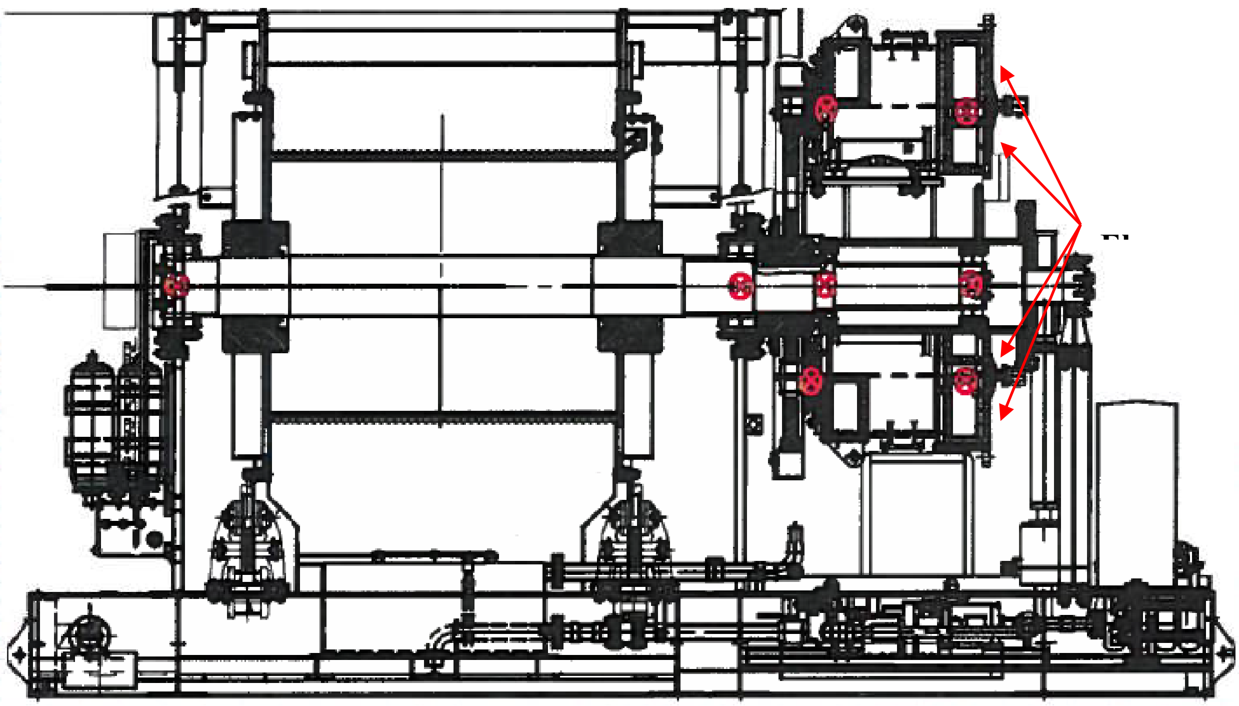


Figure 30: Measurement Point for Vibration Monitoring (Karsten Moholt 2011)

4.2.5 Baselines and Alarms

The general theoretical overview of baselines and alarms is given in chapter 2.4.6 of the thesis. The author's contribution to this part is the concept, which is aimed to present the diagnosis & prognosis information and help in decision making. The presentation of the concept is based on two international standards (IS0 13379 and ISO 13381) and discussion with the employees from SINTEF and E-Maintenance at the SPE annual conference in Bergen. The first part of the concept is the presentation of all monitoring parameters dynamics together in one graph (see Figure 31).

The x-axis reflects the time during which measurements were made. The y-axis represents the relative deviation of parameters in percent instead of life-usage as it is recommended in ISO 13381. By the relative deviation of parameters the author implies changes of measurements with respect to baseline. If the parameter changes deviate at certain degree from the baseline the y-axis in the graph will reflect it. The easiest way to show how it works is to give an example. It is given that the temperature of the bearing is increased on 110 degrees from the normal temperature (baseline). Under the temperature deviation from the baseline at 250 degrees, this type of bearing fails. It is important to remember that 110 and 250 degrees are relative values in relation to the normal temperature (baseline). The formula to calculate the percent deviation will be the following:

$$P_d = \frac{D_c * 100\%}{D_f} = \frac{110\ ℃ * 100\%}{250\ ℃} = 44\%$$

Where, P_d is a precent deviation

D_c is a current deviation of parameter

D_f is a deviation at wich maintanable item will fail

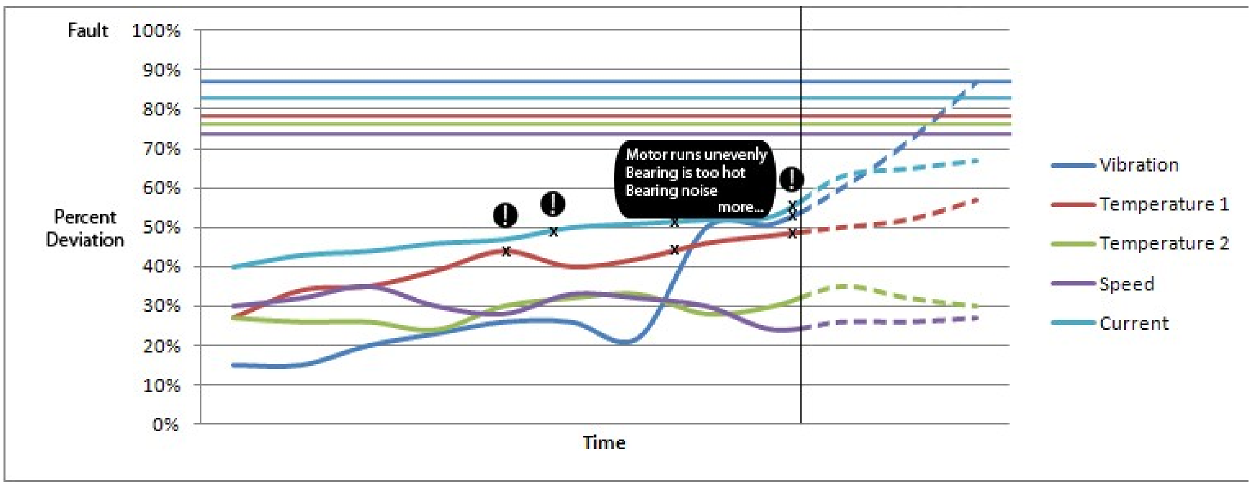


Figure 31: Example of Monitoring Information Presentation

It is important to remember that deviation can go both directions to provide a more complete picture for assessment. Once the deviation reaches a specific alarm limit, for example 44% relative deviation for the temperature in bearing, the alarm indicates a problem. If the deviation of monitoring parameter reaches the trip level (color horizontal line), machine will shut down. Failure mode can be initiated by several parameters, visually described by symptoms and possible causes with remedies. For example, if the bearing is too hot (temperature 1) and machine runs unevenly (speed), the possible cause of failure mode is that coupling forces are pulling or pushing.

The author decided to present possible alarms to operator visually by exclamation mark (!) as it is shown in Figure 31. It allows making easy notification of what parameter deviation is the reason for alarm. The operator can get the description of what symptoms are taking place by clicking on one of the "!" signs as it shown in figure 31. In order to find a possible cause and remedy the operator can click on the word "more", and the following table describing failure mode causes and remedy will appear:

Table 9: Example of Presentation Symptoms vs. Cause & Remedy

Fault			Possible causes	Remedy
Bearing is too hot	Bearing noise	Motor runs unevenly		
			Motor is mounted incorrectly	Check mounting type of motor

The Table 9 should be made according to the equipment documentation and it is often a case that the table is already prepared. The concept of presenting the monitoring parameters should be also able to predict the behavior of parameters and estimate ETTF based on mothematical models. This estimation is important due to assessment of time neede to get prepared for maintenance and plan spare parts logistics. The prognosis process may aid in ranking and priorotizing of maintainable items to be repared first. The operator should get information about the confidence level of extrapolation as well. For example the confidence interval could be used to show how often ETTF appears between two time periods. If P(130 <ETTF<250)=95% , in 95% of cases, given that the experiment will be repeated infinitely, ETTF will make between 130 and 250 minutes. It provides the degree of uncertainty that can also be used in decision-making. If the ETTF was estimated wrong and the failure appeared before, the model could be updated automatically and provide better prediction next time. The other examples of parameters presentation could be found in Appendix G.

4.2.6 CM System Design

Basics steps of condition monitoring system design are described in chapter 2.4.5.2 of the thesis. The author based the design for AHC Drawworks on recommendations from that chapter and employees of Karsten Moholodt. The first issue that can be a case and reason for choosing a particular CM system is the necessity of EXD (flameproof enclosure) certification. EXD implies that the external case of flameproof equipment is made to resist an internal explosion. The new instrumentation mounted on such type of equipment (e.g. top-drive) should be certified. If the measurement point is inaccessible for the personnel due to equipment features, the access should be extended to the safe and available place.

New technologies provide an opportunity to use the wireless receivers for getting measurement information from several machines. The technology is quiet new and expensive and it is justified only in case of several systems located closely to each other. Some vendors (e.g. NOV) provide to the companies the certified CM system together with the equipment and they are also responsible for the condition monitoring during the exact period of time. Resulting from the discussions with Karsten Moholdt AS employees the CM system design for vibration analysis was proposed (see Figure 32).

The process starting from multiplexer receiving all the signals from eight accelerometers mounted on the el. motors. Multiplexer is a device that has multiple signal inputs and one output. It can transmit the signal from one of the inputs to the output. In our case multiplexer receives data from eight vibration transducers. The output signal is transmitted further through the cable to Signalmaster. The Signalmaster system allows performing measurements, calculations, storing data and producing reports in case of emergency situations. It can be used to monitor both individual units and the whole system. The information recived from Signalmaster should be extracted from vibration signals and properly processed. It can be done by utilizing special software; Karsten Moholdt recommends to use the OMNITREND from PRÜFTECHNIK both for administration and monitoring purposes. The remote access is also possible through the Lan network or the Internet. The online monitoring department in Karsten Moholdt receives the processed information and in case of abnormal condition initiates the root cause analysis. The analysis is intended to give recommendations for failure remedy.

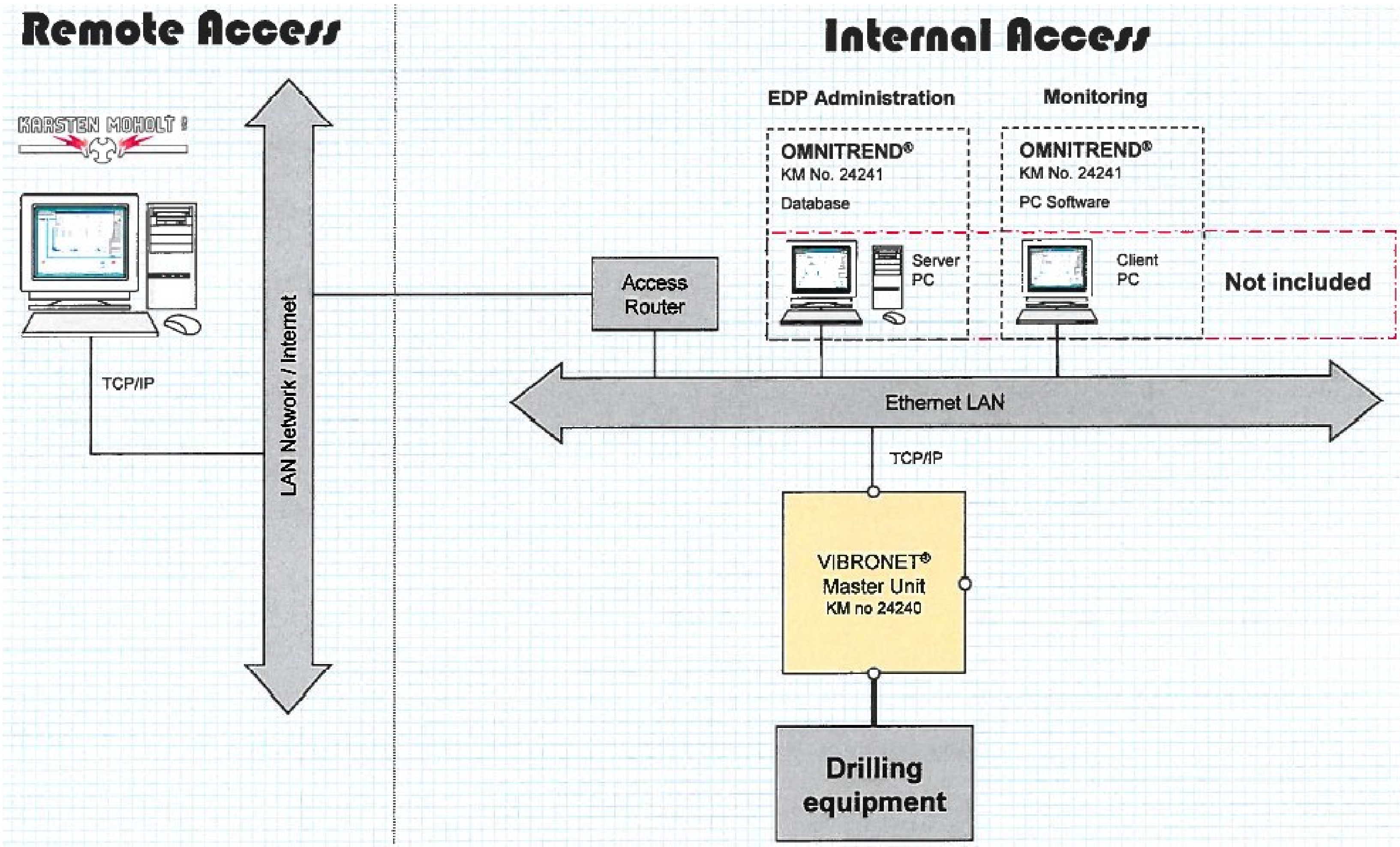


Figure 32: CM System Design for AHC Drawworks

4.2.7 Untested Parts of CBM Development Methodology

Some parts of methodology were not tested by the real case due to the lack of time and data. As the main focus of the thesis is CM, the author prioritized parts of methodology described above. After the CM system design is developed, four important blocks of methodology are needed in order to elaborate the condition-based maintenance program.

