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Department of Marine Technology

M.Sc.THESIS

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Abstract:

This M. Sc. Thesis takes basis in the Maintenance Management loop developed by the Norwegian Oil Directorate (now Petroleum Safety Authority) during the *basic study for Maintenance Management* in 1998. This MM loop is connected to Condition Monitoring (CM) as a strategy.

The thesis first discusses the influence of CM on the input and output parameters of the MM loop. Then activities related to CM have been detected and discussed in each process of the loop, with related analysis tools that may be performed. A potential processing flow of CM data from signal data to useful information for decision support with respect to maintenance and logistics has also been proposes.

It has also been looked into a typical maintenance regime for offshore separators today. Thereafter a general decision tool with respect to maintenance and logistics evaluations has been developed. This includes important technical and cost aspects needed to take into consideration when evaluating maintenance and logistics. At last this decision tool is used for evaluation of maintenance and logistics demand for an offshore separator as a case.

Keyword:

Maintenance Management, Condition Monitoring, Separator

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MASTER THESIS
for
M.Sc. student Per Olav Helms
Department of Marine Technology
Spring 2011

Condition Monitoring as a driver for Logistics and Maintenance Planning.
(Tilstandskontroll som en driver for logistikk- og vedlikeholds-planlegging)

Much of the unnecessary operational costs related to offshore process facilities can be associated with revenue losses in terms of unnecessary maintenance shut-downs and extended maintenance down-times due to failures, in which there has been limited time for preparation.

Condition Monitoring (CM) data will be an important input for maintenance and logistics planning and optimisation. By being able to accurately monitor the condition of process equipment, together with trending and prediction of equipment conditions, one can expect a reduction of revenue losses. In order to do so it is necessary to have a complete picture of equipment condition from CM instrumentation and process data. Further it is crucial to validate this data and transform it into information and knowledge that can enable decision makers to take the right decisions with respect to logistics and maintenance.

The offshore industry aim to increase oil recovery, while minimising costs and ensuring safety/environmental aspects. This calls for improved effectiveness with respect to offshore operations and logistics in terms of utilisation of available resources. The M.Sc. thesis includes the following tasks:

1. With basis in the Maintenance Management (MM) loop described in the project thesis the student shall:
    a. Discuss the input and output parameters of the loop, how CM can influence these and vice versa. Describe activities related to CM that should be performed in each step of the loop.
    b. Identify and describe the analysis tools that should be used to support the activities described in the above point.
    c. Propose how CM data should be processed from signal data, to diagnostics and trending, and finally to information that can be used for decision support with respect to maintenance and logistics.
2.
    a. Describe a typical maintenance regime for pressure vessels in the offshore industry today.
    b. Develop a tool that can be used to determine the optimum maintenance and logistics demand related to offshore equipment.
    c. Use the tool developed in the above point to determine the maintenance and logistics demand using an offshore separator as a case.

The student will be able to influence the task and the problem definitions.

The work should be carried out in close cooperation with MARINTEK. Contact person at MARINTEK is Torgeir Brurok

The thesis must be written like a research report, with an abstract, conclusions, contents list, reference list, etc.

During preparation of the thesis it is important that the candidate emphasizes easily understood and well written text. For ease of reading, the thesis should contain adequate references at appropriate places to related text, tables and figures. On evaluation, a lot of weight is put on thorough preparation of results, their clear presentation in the form of tables and/or graphs, and on comprehensive discussion.
Three paper copies of the thesis are required. A CD with complete report should also be delivered to the department. One of the paper copies and a CD should be delivered to MARINTEK by the candidate.

Starting date: 17th January 2011
Completion date: 14th June 2011
Handed in:

Trondheim 17th January 2011.

Magnus Rasmussen
Professor

Master Thesis

Condition Monitoring as a driver for Logistics and Maintenance Planning

28.06.2011
Marine Technology, NTNU
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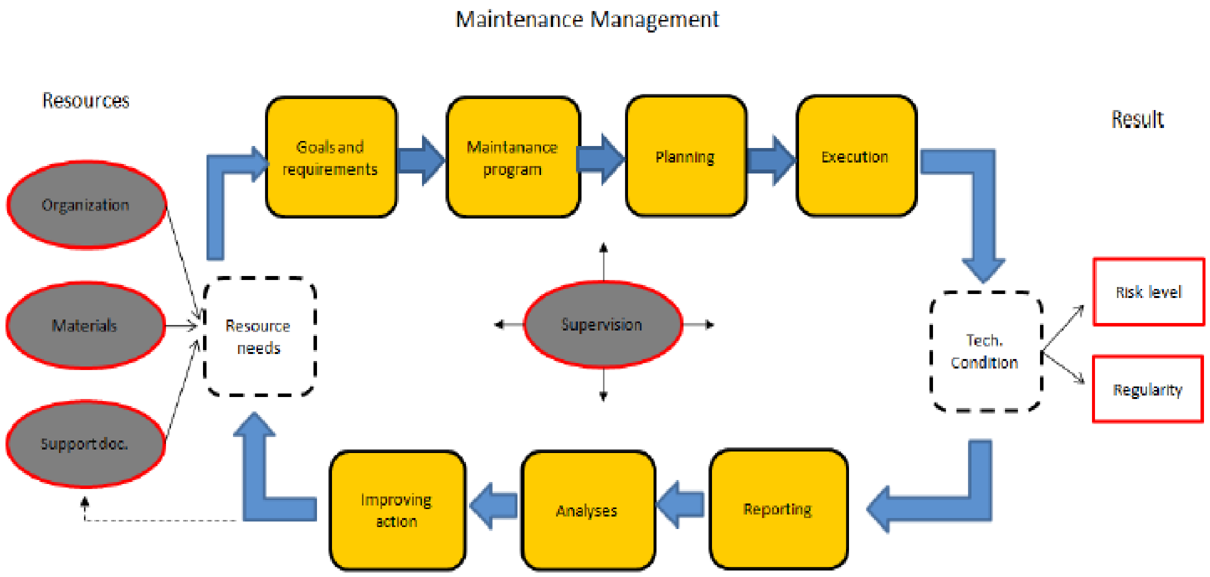