The first block is stock-control. It implies the spare-parts logistic planning and deciding on what parts are supposed to be "on board". The company should specify the particular factors to be considered in order to decide what spare parts that shall be in stock at the plant. COSL Drilling Europe AS proposes the following factors: spare-part criticality, probability of failure, time to repair, shelf life, disassembly time, anticipated usage, terms of insurance, time to repair, lead time and number of equipment items that use the spare. The ETTF described above is the input information on how the delivery of necessary part will be organized. In case of offshore installation the ETTF should be long enough for delivering the spare part without stopping the machine. The author recommends utilizing, if possible, machines consisting of blocks. In this case the block in failure mode can be removed and replaced by another one located "on board". The broken block will be repaired as soon as possible, while the machine is running with the spare ones.

The cost-benefit analysis methodology is well described in chapter 2.4.2 of the current thesis. The reason the author introduces the analysis in this part of methodology instead of the beginning is that the all costs and work used for the development of CBM program are specified at this stage. The effect from CBM program implementation on earning power of organization can be precisely calculated now by utilizing the approach presented in chapter 2.4.2. It appears to be one of the last components needed before the complete CBM program is finalized.

Another essential part before CBM program can be finally made is the responding procedures in case of possible condition deviations. The author recommends creating clear guidelines and procedures on how the personnel at the plant should react to the information coming from the internal system and follow the recommendations of the organization delivering CM services. In case of a failure mode initiation the plant personnel should be able to report the deviation and perform the possible actions to prevent the shutdown of the machine. The author considers that it is important for the employees to have a basic understanding of CM process and to be able to, for example, clearly and adequatly describe the current situation to the CM service provider and follow the provided instructions. The Karsten Moholdt AS recommends having at least 3 people with certification in condition monitoring. In this case the CM philosophy will be easier implemented in the company through people that actually see the benefits of condition monitoring.

Opportunity-based maintenance is well described in chapter 2.2.2 of the current thesis. The necessity of including it in CBM development methodology is conditioned by utilizing the monitoring information for ranking the machines to be maintained under the unplanned stop. The author recommends using the software like PROMPT that is aimed to optimize maintenance activities and perform them in case of opportunities. Such software may receive the information on machines condition through the internal network after processing and may support the decision-making process for choosing the equipment to be maintained at the unplanned shutdown.

After all four blocks of the previous methodology step are carried out and associated analyses are performed, the condition-based maintenance program can be established. CBM program includes all findings from the previous parts of the methodology. The main components of the program are condition monitoring of the machines, response on deviations and continuous searching process for root causes in order to avoid failure modes are. The following list of what the final CBM should consist of is proposed:

- Methods and techniques
- Stock control regulation
- Routines and response procedures
- Necessary resources
- Documentation e.g. justifying the choice of CM technique and system

One of the main reasons of not receiving all the benefits by the company utilizing CBM is the insufficient focus on implementation. Everybody in the company should ideally have the basic understanding of how the CBM is set up and what benefits it can bring. The discussion with Karsten Moholt AS showed that some of the companies treat CBM as a modern trend and neglect the core feature of it - finding the root-cause and improving the reliability. Condition monitoring is itself only a tool and it doesn't improve reliability alone as CBM does. In some cases data collected through CM, when it is performed offline, is not even sent further to the service company. Sometimes the recommendations from the organization performing condition monitoring are not assessed or implemented at all. CBM is the philosophy and it should be understood by all the personnel related to maintenance activities. The implementation can be done through the training. Several companies in Norway arrange introduction courses on condition monitoring and predictive maintenance philosophy. It will ensure the effective cooperation between the CM service provider and the company. In addition, the operator can better distinguish between false alarms and real problems by understanding the CM techniques and monitoring parameters. That will reduce unnecessary expenses associated with e.g. unplanned stop of the machine, purchasing spare parts and inviting CM specialists to offshore installations.

The last block before the methodology flowchart is looped, is called “Performance measurement & management”. By “performance measurement” the author understands measures of effectiveness provided by main key performance indicators (KPI’s) of the CBM program. It is done in order to show the clear relations between the implementation of the new concept, effectiveness and changes it brings. KPI’s should be chosen according to the goals of the CBM program and based on the strategy of the particular organization. Various KPI’s related to maintenance are well described in Annex E of the ISO 14224:2006 (ISO 14224 2006). Performance management describes the process of establishing, presenting, updating and reacting on KPIs changes. One of the tools that can be used for management of strategy, goals, KPI and targets is the Balanced Scorecard introduced by Robert Kaplan and David Norton in 1992 (Kaplan & Norton 1996). The main feature of this method is the possibility to determine goals of the CBM program based on the strategy of the organization and find a suitable KPI to measure the achievement of goals. An example of the balanced scorecard development based on ideas by Robert Kaplan and David Norton is shown in Figure 33. The author sticks to the point that it is important to remember that it is necessary to review regularly the performance measurement & management caused by changes in strategies and goals. At the same time all KPI's values should be presented as dashboard where the company can follow the feedback from implemented measures.

Figure 33: Example of Balanced Scorecard Development Process (Kaplan & Norton 1996)

The process of CBM program development can be repeated e.g. in order to assess other types of machines to be monitored or to change the assumptions made at the beginning of the flowchart. For example, in case of costs reduction of monitoring techniques for a particular system will make it possible to include this machine into CBM program. The loop structure of the methodology ensures the continuous improvement of the CBM program effectiveness that could be measured and showed by the performance management and measurement tools. The continuous benchmarking process should be carried out by the company that is willing to be aware of the latest technologies and trends in condition monitoring. This process is briefly described in chapter 2.4.2 of the thesis.

5. Discussion

In this section the author is presenting the analysis of the developed CBM methodology with its pros and cons. The feedback related to methodology application will be given according to the reflective discussions with representatives from the industry. In addition, possible improvements and new ideas related to the thesis outcome are discussed and recommended.

5.1 CBM Development Methodology Evaluation

The methodology and its parts presented above have their own advantages and disadvantages. The goal of this chapter is to go through the flowchart once again and discuss pros and cons related to variety of techniques used in methodology.

The outcome of the thesis is the methodology for condition-based maintenance development. It makes possible to come up with CBM by going through particular steps utilizing specific tools, which could be actually changed or modified according to the company's needs. The challenge here is that all the blocks of the flowchart presented in Figure 23 can't be precisely described. The fact is that some of the blocks need a detailed discussion in a team and can't be done only by predefined sequence of steps. The comprehensive analysis and understanding of assumptions used in different parts of the methodology should always take place. It actually implies that no flowchart can describe the total sequence of activities and ready-made solutions. The development process should be flexible and be adapted to specific conditions.

Another point is that the final methodology implies establishment of CBM program only, while reliability-centered maintenance is the combination of maintenance philosophies. The flowchart presented in Figure 23 is intended to choose the machines for the further assessment of CM possibilities. All other maintenance approaches are not touched upon. The holistic RCM development methodology should include all the maintenance polices applied for the relevant equipment. The RCM main goal is to study the machine in order to find e.g. all the possible failure modes, effects, causes and root-causes and apply the appropriate maintenance policy for the equipment.

The author would like to test the whole concept and come with a specific CBM program. In order to do that, the period of time allotted for project should have been significantly longer then it was suggested. In the current thesis only one path of analysis is followed (most critical function, highest priority failure mode and most important subunit). It could have been very useful to follow several analysis paths and assess various machines, failure modes, and subunits.

It would have been provided more information about the challenges related to the e.g. reliability assessment and detailed feedback on reliability and applicability of the methodology.

Important issue that the maintenance supervisor should be aware of is that the instrumentation itself can be the root-cause of failure. Condition monitoring sensors and other parts of the system like multiplexer, signalmasta and software can create a failure mode. The CBM development methodology could also include the part called: "Maintenance of CM equipment". Nowadays modern technologies allow sensors to check there own reliability and condition, but still the CM systems possessing the combination of different equipment may include the source of failure.

The steps of methodology presented in the current thesis contribute to the development process, but one should be aware of data used during this process implementation. Specialists often rely too much on the available data and assume its correctness. In order to avoid the wrong result due to incorrect background data, the uncertainty should be assessed. It implies the detailed investigation of what assumptions this particular value is based on. The uncertainty of background knowledge can be shown by different tools like "tornado chart", "spider-diagram" and etc. It can be expressed by words describing the subjective view on the assumptions made. The criticality ranking presented as a part of methodology may include uncertainty related to formulae and values used as an input data for calculations.

Another challengeable part of the methodology is the reliability of technical information, related to operations and maintenance, provided by vendor. This information may imply maintenance guidelines and recommendations, reliability data and troubleshooting. Technical data provided by the vendor are used during the whole development process and especially for reliability assessment. The guidelines related to maintenance activities can be excessive and may provide unnecessary instructions. The reason to this can be that the vendor wants to ensure the faultless performance of the delivered equipment during the warranty period. It can be useful to get in touch with equipment supplier and find the prerequisites for recommended maintenance activities. Thus the company utilizing equipment may change maintenance routines to the less costly after the warranty period is over.

All the maintenance activities should be approved according to the predefined requirements. The description of methodology presented in the thesis doesn't pay so much attention to it, although none of maintenance programs can be implemented and applied without carrying out this process. Maintenance program and history of activities should be checked on a regular basis. During this process a special attention is given to tests and condition of critical equipment. If the company, utilizing machines that are still under warranty, decides to change the maintenance program, changes should be verified by the vendor. In order to avoid significant time loss caused by verification process, continuous cooperation between the supplier and the company is needed during the maintenance program development.

Fault tree analysis is a complex process and requires a lot of data in order to be an effective reliability tool. FTA simplifications made by the author can be very useful in the particular cases when the fault tree structure is not so complex and all the maintainable units can be assessed together. Advantage of the FTA approach presented in the thesis is its application flexibility. Complexity of this reliability tool can be increased in the situations when it's necessary and enough time is available for its development. The important requirement for the successful FTA application is that all terms used in development of the fault tree structure should be discussed and verified. The complexity of the analysis may lead to several confusions caused by vaguely defined terms and elements for the structure. Another important issue, that is not mentioned and can be a case during the FTA development, is the depth of analysis. Personnel that are in charge of constructing the fault tree should agree on the lowest component level to be assessed during this analysis. In the current thesis, the author deals with 5-level structure: main function, sub-function, failure mode (equipment unit failure), subunit and maintainable item as the lowest assessment level.

The reliability assessment framework shows the importance of creating the reliability block diagram as basis for several assessment tools. The author decided not to make it due the lack information for creating the FTA. But it is RBD that is essential for the holistic understanding of the technical system and reliability calculations in complex systems. One of the advantages of applying the FTA during the establishment of CBM development methodology is the opportunity it provides to evaluate hardware faults and human errors together. It will give the necessary feedback not only on the reliability of machine but organizational and planning aspects as well.

Failure modes and symptoms analysis is done only for one critical function. The criticality analysis showed several functions that have the highest priority for further assessment. The ranking among them can happen by discussion about CM possibilities. Another challenge with FMSA presented in the following thesis is the difficulty with discovering complex failure modes (where one insignificant failure causes the initiation of more serious failures). It is hard to show the multiple failures using the standard FMSA approach.