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Preface

This is my M.Sc. Thesis at the Norwegian University of Science and Technology, Department of Marine Technology. The topic of the thesis is "*Condition Monitoring as a driver for Logistics and Maintenance Planning*". The thesis is within the IO Center with Marintek as supervising company.

The thesis has taken basis in the Maintenance management (MM) loop provided by the Petroleum Safety Authority Norway (PSA), and the purpose was to get a continuous connection with Condition Monitoring as a methodology. Trying to detect influences from Condition monitoring (CM) on the input and output parameters of the MM loop, in addition to activities and analysis tools connected to the processes in the loop has been quite challenging. Due to limited information on the combination of MM and CM a considerably amount of the thesis is based on own thoughts and interpretations. It has been chosen to keep the thesis on a qualitative level without performing any quantitative analyses.

I would like to thank Professor Magnus Rasmussen (NTNU), Torgeir Brurok (Marintek) and Harald Rødseth (Marintek) for general help and guidance during this project. It has been essential for my work throughout this thesis. I would also like to thank Professor II at NTNU and principal researcher at Statoil, Tom Anders Thorstensen, for valuable help with information regarding a typical maintenance regime for offshore separators today.

Trondheim 28.06.11

Per Olav Helms

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Summery

In this M.Sc. Thesis the Maintenance Management (MM) loop developed by the Norwegian Oil Directorate (now PSA) has been used as a basis. The model was developed during the "basic study for Maintenance Management" in 1998. The purpose with this thesis was to connect this MM loop with Condition Monitoring (CM) as a strategy.

This thesis can be seen as divided into two main parts as the task description shows. The first part with focus on the MM loop and CM, and the second part with focus on a decision tool for determination of maintenance and logistic demand related to offshore equipment.

First the influences of CM on the input and output parameters of the MM loop have been discussed. Here the input parameters are the resources in form of organization, materials and support documentation. The output parameters are risk level and regularity due to HSEQ and costs. A premise for implementing CM will be that the benefits from CM must exceed the extra input costs, and that CM overall will be a better strategy than conventional periodic maintenance.

Then activities in each step of the loop related to CM have been detected and discussed. Also analysis tools that may be used to support these activities have been detected and described. The most important tool detected was Reliability centered maintenance (RCM).

There is also performed an investigation on the flow of CM data from signal data to useful information used for planning and decision support with respect to maintenance and logistics. This flow diagram starts with CM and data from CM, goes through among others condition analysis, prediction of reliability and remaining useful life, and ends up with actual failure mechanisms and condition development from the planned maintenance actions.

For the second main part of the thesis, first a typical maintenance regime for offshore separators today has been briefly described. Then there has been tried to develop a decision tool with main focus on going from goals and requirements to a maintenance program for general offshore equipment. This decision tool includes the most important aspects needed to take into consideration when evaluating if CM is feasible from both a technical and a cost point of view.

At last the decision tool has been evaluated and discussed towards a separator case. The analysis results utilized here are mainly collected from the M. Sc. Thesis of Jørgen Houmstuen from last year.

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List of abbreviations

CBM	Condition based maintenance
CM	Condition monitoring
CMMS	Computerized Maintenance Management System
ERPI	Electric Power Research Institute
FMECA	Failure mode, effect and criticality analysis
FTA	Fault tree Analysis
ILS	Integrated Logistic Support
IPL	Integrated Planning
IR	Infra Red
LCC	Life Cycle Costs
LSA	Logistic Support Analysis
MM	Maintenance Management
MTTF	Mean time to failure
NASA	National Aeronautics and Space Administration
NDT	Non destructive testing
NII	Non Intrusive Inspection
OBM	Opportunity based Maintenance
OSC	Offshore Support Centre
OREDA	Offshore Reliability Data Handbook
PdM	Predictive Maintenance
PSA	Petroleum Safety Authority Norway
RBI	Risk based inspection
RCA	Root Cause Analysis
RCM	Reliability centered maintenance
SJA	Safe Job Analysis
SWOT	Strengths, weaknesses, opportunities and threats

1 Introduction

Condition monitoring is, and has been the last years, an area of focus in the offshore industry for reduction of revenue losses due to unnecessary shut-downs and extended maintenance down-times due to failures. The M. Sc. thesis utilizes the Maintenance Management loop developed by the Norwegian Oil Directorate (now PSA) in 1998 during the *basic study for Maintenance Management* [2]. The MM loop has been described in general during the project thesis [5].