The main question one should always answer while analyzing the root-causes of failure is how deep the assessment should be carried out. Advantage with investigation of several root-cause levels is mapping and understanding of the interactions between components and small problems that may result in a big failure. Disadvantage of it is that the significant resources are needed to perform a detailed RCA. Sometimes the cause of failure may be a different operational mode or environment the machine is located in. The author used the technical documentation in order to obtain necessary root-causes for maintainable items. Karsten Moholt, for instance, arranges the investigation process based on experience with the specific type of equipment, historical and technical data. The CBM development methodology doesn't specify steps needed for carrying out the RCA. The reason is that this type of analysis needs individual approach in every single case.

During the design of CM system, much attention is given to accessibility and reliability of measurements. In case of vibration analysis the important issue is the location of measurement points. It should be safe to perform measurements and information obtained should be useful for further assessment of machine conditions. It is important to be aware of that different operational modes may affect the parameters deviation. Higher RPM in electric motor causes changes in vibration trend. Methodology presented in the current thesis doesn’t include the discussion about filtering of condition monitoring data because of more general approach applied in the thesis. Though it is a very important part in CM system design and can be used in order to avoid false signals, alarms and unnecessary investigations.

The diagnosis and prognosis part of the methodology contain several “pitfalls” due to complexity of these processes. The first issue that may influence the efficiency of diagnosis is automatic trends and alarms. The complete reliance on predefined alarms can lead to unnecessary alarms and shutdowns. Each deviation from a normal condition should be assessed and severity of the problem should be verified. As stated before the reason of parameter changes can be e.g. load variations and weather conditions. The diagnosis and prognosis approach used by the author in a methodology doesn't describe holistically the initiation of one failure mode by another one. The reason is that only few studies of complex failure modes are planned during the execution of reliability analysis presented in the thesis.

The reliability assessment framework can be carried out in a more complex way then it is realized in this project. It will be actually possible to identify potential multiple failures by using the same tools. One of the ideas of data acquisition approach applied in the thesis is providing information to the operator on current FM, causes, remedy and time left until the machine shuts down. Considering the prognosis part it can be useful to show both most possible extrapolation curve and the worst case that will actually represent the degree of uncertainty related to estimated time to failure. Lots of information showed simultaneously can confuse the personnel and may require significant resources for its elaboration. Time and costs associated with the development of table 9 shown in chapter 4.2.5 should be always correlated with possible benefits it can bring. An advantage of selective presentation of information provided by the author is a convenient way to customize the dashboard according to the operator needs. If operator confirms the correct choice of failure mode, cause & remedy by software or/and adds new input information, it will be used as source for the mathematical model updating (self-learning system). Thus, accuracy of diagnosis will be increased each time the deviation of machines condition occurs. The baseline that displays the parameter deviation at the healthy condition should be able to be changed according to machine operational mode and characteristics of working environment (e.g. temperature, pressure and wind load). It will allow to assess changes in measurements in a more reliable and realistic way.

In order to develop a successful CBM program it is required to have a complete understanding of deterioration mechanisms associated with machine that is under assessment. The author shares the idea presented in the article by Wael Abouamin (Abouamin et al. 2003) on creating the team for the development of CBM consisting of designer (e.g. NOV), rig owner (e.g. COSL Drilling Europe) and the third part (e.g. DNV). By using this combination of backgrounds, equipment can be examined from different perspectives and e.g. more accurate root-cause analysis and maintenance planning can be performed.

5.2 Proposals for Improving Execution of CBM program

One of the main suggestions according to Karsten Moholdt of how to improve the CBM performance is a proper training of personnel. It includes training associated both with handling of equipment and condition monitoring philosophy. The proactive way to avoid a significant amount of machine failures is to ensure the maximum competence in operating critical equipment. By condition monitoring training the author understands the complete comprehension of main benefits, processes and necessary activities of this approach. Personnel involved in CBM program execution should be aware of their own role in the process and how to achieve the maximum output from this program implementation. It is not necessary to send all the maintenance personnel to the advanced level course; it is enough, for example, to send three engineers from one offshore installation. The benefits associated with training are already briefly described in the thesis. A good example of reducing costs and downtime by providing proper training is fixing problems related to balancing and alignment of a machine. If at least one on the platform knows how to use the equipment to identify misalignment, all the instructions can be given by phone and there is no need of sending personnel from CM services provider to offshore.

One of the biggest dangers related to unnoticed failure is the secondary damage. If the vibration of gas turbine increases due to the damaged in bearing, may coupling or bearing of generator be exposed to failure as well. A big challenge here is to present how the failure of one machine may lead to the failure of another one. During the work on the thesis the author came up with idea to utilize so-called “heat-map” for this purpose. It is the approach of graphical presentation of area to be influenced by current damage. After the detection of failure mode the software can show values of components failure probability of the same or another machine exposed to secondary damage by using heat-maps color gradient (from red to blue).

The CBM program will increase its effectiveness by implementing manual condition monitoring routines together with automatic techniques. For example, unusual sounds or vibration located in non-measurable areas can be noticed by the operator. Possible leaks, performance reduction, color of oil and etc. can be detected by the personnel and added to the mathematical model of the machine by using special forms. Only combination of both human and computer contributions will result into holistic utilization of CBM program.

It was already mentioned in previous chapters about using the data obtained from CBM execution to CMMS. It can be done by integrating CM into the computerized maintenance management and decision-support systems. CMMS usually consists of several modules where CM can be one of them providing information e.g. about equipment condition, updating criticality & failure rates and historical data. Some of the existing decision-support systems can analyze the historical data and investigation reports, compare them with the current situation and assist in root-cause analysis and the remedy.

Another effective way to improve the performance of CBM program is a close cooperation between the equipment supplier and user. It is important that the information on condition of the equipment delivered by the vendor is available for vendor itself. With help of this collaboration the design of the machines can be significantly improved, furthermore degradation mechanisms can be studied in detail and provided to the company utilizing equipment. It can lead to higher reliability and availability of the operating equipment. Another advice considering cooperation work with vendors is provided by Karsten Moholt. It implies that if machine is delivered with in-built sensors and CM system, the assessment of CM information should be done by the third party company instead of the vendor if it’s possible. The reason is that the equipment supplier might decide to avoid the unplanned shutdown during the warranty period by performing extra and not always necessary work.

6. Conclusion

In the final chapter of the thesis the author presents the summary of the obtained results together with conclusions. Possible future work based on the current project is proposed as well. The last part of this chapter is devoted to possible application areas.

6.1 Summary of Results

By performing the current project the author answers to the following main questions:

- What tools and data should be used in establishing condition-based maintenance program?
- How to integrate different reliability methods together into one sequence?
- What equipment is necessary to be monitored using CM techniques?
- How to use the information related to equipment condition in decision-making?
- How to ensure profitability of maintenance activities?

The main conclusion of the thesis is that the CBM development methodology is a necessary & effective tool to be created and adapted according to the company features in each particular case. The implementation process plays a significant role in the success of the CBM program, when employees from technical to administration department share and follow the CBM philosophy. That can be achieved by introducing this maintenance approach and providing more specialized courses (e.g. vibration analysis course).

Regulatory authority follows International and Norwegian standards that contain special requirements for approval/certification of equipment, activities and etc. The author considers that it is important to remember that ISO and Norsok also include tools and methods that can be modified and adapted for each particular case. Using standards as the starting point for CBM program development is absolutely recommended by the author. Reliability tools are very effective methods for mapping the ability of equipment to perform its functions and finding possible failures and associated causes. The assessment is more effective when several tools are used in combination with each other. The reliability framework developed by the author demonstrates the effectiveness of this approach.

The condition monitoring approach is applicable in case if the technical & mechanical structure, degradation mechanisms and equipment criticality, exposed to monitoring, are investigated and comprehended. It should be done in order to establish a prerequisite for further

CBM development process. From the author's point of view, the idea of creating a common database (like OREDA) for reliability and maintenance data provided by several companies will be more popular in the nearest future. This type of databases may become more common due to increased amount of complex operations (e.g. Arctic drilling) where consequences of failure can be dramatic for the whole society. By sharing maintenance history and reliability information, operations can become safer.

Currently it is useful to order a CM service from the company specializing in condition monitoring and having a vast experience. Thus, the CBM program development and execution will be based on experience acquired during the work with several companies. While working on the development of maintenance program it is important to assess its progress from different perspectives and backgrounds. That's why it is so important that the team working with CBM elaboration is entered by experts from several relevant fields with unique experience and background.

The reason that companies are interested in implementing CM is the profitability of this approach. In order to ensure the balance between costs and effects, key performance indicators, derived from the strategy and main goals of the company, should be determined. By identifying interdependences between KPIs of maintenance effectiveness and earning power, it is possible to assess profitability changes due to alteration in the maintenance strategy. The information obtained by CM system should be integrated and used in decision-making process. For example, decisions related to choosing of machine for maintenance operations during the unplanned shutdowns and possible modifications, could be taken faster and more accurately when the decision-making process is based on CM data and rates.

6.2 Future Work

The CBM development methodology presented in the current thesis is tested on too few equipment and not all the parts of the methodology are applied in the case study. Therefore the first recommendation related to future work should deal with the development of the complete CBM program for a specific drilling company. It can show the applicability level of the methodology and contribute to its further improvement process. Another project that can be a topic for a master thesis is: "CM equipment maintenance and reliability". It implies focusing on the CM system as a possible source of failure and ensuring the maximum and reliable performance of it. This topic that is often neglected can be assessed as a part of CBM development methodology presented in the current thesis.

Another part of the methodology that can be studied as a separate project is the "data acquisition and analysis" (prognosis and diagnosis). This project might show how the mathematical model aids in assessment of the equipment condition, finding possible solutions and predicting future behavior. The model should be able to improve itself through the self-learning process. The extrapolation process of the parameter trend can be also a complex and demanding task.

The fourth suggestion for the topic of the possible master thesis is transformation of CBM development methodology into RCM concept development. It may include, for example, application of several maintenance policies to the methodology as possible strategies for relevant equipment and studying the process of root-cause analysis on a more detailed level.

6.3 Application Area

The current thesis provides a detailed overview of modern CM philosophies, trends, tools and feedback from the companies that actively utilize them in day-to-day activities. It can be useful both for students and organizations that are interested in applying RCM and CBM in particular. The CBM development methodology can be used both partially and as a whole. Each step of the methodology is a complete stand-alone tool to be applied in different circumstances.

The methodology is designed basically for top-side drilling equipment, but it can be also used for other critical equipment in different industrial areas under necessary modifications. The CBM development methodology is guidelines of what steps the organization has to go through in order to build up a condition-based maintenance program. By implementing the given methodology, organizations can reduce risk and costs associated with reliability and maintenance of top-side drilling equipment. It implies increase of the machines availability & performance, decrease of undesired corrective maintenance activities and extension of equipment lifetime. As a result, the total production effectiveness can be improved.

The application of CBM development methodology will contribute with detailed mapping of equipment and its criticality. It may imply detailed description of degradation mechanisms and allocation of main interrelationships among equipment, its components and failure mechanisms. The main goal of the methodology is to arrange tools and methods into one sequence of steps aimed at creating a complete CBM program as a part of RCM approach by implementing well-known practices and describing advantages & limitations of its application.

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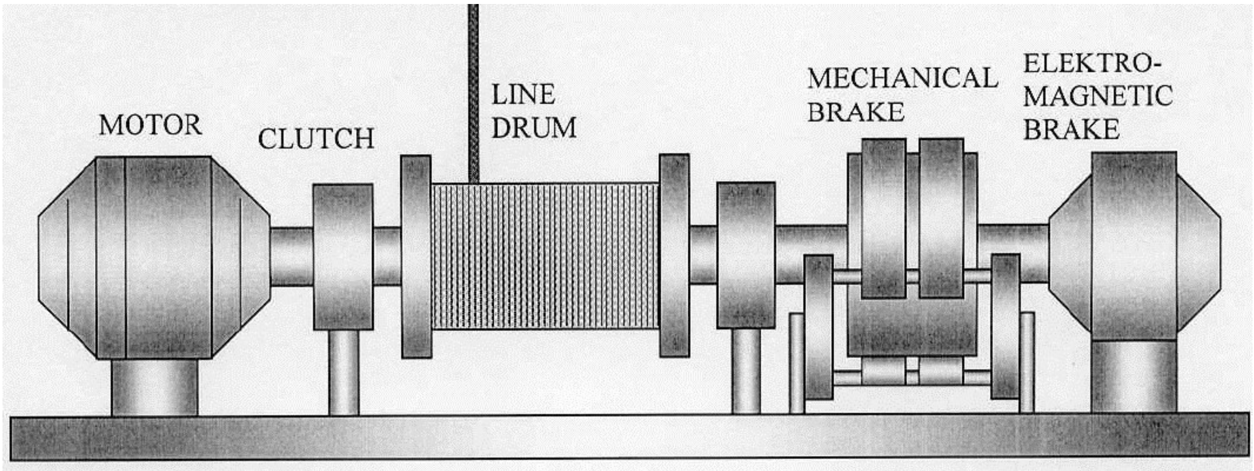
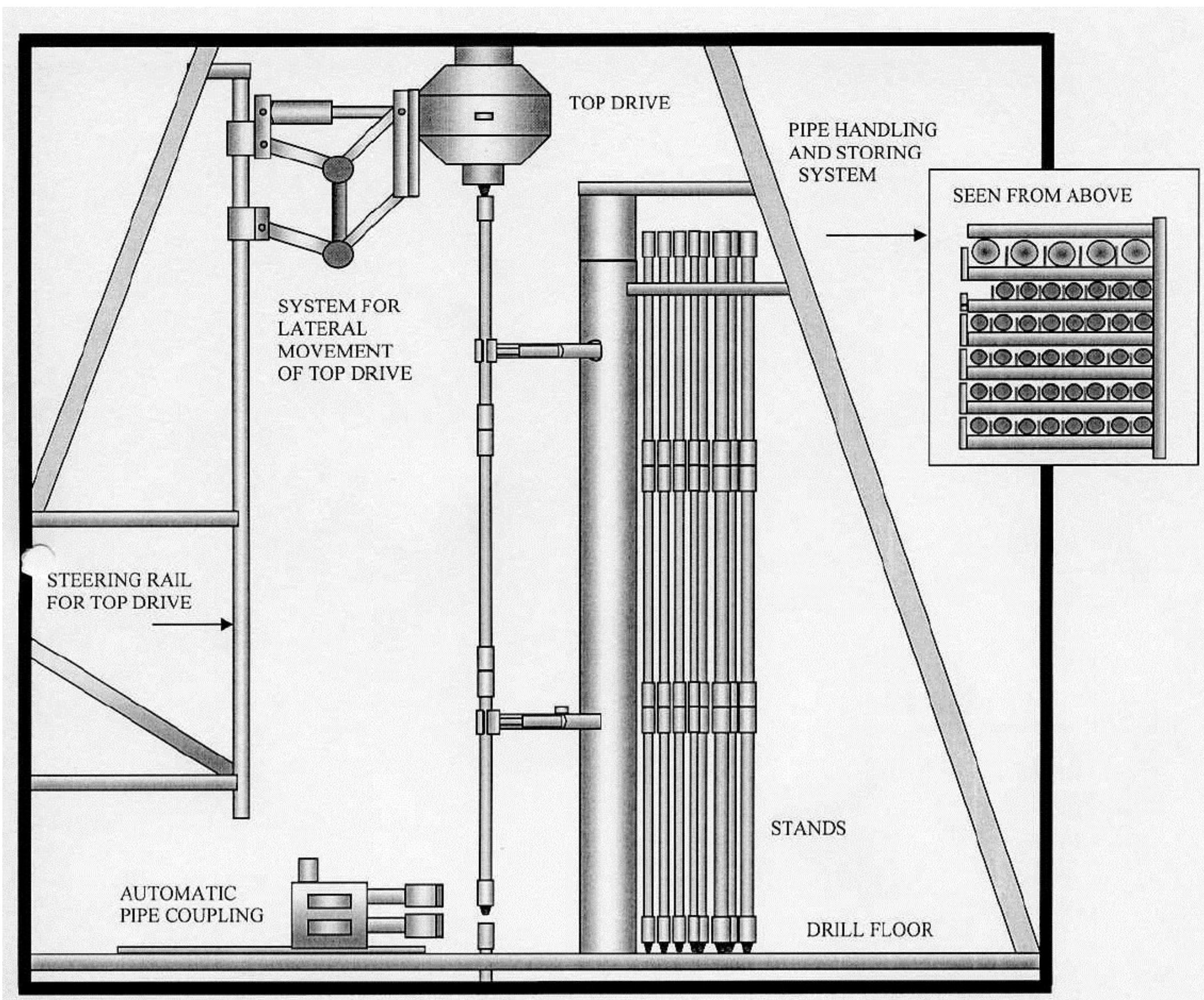
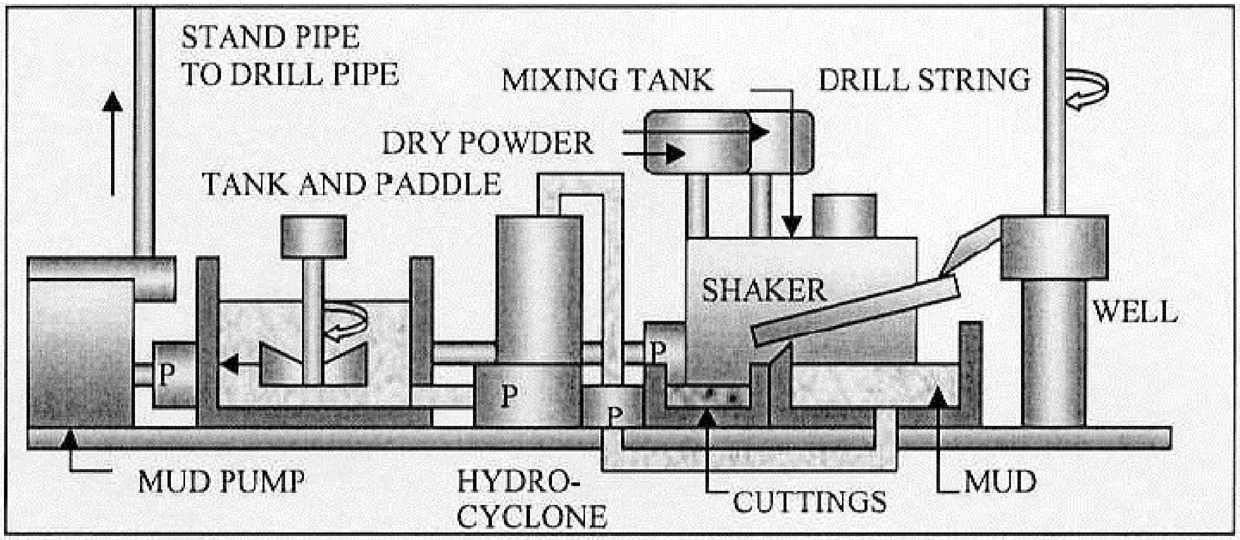
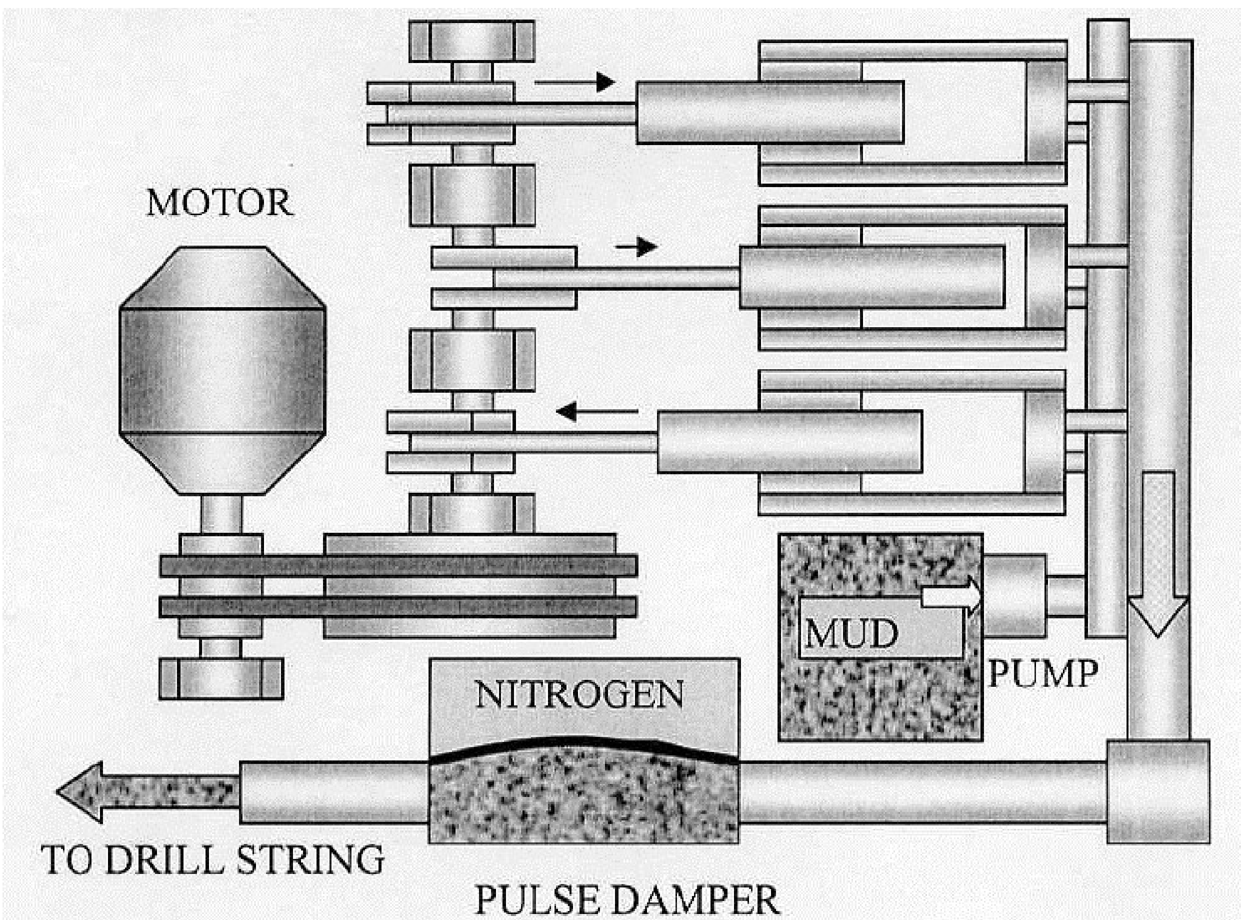
Appendix A: Drilling Equipment and Mud System (Skaugen 2011)






STAND PIPE
TO DRILL PIPE
MIXING TANK
DRILL STRING
DRY POWDER
TANK AND PADDLE
SHAKER
WELL
P
P
P
P
MUD PUMP
HYDRO-
CYCLONE
CUTTINGS
MUD


MOTOR
MUD
PUMP
NITROGEN
TO DRILL STRING
PULSE DAMPER

Appendix B: Examples of Key Performance Indicators Using Reliability and Maintenance (ISO 14224 2006)

KPI parameter	**Relevant taxonomy hierarchies** (see Table E.2)	**Units**	**Explanation and calculation**	**Purpose and value**	**Involved personell**
7) AT Technical Availability	6	% time available for operation of the equipment when corrective maintenance only is included in the down time	Normally on Equipment Unit level	The key technical availability indicator. Shows trend in equipment availability focusing on intrinsic reliability (see Annex C3.1)	SM and MM Operations Maintenance Inspection SME's and RE's
8) Preventive Maintenance (PM) manhours ratio	4 - 6	% of total maintenance manhours spent on PM (not including modifications)	Total PM WO manhours divided by total WO manhours, by equipment classification or types	Indication of amount of proactive preventive maintenance work	SME's and RE's Operations Maintenance
9) Corrective Maintenance manhours ratio	4 - 6	% of total maintenance manhours spent on corrective maintenance	Total CM WO manhours divided by total WO man hours, by equipment classification or types	Indication of amount of corrective maintenance work	SME's and RE's Operations Maintenance
10) PM's Overdue	4 - 6	No. of or % of PM WO's overdue by category	Count of Outstanding PM WO's by equipment classification or as a % of total PM WO's One may also select only safety critical equipment, or production critical equipment to differentiate into groups.	Indication of outstanding PM backlog	Operations Maintenance

Appendix C: Criticality Ranking Test

	COSLPioneer			
	Document title:	Criticality Ranking Test	Date:	13.02.2012
			Res.:	Ilya Sizov
	Week number:	7	Page:	1 of 1

Goal: The following document is made to test a rough ranking method of critical drilling equipment that represents a first step in establishing a condition monitoring program for drilling equipment.

Objective: Assign a single Criticality Value between 1 (min. critical) and 10 (max. critical) for each function in the table below.

Additional information: The assessment can be based on information given in the table and/or your own perception of criticality for particular function. All data presented in the table are collected from criticality assessment reports assigned to COSLPioneer drilling equipment.