The M. Sc. Thesis is a part of project 3.2 Condition monitoring of oil and gas facilities, at the center for integrated operations in the petroleum industry (IOCenter). Contact person and supervisor at Marintek for this thesis is Torgeir Brurok.

The *basic study for Maintenance Management* is designed as questions to the operating companies in the study. The questions are mostly on a general level with little focus on Condition monitoring (CM). A considerably amount of this thesis is therefore used for connecting the MM model with CM. This includes influence of CM on input and output parameters of the loop, activities related to CM in the processes of the loop and analyses connected to these activities.

An overview on the data processing flow of CM data will also be gone through. This will show the flow of CM data from signal data to useful information for decision support related to maintenance and logistics.

Also a brief investigation into common maintenance regimes for offshore separators today will be performed. There will be tried to develop a universal decision model/tool that may be used for determination of maintenance strategy and logistics demand for offshore equipment. This will include various analysis tools and evaluation criteria's to be considered for maintenance evaluations. At last the decision tool will be used in relation to a case with an offshore separator as the object for evaluation.

2 Introduction to Maintenance management and Condition Monitoring

With the increasing need for advanced maintenance strategies and high risks involved due safety, environment and economics it is necessary to have a systematically approach for the maintenance function. High competition between the companies also increases the importance of efficiency within the maintenance work for not loosing market compared to competitors.

A definition of maintenance management is given I the Norwegian standard NS-EN 13306: ***"****All activities of the management that determine the maintenance objectives, strategies and responsibilities and implement them by means such as maintenance planning, maintenance control and supervision, improvement of methods in the organization including economical aspects"* [1].

Another definition is given in NEK IEC 60300-3-14 Dependability management Part 3-14: Application guide Maintenance and maintenance support: *"The management of maintenance and maintenance support activities consists of*

- *Developing and updating the maintenance policy*
- *Providing finances for maintenance*
- *Coordination and supervision of maintenance "* [4]

There are several good models for Maintenance Management in use, but this report focus on PSAs model since this is the model which is used to the greatest extent on in the Norwegian offshore segment.

2.1 PSA MM model

PSA's model for Maintenance Management (MM) is developed on the basis of a project performed by the earlier Norwegian Oil Directorate (Now PSA) from 1996 until 1998 called "Basic study for Maintenance Management". The purpose for the project was to be able to develop a method for systematic and holistic evaluation of the MM systems of the companies, and to improve the information flow from OD to the operators about expectations and regulations due to MM. [2]

Reasons for the this project was among other;

- Insufficient internal supervision in the companies due to maintenance.
- Demand for following up was larger than the capacity of OD.
- Need for more accurate MM due to ageing of equipment.
- More advanced optimization techniques requires more advanced management systems. [2]

"Pilot studies" of this evaluation concept were performed on Norwegian Shell, Elf Petroleum Norway, and Norwegian Hydro during the period 1997-1998, which was crucial in the development of the MM model [2]. It has also been several evaluations of MM later for further development. Among these there was a general study of the five companies Statoil, Norwegian Hydro, ExxonMobil, ConocoPhillips and Pertra in 2004 [3].

Quality in all parts of the MM system was important during the development of the model in the basic study, and maintenance systems are meant as a contributor for continuously improvement due to activities, products, services and identification of problems. There should also be focus on standardization of good solutions. Due to problem solving; improvement of work processes, proactive attitude, and "organization thinking" was key words. Work processes designed as quality loops should include all phases of a problem solving process [2].

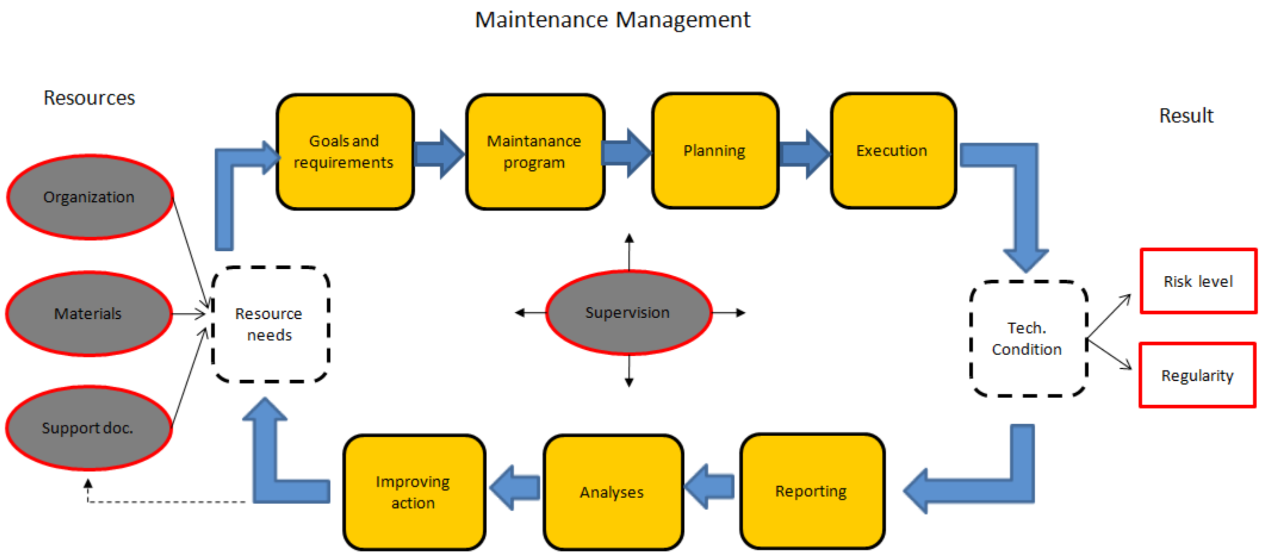

Figure 1 PSA's model for MM [2]

2.1.1 Explanation of the model

Safety related maintenance management is the superior process [2]. The main purpose is control over the resources (maintenance personnel, maintenance organization, materials and support documentation) and to achieve the desired result in terms of technical conditions, risk level and regularity. In other words a control-loop is a tool to get an overview of the facilities, systems, or part systems and secure that they are able to perform the required functions [2].

The first step is to establish goals and requirements, and then develop maintenance programs that fulfill the requirements. Then it's important that the maintenance is planned and executed according to the program. When the results are found they are reported back and analyzed, and improvements are implemented. Finally when all this activities are performed the control-loop is closed [3].

2.2 Introduction to Condition Monitoring

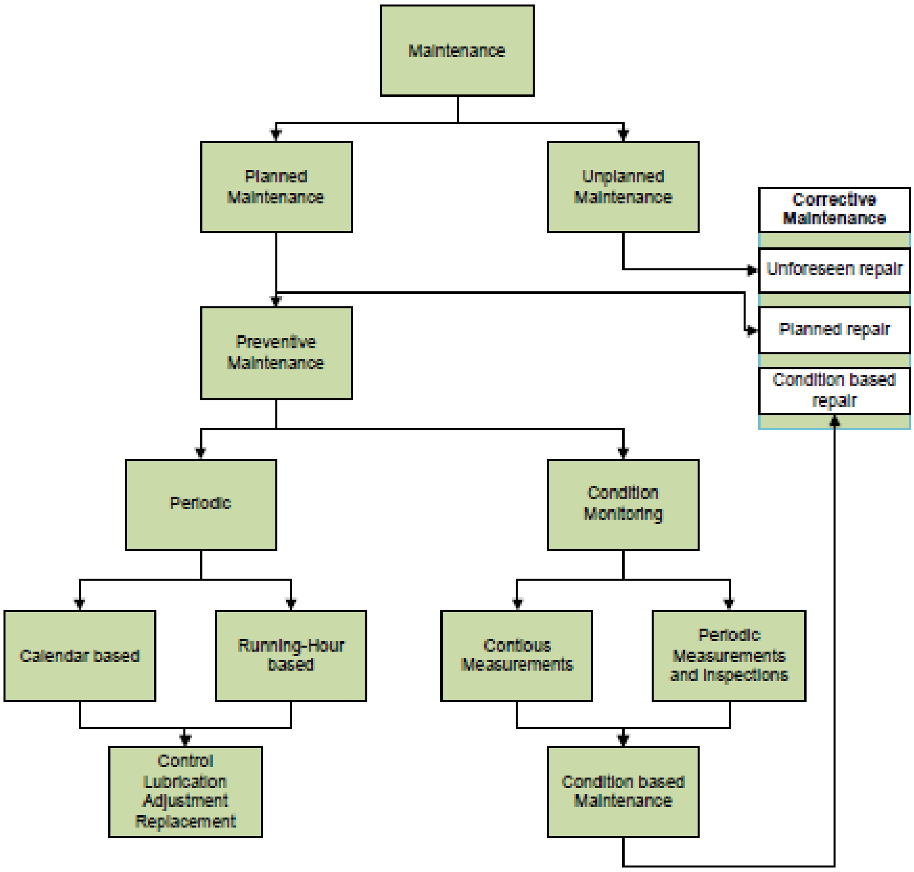

Figure 2 Maintenance types and control categories [6]

As shown in the figure above Condition Monitoring (CM) is a sub-group/ control category within preventive maintenance. CM can be defined as “The detection and analysis of developing faults early enough to prevent failure and limit loss” [7]. CM consists of continuous online CM, offline CM and inspections. Condition-based maintenance (CBM) is defined as “The preventive maintenance initiated as a result of knowledge of the condition of equipment observed through routine or condition monitoring” [8]. In the literature CBM is often mixed with the term Predictive maintenance (PdM).

2.2.1 Failure frequency distributions

There are three main categories of failure frequency distributions related to equipment in use in offshore process facilities and process plants in general. The first one is wear-out failure, which is typical for equipment in direct contact with the process medium causing corrosion and/or material fatigue. The second one is “running-in” failure. Here the probability of failure will be at the highest just after installation since some units have built-in defects causing failures after a short period of time. The third category is random failure. Here the reliability is the same with maintenance as it is without. Examples on that is typically a light bulb which usually fails without any warnings. A premise for CM and preventive maintenance in general is that the equipment type has a dominance of wear-out failure [9].