№	Type of function	Function tittle	Safety	Production	Oil spill	Capacity*	Probability of failure			Criticality Value (1-10)
332		**BOP Control System**	Consequences**				High	Medium	Low	
33201	MF	Hydraulic Power Unit (HPU)	2	3	1	100%	Low			
33209	MF	Accumulator Bottle Rack Assy Surface	2	2	1	100%	Low			
33202	MF	BOP/Diverter Control Unit/Panel	3	3	3	100%	Low			
	SF-IND	Local Indication	1	1	1	100%	Low			
33203	MF	BOP Fluid Recovery System (FRS)	1	1	3	100%	Low			
33204	MF	BOP Remote Operated Control Panels	3	3	3	100%	Low			
33205	MF	BOP Control Pod Hose and Reels	2	3	1	200%	Low			
33401	MF	Diverter With Control System	2	2	3	100%	Low			
33208	MF	BOP Acoustic System ACS 433	3	3	3	100%	Low			
33206	MF	BOP Control Pods	2	3	1	200%	Low			
	SF-Control	Regulating	2	3	1	200%	Low			
33109	MF	Flexjoint, Kick out Subs and Flex-loops	3	3	3	100%	Low			
33207	MF	Other Hydraulic Valves and other Equipment	2	3	1	100%	Low			

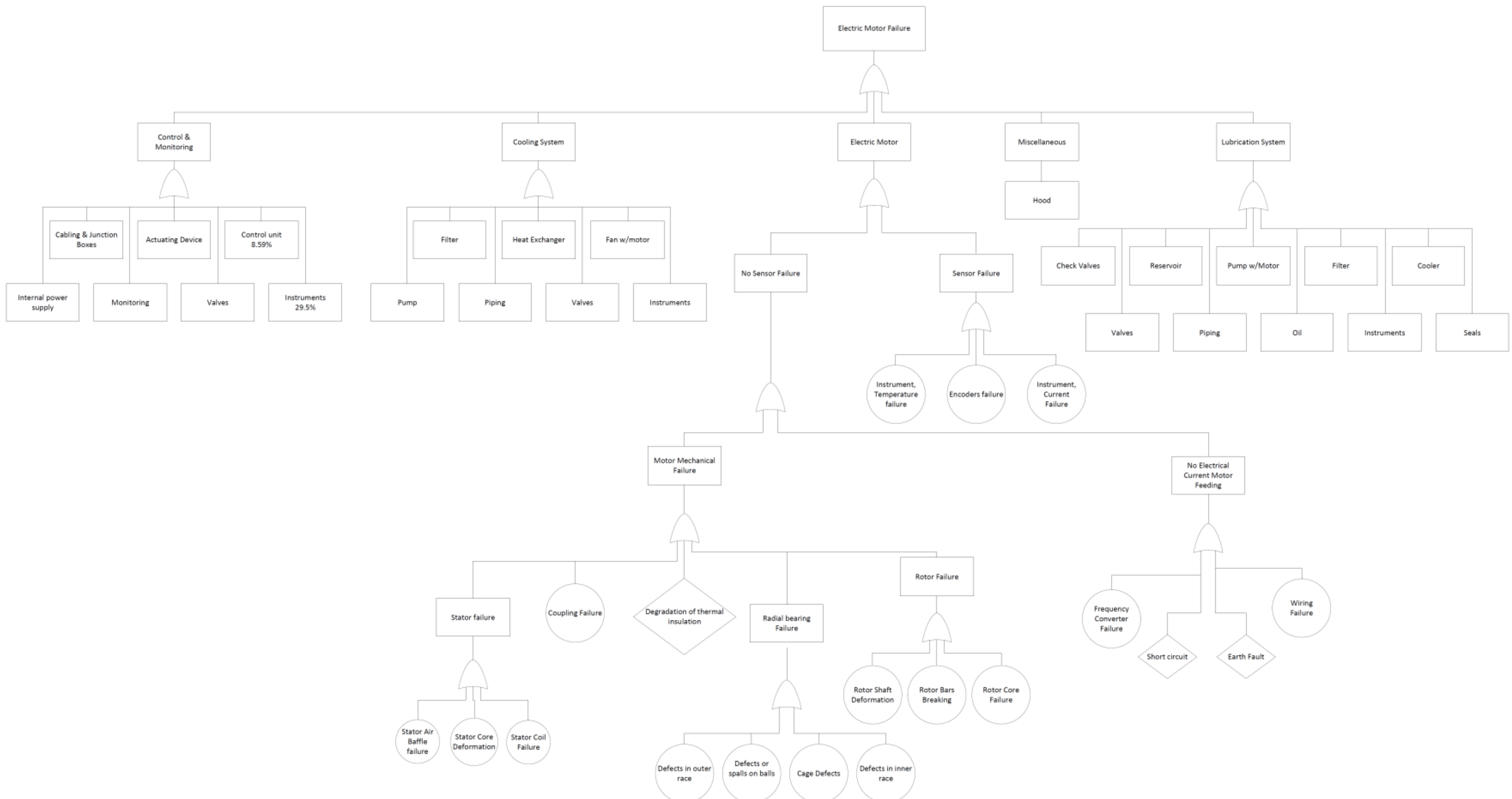
*capacity here implies a total capacity which is calculated by adding single capacities of all units performing the same function

**1 = Low critical consequences, 2 = Medium critical consequences, 3 = High critical consequences

Appendix D: Calculation of Birnbaums Importance Measure

Subunits	MTTF	MTTF hours	MTTR	Exposed period	Unavailability (Q(T))	Improtance measure	1-Importance measure
Control and monitoring	7.7	67452	8		1.19E-04	0.999309496	6.91E-04
Cooling System	30.6	268056	6		2.24E-05	0.999213354	7.87E-04
Electric motor	6.2	54312	31		5.70E-04	0.999761303	2.39E-04
Lubrication System	47.1	412596	12		2.91E-05	0.999220049	7.80E-04
Miscellance	53.2	466032	32		6.87E-05	0.997496826	2.50E-03
System	2.7	23652	21		8.87E-04		
					0.000809011	1	

Appendix E: Fault Tree of Electric Motor



Appendix F: Form for Recording Typical Machine Details (ISO 17359 2011)

Table C.1 — Form for recording typical machine details

General

Record No.: ______________________ Installation site: ______________________

Date: ______________________ Measured by: ______________________

Details of machine/train

Unique machine ID No.: ______________________ Type/Serial No.: ______________________

Type: motor/generator/turbine/comp./pump/fan[1] Powered: electric/steam/gas/RIC/diesel/hydraulic[1]

Configuration: direct/belt/shaft[1] drive/driven[1] Function: driver/driven[1] Coupling: rigid/flexible[1]

Rated speed: ______________ r/min Rated power: ______________ kW

Actual speed: ______________ r/min Power during measurement: ______________ kW

Mounting: rigid/resilient[1] directly/on baseplate[1] Running hours: ______________________

Manufacturer: ______________________ Bearing type(s): ______________________

Details of each measuring system

Instrument type: ______________________ Make: ______________________

Transducer type: __________ Make: __________ Attachment: __________ Units: __________

Transducer type: __________ Make: __________ Attachment: __________ Units: __________

For reciprocating machine:

Number of cylinders: 2/3/4/5/6/8/12/16[1] Working cycle: two/four/single/double[1] stroke/effect[1]

Diagram Sketch machine below.

Measurement records, readings, diagrams, etc. should be attached, giving locations and points of measurement, as well as the conditions at the time of measurement, if applicable.

1) Delete/supplement as appropriate.

Appendix G: Example of Presentation Symptoms vs. Cause & Remedy

Fault			Possible causes	Remedy
Bearing is too hot	Bearing noise	Motor runs unevenly		
■			Too much grease in bearing	Remove excess grease
■			Bearing dirty	Replace bearing
■			Belt tension too high	Reduce belt tension
■			Coolant temperature above 40 C	Adjust temperature of cooling air
■			Bearing grease dark colored	Check bearing currents

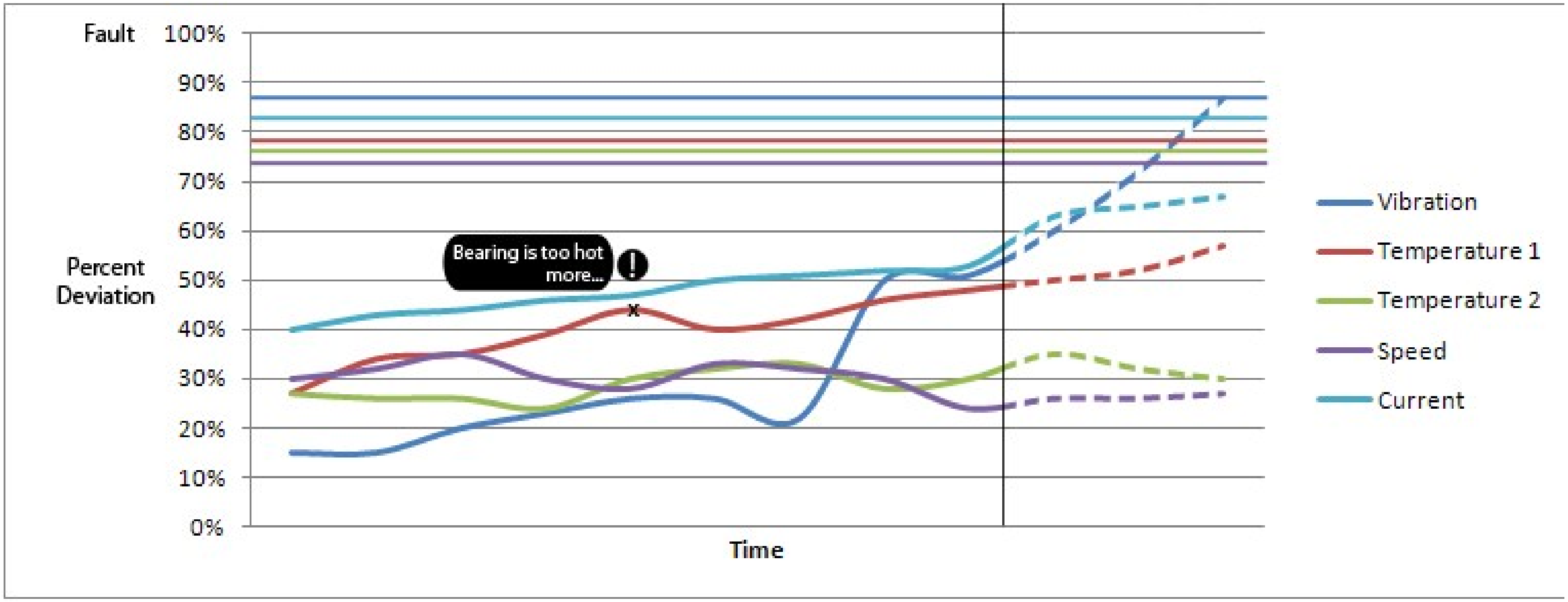
Fault			Possible causes	Remedy
Bearing is too hot	Bearing noise	Motor runs unevenly		
		■	Unbalance caused by pulley or coupling	Exact balancing
		■	Motor fastening unstable	Check fastening