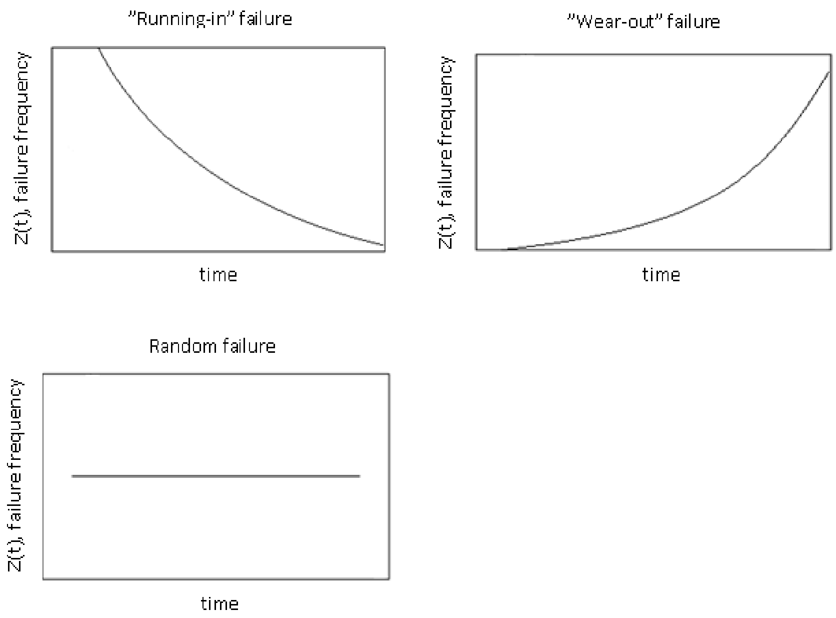

Figure 3 Failure frequency distributions [9]

2.2.2 Categories of CM

This is a brief version of the categories of CM presented in the project thesis [5].

Online Condition Monitoring gathers information through sensors without or with a minimum of human interaction. All data and information are usually gathered into a database. Each condition parameter is measured continuously which makes trending easier and more accurate. The cost of the online CM-equipment can itself be quite expensive, but reduced need of manpower on site will usually contribute with reducing the total maintenance costs. Online CM is today most used on rotating equipment with respect to vibration monitoring.

Offline CM requires to a larger extent human interaction when gathering data and information. The CM equipment here is less complex than online equipment, so the implementation costs are usually less. Collecting data is mainly done through use of an offline data collector which is basically a portable computer storing data. The data collector is connected to a sensor on the maintainable item, or the data collector itself has sensors mounted. Use of sensors mounted on the data collector can often give logistical benefits due to replacement of sensors and only needing to use one set of sensors for larger groups of equipment. However access to measuring points can often be restricted in periods due to workers safety, which requires sensors mounted on the equipment. Offline CM often requires the system or at least parts of the system to be shut down, so for critical systems this can be quite expensive.

Inspections has many similarities to offline CM but is more manually and labour-intensive. The inspection intervals are usually set based on a risk based inspection (RBI) program. Inspection activities can vary from simple checks with only use of human senses, to complex use of advanced technology. Some inspections can be performed during operation, while other inspection methods require shut downs of systems or sub-systems. [5]

2.2.3 Opportunity based maintenance

Opportunity based maintenance (OBM) is not a CM category, but a policy that says that preventive maintenance is carried out if an opportunity arise [11]. An opportunity in this relation means a situation that makes it convenient to perform preventive maintenance with respect to the availability of the equipment. Opportunities for maintenance can for instance arise from internal events such as planned maintenance on components nearby, breakdowns from sudden failures or natural production breaks. An opportunity can also arise from external events such as price fluctuations, weather conditions or waiting time for loading/unloading etc. [8], [12]

The reason for mentioning OBM in relation to CM is the possible beneficial results of combining them in some cases. The main reason for CM is as mentioned earlier to increase the time from a beginning failure is detected to the time is gets critical, i.e. to increase the length of the p-f interval. This increased insight in equipments condition can hopefully be used to perform detected needs for smaller preventive maintenance actions when opportunities arise.

3 CMs influence on the input and output parameters in the loop

The resources put into the MM model are the maintenance organization, materials and support documentation and the main purpose with the loop is an increased technical condition in form of safety and regularity. In addition reduced cost is a wanted benefit. Implementation of a new maintenance strategy will only be done if the company will get an overall benefit compared to existing maintenance strategy. It can be seen as an equation where the resulted benefits have to exceed the extra input costs. In addition there can be an economical benefit on the input-side due to a higher degree of control on equipment failures.

Experience from many production plants shows that implementation of a condition based/predictive maintenance program can provide huge benefits for the maintenance efficiency. According to [13] a survey of 500 plants that have implemented predictive maintenance methods showed huge improvements related to reliability, availability and operating costs. This survey revealed a reduction of more than 50 percent of the actual costs associated with maintenance operation. This comparison of maintenance costs included actual labor, actual materials cost of repair parts and equipment required to maintain plant equipment. Lost production time, variances in direct labor or other costs attributed to inefficient maintenance were not included in the analysis [13].

It has not been detected results from a similar study from offshore production facilities, and therefore it is a little dangerous to say that implementation of CBM/predictive maintenance will lead to the same dramatic improvements there. However there is a strong reason to believe that CBM will provide many of the same benefits offshore, since much of the equipment is the same and most CM methods can be applied also on offshore equipment.

3.1 Organization

Hopefully use of condition based maintenance can have a positive influence on the overall organization and the maintenance organization. Maintenance related cost, and especially downtime costs due to failures and unnecessary maintenance actions are often very costly for the companies, and forms a quite high amount of the total costs. In manufacturing for instance, the maintenance cost can constitute from 2 to 10 percent of the total revenue for a company. In the transport industry maintenance costs can be up to 24 % of the revenue, so cost-efficient maintenance is of high value [14]. In many heavy industries the maintenance costs may represent up to 40 percent of the total production costs [13].

If a company is able to perform more efficient maintenance to a lower cost, this will hopefully release money that can be spent in other parts of the overall organization.

As described in the project thesis [5] the maintenance organization focuses on requirements and practice related to work processes in addition to taking care of demands regarding manning, competence, training, prequalification etc. If the maintenance personnel to a larger extent are able to foresee when equipment will fail due to CM the work related to manning will be more predictable. At the same time there may be cost savings due to less emergency repairs generating high costs in form of expensive equipment (rush-ordering etc.), overtime-work and down-time of equipment.

The overall organization and especially the maintenance organization will on the other hand obviously influence the work related to CM. Responsibility, authorities and lines for reporting and communication have to be clearly understood and accepted among all connected to the maintenance function. All CM data needs to be transformed into useful tools for decision making. If the organization is not well-structured and the communication between the people connected to the maintenance function is not optimal this will probably influence the CM work.

Implementation of a new maintenance strategy will always lead to changes in the maintenance organization. A higher degree of CM will require more use of expert personnel. That will probably give a positive influence on the maintenance work itself but may also contribute negatively when it comes to salary-costs. Implementing a condition based maintenance (CBM) strategy will often require extensive training in the CM methods and the CBM methodology. The training costs will therefore probably increase compared to earlier. Design of work processes in general will probably be more advanced and demanding, but if the result is more efficient work-processes there are potential for benefits.

Dependent on the CM methods to apply and the in-house competence of the company, there is a question regarding use of in-house personnel or outsourcing much of the CM work. Here the economical perspective is important when it comes to decide either to assure enough of the wanted competence within the company, outsource or hire in expert personnel from another company, or a combination of the alternatives. If the company needs to hire in contractors for CM work there might be less freedom of choice related to prequalification if a limited amount of the contractors in question holds the wanted competence regarding the CM methods to use. This could be an advantage for the contractor which can increase the price-level for the services, but a disadvantage for the company which to a less extent can set the premises.

For companies with limited resources, lack of qualified personnel can cause problems if they can't afford either permanent appointments or hire in personnel from other companies. Then "tearing" on qualified personnel could be a consequence which could result in tired and unmotivated personnel. [2], [5]

3.2 Materials

Material handling is a very important area within maintenance management. To assure that the company has the correct materials for a given operation with the required quality is very important with respect to safety and economics.

According to [14] there are six key points when it comes to managing materials and spare parts:

1. Effective coordination between maintenance and stocking policy to minimize ordering, holding and shortage costs.
2. Effectively coordination with suppliers to maximize organization benefits.
3. Safe keeping of all supplies.
4. Maintain and update records.
5. Keep the stores orderly and clean.
[14]

Seen from a maintenance perspective the most important aspect within materials is Supply support. It is essential from an economical point of view to have a satisfactory level of spare parts for all critical equipment for avoiding expensive downtime of systems. Supply support includes all spare/repair parts and all associated inventories. Among spares we have repairable units, assemblies and modules etc. Repair parts means parts for replacement of non-repairable components. In addition supply support covers consumables (liquids, lubricants etc.), special supplies related to maintenance, computers and software, test and support equipment, equipment for handling, transportation and training and related documentation [15].

Especially on offshore platforms where storing costs are high due to limited storing capacity and the time it takes to transfer equipment from onshore to offshore is long, having the required spares and associated equipment when needed is absolutely essential. The cost of a stop in production can in many cases be incredibly high, so even small periods of lost production can cause a large economical damage.

The Lead time, i.e. the period from a demand for a spare item occur until a recovered item is installed and ready for use depend on many factors and it is necessary with accurate evaluations regarding where to repair and store equipment. If critical equipment suddenly fails and the company needs resupply from onshore due to lack of spare parts, the lead time can take several days in some cases. Therefore evaluating various repair and storing alternatives will be important [16].

Condition based maintenance will hopefully with proper use and good routines with respect to handling of equipment data ease the work with ordering materials and spare parts within time. Especially materials and spare parts for rotating equipment will be easier to handle since methods for condition monitoring and the condition based maintenance methodology have been utilized for a long time on this equipment. SKF (Svenska kullagerfabriken AB) is one of the most the most experienced companies when it comes to CM of bearings and other rotating equipment. They claim that condition based maintenance has huge potential for optimization of costs and work load, increase the reliability of equipment and discover failures earlier than with use of ordinary maintenance based on statistics. This will gives huge benefits when it comes to reduce storing costs and avoid revenue losses as a consequence of spare shortage if the company manages to keep the cost of condition monitoring itself at a moderate level [17], [18].The survey done in [13] showed that the ability to predict equipment failures and the specific failure modes in average reduced the inventory of spare parts by more than 30 percent, because of the increased lead time to order spares [13]. Also on static equipment CM will hopefully give some of the same benefits as on rotating equipment, but the CM methods have not come so far in the development here as it has for rotating equipment.