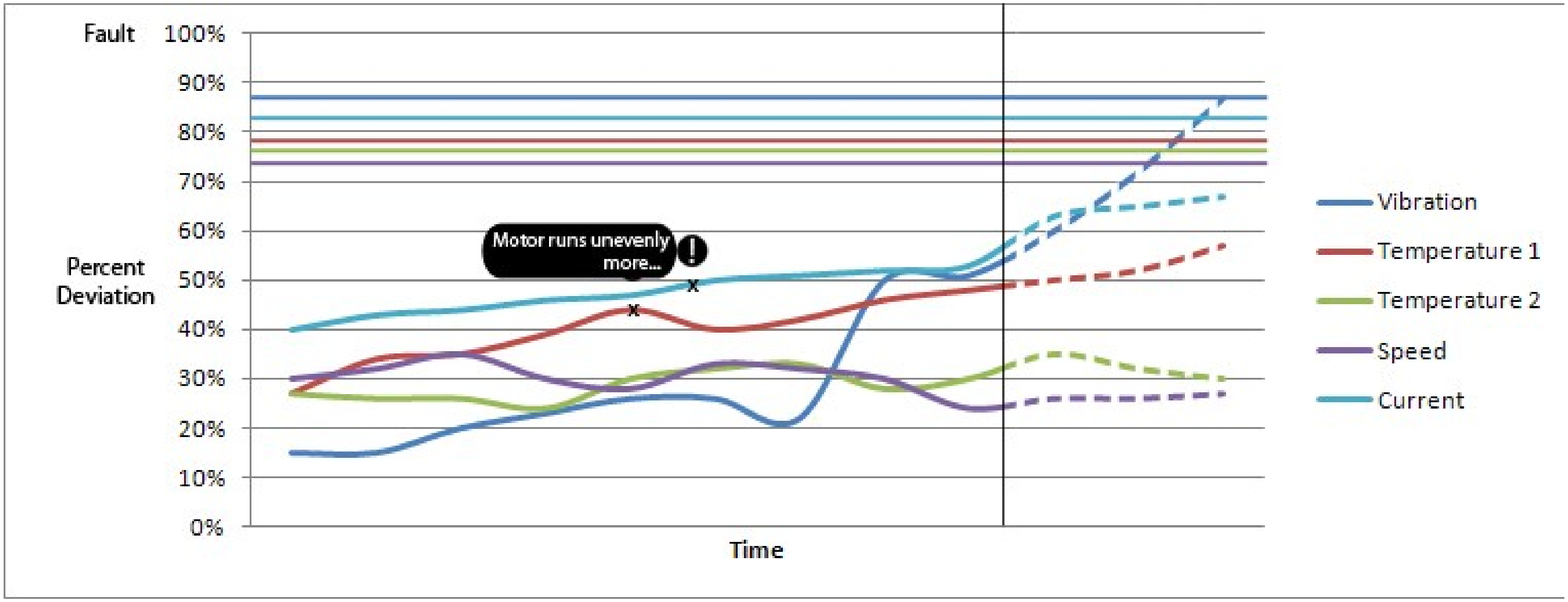
Fault			Possible causes	Remedy
Bearing is too hot	Bearing noise	Motor runs unevenly		
■		■	Coupling forces are pulling or pushing	Realign motor, correct coupling

Fault			Possible causes	Remedy
Bearing is too hot	Bearing noise	Motor runs unevenly		
■	■	■	Motor incorrectly mounted	Check mounting type of motor

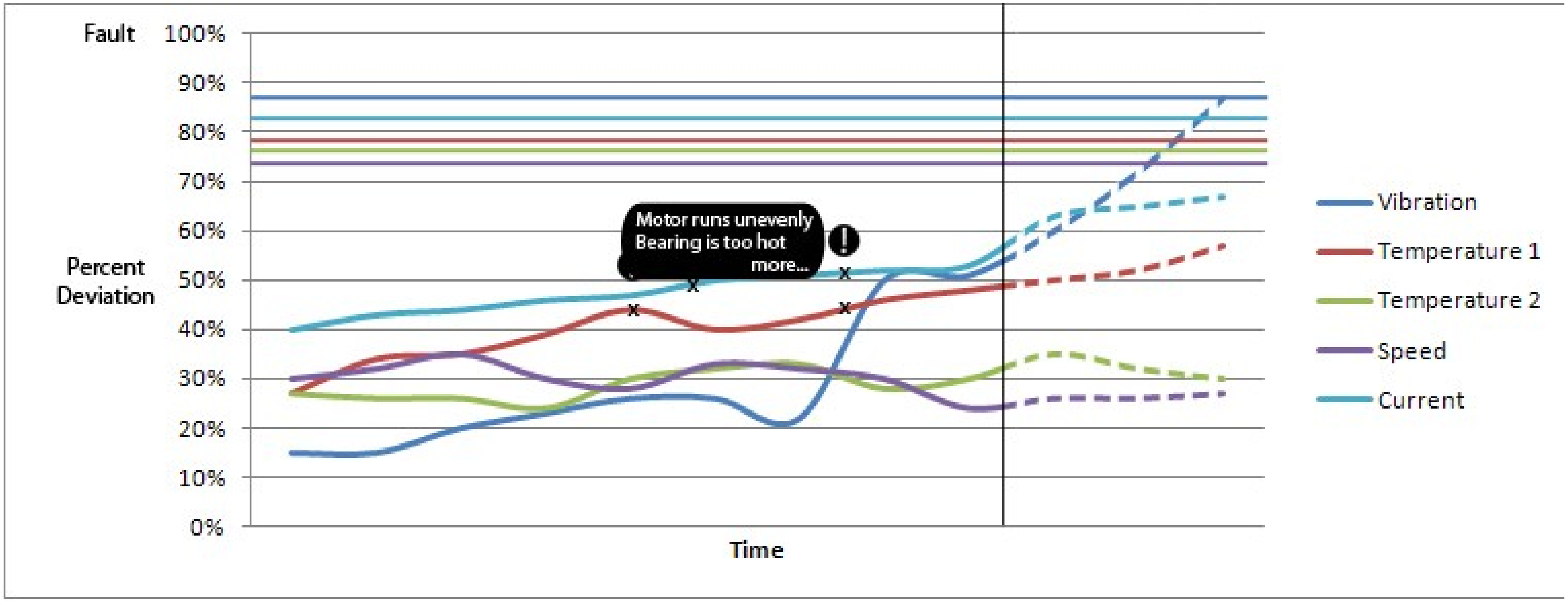
Fault			Possible causes	Remedy
Bearing is too hot	Bearing noise	Motor runs unevenly		
■			Too much grease in bearing	Remove excess grease
■			Bearing dirty	Replace bearing
■			Belt tension too high	Reduce belt tension
■			Coolant temperature above 40 C	Adjust temperature of cooling air
■			Bearing grease dark colored	Check bearing currents
■	■		Not enough grease in the bearing	Grease according to specifications
		■	Unbalance caused by pulley or coupling	Exact balancing
		■	Motor fastening unstable	Check fastening
■		■	Coupling forces are pulling or pushing	Realign motor, correct coupling
■	■	■	Motor incorrectly mounted	Check mounting type of motor
	■		Scoring at bearing inner race e.g. caused by motor start with locked bearing	Replace bearing, avoid vibrations at standstill

Appendix H: Presentation of Condition Monitoring Information (Example)

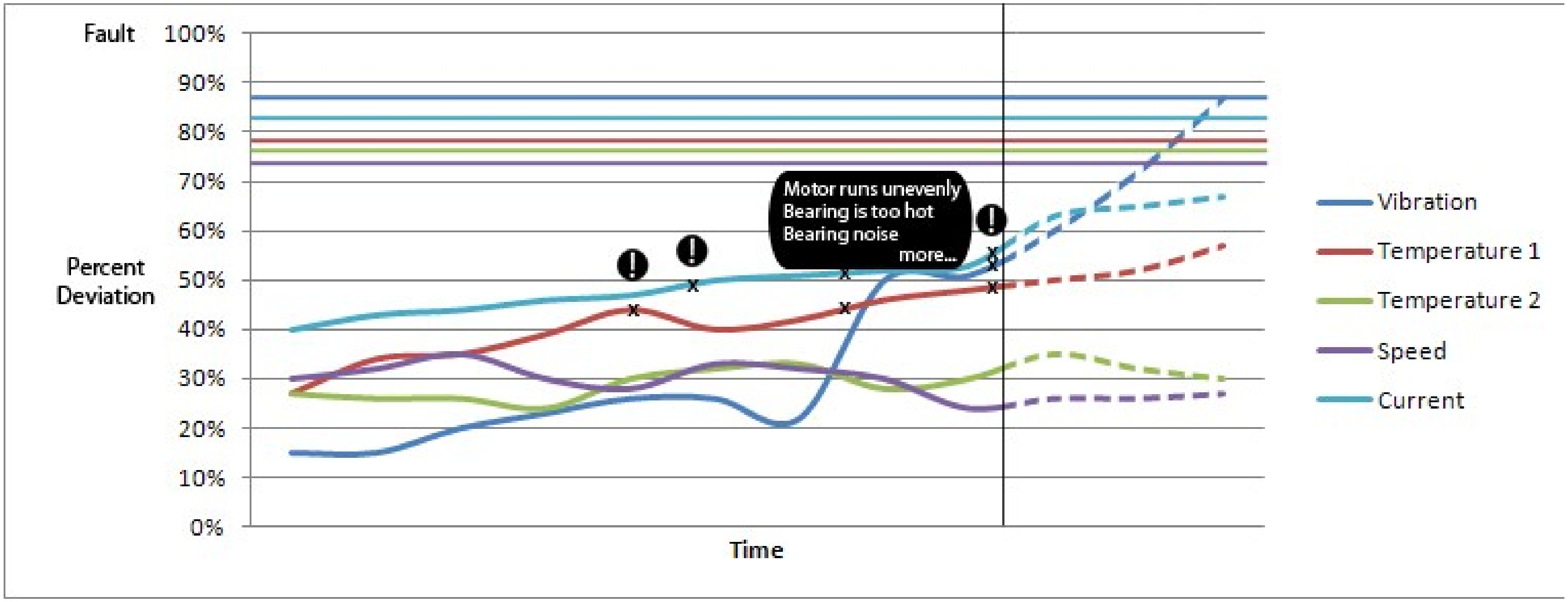




Fault
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Percent Deviation
Motor runs unevenly more...
Time
Vibration
Temperature 1
Temperature 2
Speed
Current

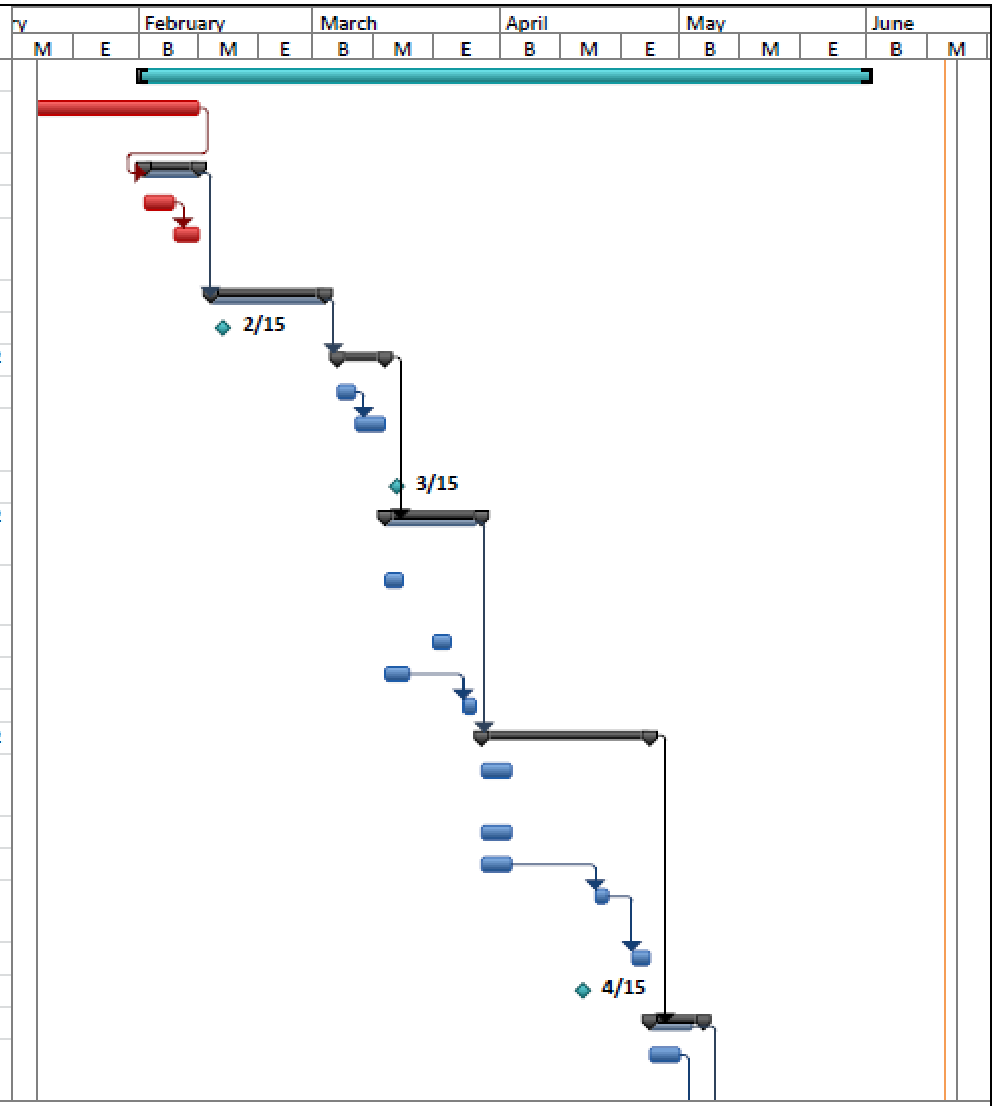


Fault
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Percent Deviation
Motor runs unevenly
Bearing is too hot
more...
Time
Vibration
Temperature 1
Temperature 2
Speed
Current