The most important factor related to condition monitoring is the p-f interval. The p-f interval is the interval from detection of a potential failure until the failure is critical. The length of the p-f interval is particularly important when operating offshore because of the long lead time for supply from land. As mentioned earlier a company can save costs from reducing the spares stored offshore, but there will always be a degree of uncertainty with the CM method which makes “under-dimensioning” of the spares risky even if the order-period of spares is accurate. If the uncertainty lay’s in other areas than in the failure identification-process, the CM work can in some cases be superfluous. For instance to use a lot of resources to detect a 2 day’s p-f interval if the lead time varies a lot because of marked variations, will for instance be quite wasteful use of time and resources.

Since condition based maintenance only wants to perform maintenance actions when its needed (based on the measured condition), the maintenance costs, and thereby material costs, will from year to year will probable vary a little more with CM than it will with use of a standard periodic maintenance.

3.3 Support documentation

It's important that both technical and administrative support documentation holds the wanted quality, availability and updates. Support documentation can be registers for equipment history, drawings (P&IDs, flowcharts etc.) and maintenance procedures. Data from both on –and offline measurements should be a good help with respect to trending and keeping track on equipment history, but will probably at the same time increase this work load related to support documentation.

It's important with good routines for updating all documentation. All relevant support documentation needs to be available and easy to understand for the responsible personnel for the maintenance actions and the personnel that perform the actual work. A database system with a user-friendly interface for document handling will be an important tool to save time when it comes to preparation of the CM actions. A database with accurate equipment data and history will provide useful input to SAP or other computerized maintenance management systems (CMMS).

More advanced technical documentation can be difficult to combine with readability and comprehensibility. This requires a higher level of competence from the personnel. "Overflow" of data may cause a lot of extra work related to the procedures and documentation and "rush-errors" might occur. The documentation cost will then increase if a higher amount of working hours and personnel has to be spent on this. The drawings and procedures related to CM needs to be correct and as easy as possible to understand since most human errors in the CM work can lead to huge costs and spoil the benefits of CBM. Implementation of CBM as a strategy will probably in many companies lead to an increased cost related to training of the employees. [2], [5]

The increasing use of integrated operations (IO) is also a helpful supplement when it comes to interaction between the different personnel connected to the maintenance function. Today all oil-fields are driven interactively. Maintenance personnel on-and offshore can discuss procedures and data through monitors which add a more human element in the communication, and any misunderstandings regarding procedures and documentation for CM work are easier to clarify [19].

3.4 Technical condition

One of the main purposes with maintenance management is to increase the technical condition of the equipment. That means that the company's maintenance related goals are to decrease the risk level and increase the regularity. Of course cost-effective maintenance also has a high priority but a safe work-environment for the employees, and focus on environmental issues should always be prioritized the highest.

In traditional periodic maintenance the intervals are set on basis of statistics for what kind of failures that may occur, and when they usually occur. By choosing this strategy the degradation status of the equipment is unknown and it's hard to predict a failure before it actually happens. Possibility for noticing beginning and potential failures on safety critical equipment before it gets critical is the most important aspect within CBM. Hopefully many earlier accidents could have been avoided or at least reduced with proper use of condition monitoring. The greatest probable benefits as a result of proper use of a CBM strategy are improved availability of equipment and enhanced equipment life. [5], [20]

According to the survey made in [13] regular monitoring of the actual condition of process machinery and systems reduced the amount of critical, unexpected machine failures by 55 percent on average. The survey also indicated that an approximately 90 percent-reduction can be achieved through regular monitoring of machine condition in the future. Mean time to repair, MTTR, was reduced on average with 60 percent mainly because of the ability to predetermine specific repair parts, tools and labor skills needed.

When it's possible to get a constantly or partly constant overview of the equipment condition a huge amount of time and money can be saved due to avoiding unnecessary maintenance actions. Maintenance actions can sometimes itself be a source to failures because of faulty procedures, wrong adjustment, damage on parts and damage during the maintenance action. Especially if the maintenance work is a "rush job" due to avoiding expensive down-time of equipment, the probability for introducing new failures increases. Therefore being able to reduce unnecessary repairs is very useful. By implementing more extensive use of CM the equipment/components can be repaired or replaced when it is needed, and not because of predefined intervals or procedures. [20], [21], [8]

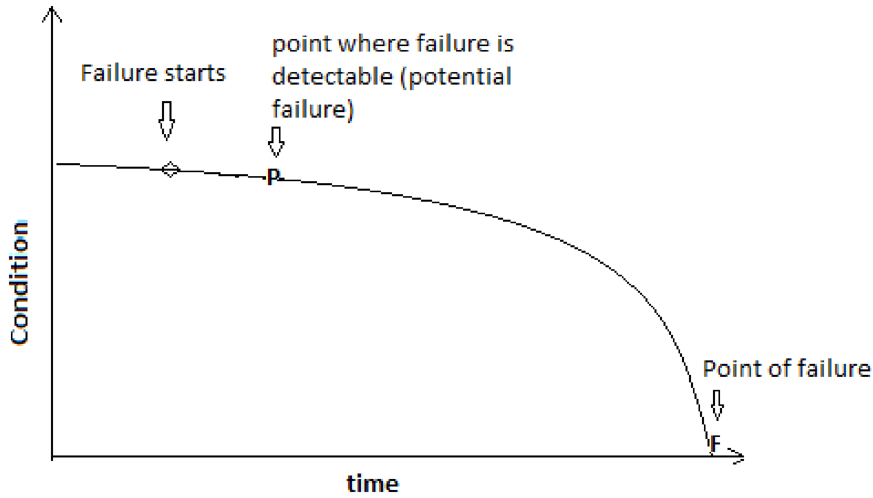

Figure 4 P-F interval [22]