Fault
Percent Deviation
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Motor runs unevenly
Bearing is too hot
Bearing noise
more...
Time
Vibration
Temperature 1
Temperature 2
Speed
Current

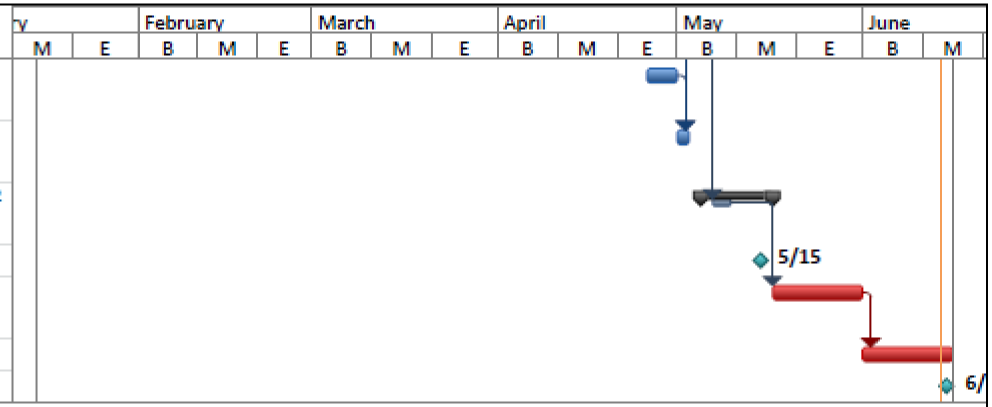
Appendix H: Master Thesis Work Schedule

Task Name	Duration	Start	Finish
1 Writing a report	88 days	Wed 2/1/12	Fri 6/1/12
2 Studing drilling systems and maintenance approach on COSLPioneer	21 days	Sun 1/15/12	Fri 2/10/12
3 Prioritize critical systems	**7 days**	**Thu 2/2/12**	**Fri 2/10/12**
3.1 Develop criterias for rough ranking	3 days	Thu 2/2/12	Mon 2/6/12
3.2 Apply criterias for COSLPineer drilling systems	4 days	Tue 2/7/12	Fri 2/10/12
4 Risk Assessment	**15 days**	**Mon 2/13/12**	**Fri 3/2/12**
5 Status report 2	0 days	Wed 2/15/12	Wed 2/15/12
6 Final prioritizing of critical systems	**6 days**	**Mon 3/5/12**	**Mon 3/12/12**
6.1 Develop criterias for final ranking	3 days	Mon 3/5/12	Wed 3/7/12
6.2 Apply criterias for COSLPioneer drilling systems	3 days	Thu 3/8/12	Mon 3/12/12
7 Status report 3	0 days	Thu 3/15/12	Thu 3/15/12
8 Determine rough list of parameters to monitor for several most essential systems	**12 days**	**Tue 3/13/12**	**Wed 3/28/12**
8.1 Define main Key Performance Indicators	3 days	Tue 3/13/12	Thu 3/15/12
8.2 Identify current system state	3 days	Wed 3/21/12	Fri 3/23/12
8.3 Study degradation mechanisms	4 days	Tue 3/13/12	Fri 3/16/12
8.4 Make a list of parameters	2 days	Mon 3/26/12	Tue 3/27/12
9 Select CM technique	**20 days**	**Thu 3/29/12**	**Wed 4/25/12**
9.1 Choose the parameters that could be monitored	3 days	Thu 3/29/12	Mon 4/2/12
9.2 Study parameters interdependences	3 days	Thu 3/29/12	Mon 4/2/12
9.3 Develop the CM approach	3 days	Thu 3/29/12	Mon 4/2/12
9.4 Develop final list of parameters that should be monitored	2 days	Tue 4/17/12	Wed 4/18/12
9.5 Choose monitoring systems	3 days	Mon 4/23/12	Wed 4/25/12
10 Status report 4	0 days	Sun 4/15/12	Sun 4/15/12
11 Establish baselines and alarm levels	**7 days**	**Thu 4/26/12**	**Fri 5/4/12**
11.1 Develop a methodology for deciding baselines and alarms	3 days	Thu 4/26/12	Mon 4/30/12

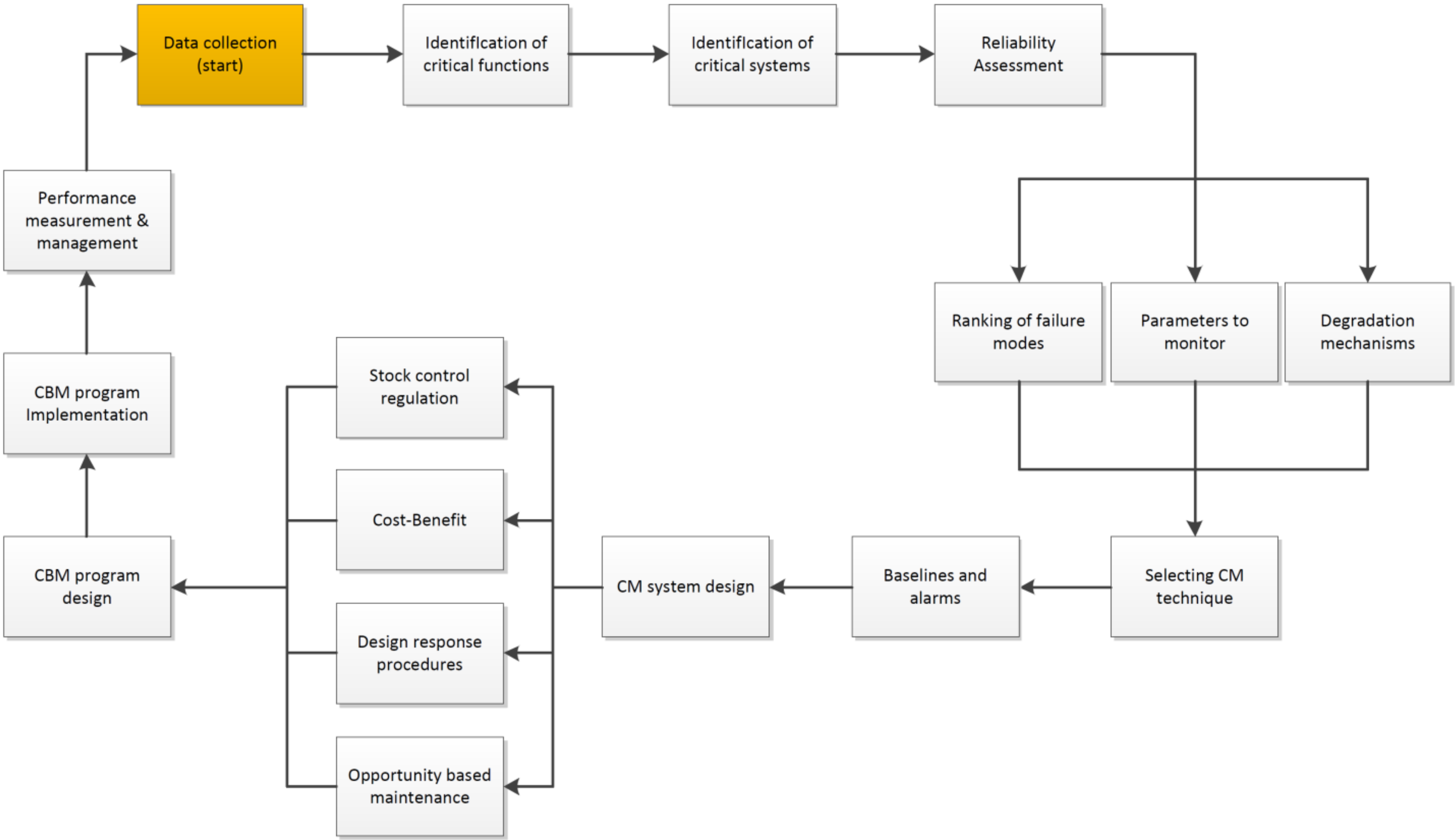


Page 1

Task Name	Duration	Start	Finish
11.2 Make the dynamic model of BL and A change	3 days	Thu 4/26/12	Mon 4/30/12
11.3 Apply methodology and model for COSLPioneer systems	2 days	Tue 5/1/12	Wed 5/2/12
12 Determine the process of data collection, assessment and response	**9 days**	**Sat 5/5/12**	**Wed 5/16/12**
13 Status report 5	0 days	Tue 5/15/12	Tue 5/15/12
14 Develop a concept for continuos CM system review and improvement	11 days	Thu 5/17/12	Thu 5/31/12
15 Review the project	11 days	Fri 6/1/12	Fri 6/15/12
16 Project submission	0 days	Fri 6/15/12	Fri 6/15/12



Appendix I: Methodology for CBM Program Development



Appendix J: Failure Mode and Symptom Analysis of AHC Drawworks

Function	Code	Sub-Functions	Failure modes	Symptoms	Failure mechanisms (ISO 14224)	Failure modes (ISO 14224)	DET	SEV	DGN	PGN	MPN
Hoist	MF	MF Equipment (Heave Compensating Drawworks)	Motor Blower Skid 1, 2 failure	1. Blower fan works only on one speed, usually high	1.2 Vibration	BRD-Breakdown	5	3	4	4	240
				2. Generating additional noise	1.4 Deformation	FRO-Fail to rotate					
				3. Abnormal vibration	1.5 Looseness	FTI-Fail to function as independent					
					2.2 Corrosion	FTS-Fail to start on demand					
						NOI-Noise					
						VIB-Vibration					
						STP-Fail to stop on demand					
						SER-Minor in - service problem					
						OWD-operation without demand					
						OHE-overheating					
			Drum failure	1. Metallic clanking (rotating)	2.5 Breakage	BRD-Breakdown	5	4	5	4	400

				2. Not enough clutch of drum (drum rotates)	2.4 Wear	DOP-Delayed operation					
				3. Hook slips when hoisting hook	3.4 Out of adjustment	FRO-Fail to rotate					
				4. Brake power is not enough	1.5 Looseness	FTS-Fail to start on demand					
				5. Brake band wears quickly	1.3 Clearance/alignment	LOA-Load drop					
					1.2 Vibration	LOP-Loss of protection					
					1.4 Deformation	NOI-Noise					
						UTS-Unexpected stop					
						VIB-Vibration					
			Gearbox failure	1. Excessive or unusual noise exterior	1.1 Leakage	AIR-Abnormal instrument reading	5	4	4	4	320
				2. Metallic clanking (rotating)	1.2 Vibration	BRD-Breakdown					
					1.4 Deformation	ELF-External leakage - Fuel					
					1.5 Looseness	ELU-External leakage utility medium					
					2.2 Corrosion	ERO-Erratic output					

					2.5 Breakage	FTS-Fail to start on demand					
					2.7 Overheating	INL-Internal leakage					
					2.5 Breakage	LOO-Low output					
					3.1 Control failure	NOI-Noise					
					4.3 No power/voltage	OHE-overheating					
						PDE-Parameter deviation					
						SER-Minor in -service problem					
						SPO-Spurious operation					
						UST-Spurious stop					
						VIB-Vibration					
			Brake Hydraulic System failure	1. Excessive or unusual noise exterior	1.1 Leakage	AIR-Abnormal instrument reading	5	3	3	3	135
				2. Improper functioning brakes	1.2 Vibration	BRD-Breakdown					
				3. Calipers don't hold	1.3 Clearance/alignment	ELP-External leakage - Process medium					
				4. Calipers response slow	1.4 Deformation	ELU-External leakage utility medium					

				5. Squealing or grinding	1.5 Looseness	FRO-Fail to rotate					
					2.1 Cavitation	FTI-Fail to function as independent					
					2.2 Corrosion	FTS-Fail to start on demand					
					2.4 Wear	IHT-Insufficient heat transfer					
					2.5 Breakage	INL-Internal leakage					
					2.7 Overheating	NOI-Noise					
						OHE-overheating					
						PDE-Parameter deviation					
						PLU-Plugged/choked					
						SER-Minor in -service problem					
						SPO-Spurious operation					
						STP-Fail to stop on demand					
						VIB-Vibration					
			Hydraulic Tank failure, DW Hydraulic System	1. Excessive or unusual noise interior	1.1 Leakege	AIR-Abnormal instrument reading	4	2	3	3	72

				2. Improper functioning brakes	1.2 Vibration	BRD-Breakdown					
				3. Oil leakage	1.4 Deformation	ELP-External leakage - Process medium					
					2.1 Cavitation	ELU-External leakage utility medium					
					2.2 Corrosion	FCO-Failure to connect					
					2.4 Wear	FTI-Fail to function as independent					
						FTS-Fail to start on demand					
						IHT-Insufficient heat transfer					
						INL-Internal leakage					
						PDE-Parameter deviation					
						PLU-Plugged/choked					
						PTF-Power/signal transmission failure					
						SER-Minor in -service problem					

						STD-Structural deficiency					
						STP-Fail to stop on demand					
			Lubrication Oil Cooler failure	1. Doesn't respond on regulation	1.1 Leakage	AIR-Abnormal instrument reading	5	3	3	3	135
					1.2 Vibration	BRD-Breakdown					
					1.3 Clearance/alignment	ELP-External leakage - Process medium					
					1.4 Deformation	ELU-External leakage utility medium					
					1.5 Looseness	FCO-Failure to connect					
					1.6 Sticking	FTI-Fail to function as independent					
					2.4 Wear	IHT-Insufficient heat transfer					
					2.5 Breakage	INL-Internal leakage					
					2.7 Overheating	LOO-Low output					
					3.1 Control failure	NOI-Noise					
					3.2 NO signal/indication/alarm	OHE-overheating					

					3.3 Faulty signal/indication signal	PDE-Parameter deviation					
					5.1 Blockage plugged	PLU-Plugged/choked					
					5.2 Contamination	SPO-Spurious operation					
						STD-Structural deficiency					
						STP-Fail to stop on demand					
						VIB-Vibration					
			High Pressure Filter failure, DW hydraulic System	1. Wrong indication	1.1 Leakage	AIR-Abnormal instrument reading	5	2	3	5	150
				2. Opens randomly	1.3 Clearance/alignment	BRD-Breakdown					
				3. Leaking in closed position	1.4 Deformation	FTI-Failure to function as intendent					
					5.1 Blockage plugged	LOO-Low output					
					7.3 Improper capacity	OHE-Overheating					
						PLU-Plugged/choked					
						SER-Minor in -service problem					

Lower	SF-Alarm	Alarm	AHC mode on, indication lamp failure	1. No indication	3.2 NO signal/indication/alarm	BRD-Breakdown	4	2	3	1	24
						FOV-Faulty output voltage					
						NOO-No output					
			DW Block Ref. Position failure	1. No signal	3.2 NO signal/indication/alarm	AIR-Abnormal instrument reading	3	2	3	1	18
						BRD-Breakdown					
						LOA-Load drop					
						NOO-No output					
						PDE-Parameter deviation					
						FTI-Failure to function as intendent					
			DW Upper Warning failure	1. No Alarm	3.2 NO signal/indication/alarm	BRD-Breakdown	3	2	3	1	18
						FTI-Fail to function as independent					
						LOP-Loss of protection					
						OWD-operation without demand					

						PTF-Power/signal transmission failure					
						SHH-Spurious high level alarm signal					
						SLL-Spurious low level alarm signal					
Hold	SF-Control	Regulating	DW MRU cabinet failure	1. Improper functioning brakes	3.2 NO signal/indication/alarm	AIR-Abnormal instrument reading	3	4	2	2	48
				2. Not proper heave compensation	3.3 Faulty signal/indication signal	BRD-Breakdown					
					1.3 Clearance/alignment	LOA-Load drop					
						NOO-No output					
						PDE-Parameter deviation					
						FTI-Failure to function as intendent					
						FOV-Faulty output voltage					
						HIO-High output					
						LOO-Low output					
						NOO-No output					

						VLO-Very low output					
			Low Level Switch failure, Hydraulic Oil Tank	1. Does not switch	3.2 NO signal/indication/alarm	AIR-Abnormal instrument reading	3	2	2	2	24
				2. Switches incorrectly	3.3 Faulty signal/indication signal	AOH-Abnormal output - High					
				3. Sporadic faulty switching	3.1 Control failure	AOL-Abnormal output - Low					
				4. Switches incorrectly after power failure	4.3 No power/voltage	BRD-Breakdown					
					4.4 Faulty power/voltage	FOF-Faulty output frequency					
						FOV-Faulty output voltage					
						HIO-High output					
						LOO-Low output					
						NOO-No output					
						VLO-Very low output					
			See Glass failure, Hydraulic Oil Tank	1. loss of indication	3.2 NO signal/indication/alarm	AIR-Abnormal instrument reading	3	2	1	2	12
					3.3 Faulty signal/indication signal	AOH-Abnormal output - High					

						AOL-Abnormal output - Low				
						BRD-Breakdown				
						NOO-No output				
						VLO-Very low output				
			Temperature Transmitter failure, Hydraulic	2. Loss of regulation	3.2 NO signal/indication/alarm	AIR-Abnormal instrument reading	3	2	2	2	24
					3.3 Faulty signal/indication signal	AOH-Abnormal output - High				
					3.1 Control failure	AOL-Abnormal output - Low				
					3.4 Out of adjustment	BRD-Breakdown				
					4.1 Short circuiting	HIO-High output				
					4.2 Open circuit	HIU-High output, unknown reading				
					4.3 No power/voltage	NOO-No output				
					4.5 Earth/Isolation fault	VLO-Very low output				
	SF-PSD	Safety Critical Equipment	DW Control Cabinet failure	1. Improper functioning brakes	3.1 Control failure	AIR-Abnormal instrument reading	2	4	2	2	32
				2. Control failure	3.2 NO signal/indication/alarm	AOH-Abnormal output - High				

				3. Error LED - external fault	3.3 Faulty signal/indication signal	AOL-Abnormal output - Low					
				4. Error LED - internal fault	4.3 No power/voltage	BRD-Breakdown					
					4.4 Faulty power/voltage	FOV-Faulty output voltage					
						HIO-High output					
						LOO-Low output					
						NOO-No output					
						VLO-Very low output					
						LOU-Low output, unknown reading					
						HIU-High output, unknown reading					
			Local DW Emergency Stop failure	1. DW doesn't stop in emergency	3.2 NO signal/indication/alarm	AIR-Abnormal instrument reading	2	4	3	2	48
					3.3 Faulty signal/indication signal	AOH-Abnormal output - High					
						AOL-Abnormal output - Low					
						FOF-Faulty output frequency					
						FOV-Faulty output voltage					

						HIO-High output				
						HIU-High output, unknown reading				
						LOO-Low output				
						LOU-Low output, unknown reading				
						NOO-No output				
						VLO-Very low output				
			Derrick Proxes failure	1. Fail during test	3.1 Control failure	AIR-Abnormal instrument reading	4	4	4	3	192
					3.2 NO signal/indication/alarm	AOH-Abnormal output - High				
					3.3 Faulty signal/indication signal	AOL-Abnormal output - Low				
					3.4 Out of adjustment	BRD-Breakdown				
					4.1 Short circuiting	FOF-Faulty output frequency				
					4.2 Open circuit	FOV-Faulty output voltage				
					4.3 No power/voltage	HIO-High output				

						HIU-High output, unknown reading					
						LOO-Low output					
						LOU-Low output, unknown reading					
						NOO-No output					
						VLO-Very low output					
			DW Upper Stop failure		3.3 Faulty signal/indication signal	BRD-Breakdown	4	4	4	3	192
						FTI-Fail to function as independent					
						LOP-Loss of protection					
						OWD-operation without demand					
						PTF-Power/signal transmission failure					
						SHH-Spurious high level alarm signal					
						SLL-Spurious low level alarm signal					

	SF-LUBPUMP	Lube oil pumps w redundancy	Drawworks Lubrication Oil Pump (Gear Pump) A and B failure	1. Noisy pump	1.1 Leakege	AIR-Abnormal instrument reading	5	3	3	3	135
				2. Errosion on barrel ports & port plate	1.2 Vibration	BRD-Breakdown					
				3. High wear in pump	1.3 Clearance/alignment	ELP-External leakage - Process medium					
				4. Pressure shocks	1.4 Deformation	ERO-Erratic output					
				5. Heating of fluid	1.5 Looseness	FTS-Fail to start on demand					
				6. Decrease in set pressure	1.6 Sticking	HIO-High output					
				7. Pressure doesn't rise	2.2 Corrosion	INL-Internal leakage					
				8. Insufficient flow	2.4 Wear	LOO-Low output					
				9. Improper functioning brakes	2.5 Breakage	NOI-Noise					
				10. Metallic clanking (rotating)	2.6 Fatigue	OHE-Overheating					
					2.7 Overheating	OTH-Other					
					2.8 Burst	PDE-Parameter deviation					
					3.1 Control failure	SER-Minor In - service deviation					

					3.2 NO signal/indication/alarm	STD-Structural deficiency					
					3.3 Faulty signal/indication signal	STP-Fail to stop on demand					
					3.4 Out of adjustment	UST-Spurious stop					
					4.3 No power/voltage	VIB-Vibration					
					4.4 Faulty power/voltage						
					5.1 Blockage plugged						
					5.2 Contamination						
	SF-Motor	Electro Motors with Redundancy	Motor, El., #1,2,3,4 failure	1. Excessive or unusual noise exterior	1.1 Leakage	AIR-Abnormal instrument reading	5	4	4	3	240
				2. Bearing is too hot	1.2 Vibration	BRD-Breakdown					
				3. Bearing noise	1.3 Clearance/alignment	ELF-External leakage - Fuel					
				4. Motor runs unevenly	2.2 Corrosion	ELU-External leakage - Utility medium					
				5. Motor doesn't start	2.5 Breakage	ERO-Erratic output					
				6. Motor is too hot	2.7 Overheating	FTS-Fail to start on demand					
				7. High decrease in speed	3.1 Control failure	HIO-High output					

				8. Protective device triggers	3.4 Out of adjustment	LOO-Low output					
				9. Vibration	4.1 Short circuiting	NOI-Noise					
					4.2 Open circuiting	OHE-Overheating					
					4.3 No power/voltage	PDE-Parameter deviation					
					4.4 Faulty power/voltage	SER-Minor In - service deviation					
					4.5 Earth Isolation fault	SPO-Spurious operation					
						STD-Structural deficiency					
						STP-Fail to stop on demand					
						UST-Spurious stop					
						VIB-Vibration					
	SF-Brake	Brake Pumps and ACC w Redundancy	Accumulator Bottle #1, #2 failure, DW Hydraulic System	1. Oil leaking	1.1 Leakage	AIR-Abnormal instrument reading	3	2	3	2	36
				2. Pressure fall	1.4 Deformation	BRD-Breakdown					
					2.1 Cavitation	ELP-External leakage - Process medium					

					2.2 Corrosion	ELU-External leakage - Utility medium					
					2.3 Erosion	FCO-Failure to connect					
					2.4 Wear	FTI-Failure to function as intendent					
					2.5 Breakage	FTS-Fail to start on demand					
					2.7 Overheating	INL-Internal leakage					
					3.2 NO signal/indication/alarm	LOO-Low output					
					3.3 Faulty signal/indication signal	OHE-Overheating					
						PDE-Parameter deviation					
						PLU-Plugged/Choked					
						SPO-Spurious operation					
						STD-Structural deficiency					
						STP-Fail to stop on demand					

	SF-NON-ESS	Non-Essential Equipment	Hand Pump failure (Reciprocating), Drawworks Hydraulic System	1. Cylinder advances, but doesn't hold pressure	1.1 Leakage	BRD-Breakdown	2	1	2	2	8
				2. Cylinder does not advance	1.4 Deformation	ELP-External leakage - Process medium					
				3. Cylinder advances slowly	1.5 Looseness	ELU-External leakage - Utility medium					
				4. Cylinder advances in spurts	2.2 Corrosion	ERO-Erratic output					
				5. Cylinder doesn't retract	2.3 Erosion	FTS-Fail to start on demand					
				6. Cylinder retracts part way	2.4 Wear	HIO-High output					
				7. Cylinder retracts more slowly than normal	2.5 Breakage	INL-Internal leakage					
					2.6 Fatigue	LOO-Low output					
					2.7 Overheating	STD-Structural deficiency					
						UST-Spurious stop					

	SF-Valve	Manual Shut-off (not accurate)	Gate Valve For Cooling Water Supply To Drawworks failure		1.1 Leakage	BRD-Breakdown	4	3	2	2	48
					1.5 Looseness	DOP-Delayed operation					
					2.1 Cavitation	ELC-External leakage medium					
					2.2 Corrosion	ELF-External leakage - Fuel					
					2.3 Erosion	ELP-External leakage - Process medium					
					2.4 Wear	ELU-External leakage - Utility medium					
					2.5 Breakage	ERO-Erratic output					
					5.1 Blockage/plugged	FTC-Fail to close/lock					
					5.2 Contamination	FTF-Fail to function on demand					
						FTI-Fail to function as intendent					
						FTO-Fail to open/unlock					
						FTR-Fail to regulate					

						FTS-Fail to start on demand					
						STD-Structural deficiency					