The main reason for utilizing condition monitoring is as earlier mentioned to increase the time from a potential failure is detected to the point of failure. This "warning time" is called a P-F interval. Through various inspection and monitoring techniques abnormal equipment behavior usually can be detected earlier than the human senses are able to, and efforts can be made before the failure gets critical. Possibilities for good decision-making and plan actions usually increase the longer a P-F interval is, and with that the financial and safety impacts on the organization usually will decrease as a cause of the increased planning time. [22]

In the earlier mentioned survey [13] early detections of machinery-and systems problems and prevention of catastrophic failures increased the useful operating life of the plant machinery with 30 percent in average. This was achieved through five years of operating following implementation of a predictive maintenance program. In the calculation frequency of repairs, severity of machine damage, and actual condition of machinery following repair was included. Easier monitoring of Mean time between failure, MTBF, will also be a useful side-benefit with predictive maintenance. This gives the company a better opportunity to provide more cost-efficient maintenance and replace equipment when the maintenance costs exceed the replacement costs. Also the average availability of the process-systems for the 500 plants was in average increased by 30 percent. This improvement only included machine availability, and not potential increased process efficiency. Condition based/predictive maintenance can also provide other benefits related to equipment condition such as better verification of the condition of new equipment (purchased-condition), verification of repairs and rebuild work, and product quality improvements. [13]

In the literature mostly the benefits with CM has been enlightened. Still there can be possible disadvantages with relying the technical equipment only on CM. First of all it's important to secure a highest possible reliability of the CM-method. If the method is not able to detect the potential degradation mechanisms, this may lead to a "false security" and failures can lead to potentially severely impacts with respect to safety and/or economy if it is not detected before it gets critical.

It's important to understand that collecting a lot of equipment data itself not necessary will lead to a positive result in technical condition and equipment reliability. The key point to perform a successful CM strategy is to be able to read and analyze the data so that good decisions can be made. One typical failure many companies do is to buy a lot of costly monitoring equipment and collect large amount of data, but then the data are misinterpret and not used in a correct way. [21]

Regularity in this context means to be able to achieve results as close as possible to the goals and requirement and expected results. Here CM hopefully will provide generally improved predictability due to the increased "warning time" for potential failures. Also here the reliability of the CM methods, and interpretation process of data have to be taken closely into consideration.

3.5 Sum-up of Pros. and Cons.

A sum- up of the possible pros. and cons. of CM related to the input and output parameters of the loop are done in the table below.

	Potential Pros.	Potential Cons.
Organization	- Potential cost savings (less emergency repairs, overtime etc.) - Increased predictability will ease the manning work. - More use of expert personnel. - Potential increased safety for personnel. - Generally more planning opportunities. - Reduced time consume/costs due to unneccesary repairs.	- more comprehensive training with related costs and time consume - Work processes may be more advanced and demanding. - Potential for "tearing" on expert personnel if the capacity is limited within organization. - Less freedom of choice related to prequalification of contractors.
Materials	- Decreased risk for spare shortage. - Potential for reduced storing costs. - Increased planning predictability - Less chance for ordering unfeasiable spares and equipment in general due to increased planning time.	- Cost of Monitoring eqipment - Possible cost savings related to materials depend on the reliability of the CM method(s). - Company vulnerable if there is uncertainty in other areas, for instance in lead time from supplier. - Material costs due to CBM may vary from year to year.
Support Doc.	- Easier to keep track on equipment. - Better trending possibilities. - Coordination with SAP or other CMMS systems makes acess to dokumentation better.	- Technical documentation may become more advanced and comprehensive. - potential for "overflow" of data and procedures. - Potential for increased documentation costs.
Tech. Cond.	- Improved equipment reliability and availability. - Reduced risk for accidents/unwanted incidents - Failure detections at the ealiest possible stage. - Less chance introducing new failures through "unneccessary" maintenance actions. - Less chance for corrective "rush jobs" - Potential for enhanced Equipment life. - Generally improved predictability.	- Reliability of the CM method(s) - Failures due to misinterpretation of the CM data etc. - Time consume and costs related to CM.

Table 1 Potential pros. and cons. for CM

4 CM related activities in the PTIL loop

All processes in the PTIL maintenance management loop have to be taken care of with the required level of quality to obtain good results in form of increased technical condition and lower maintenance costs. This model for maintenance management is a general model and a change from traditional maintenance strategy to CBM leads to new challenges in all parts of the loop. Here some of the CM-related activities in each step of the loop will be discussed and presented.

4.1 Goal and Demands

This part of the MM loop deals with work processes for converting superior rules, regulations and goals into maintenance-related goals and demands. A company always has a lot of stakeholders, i.e. organizations or groups that influences the company. The main focus with this "box" in the MM-loop related to CM is to combine the different goals and demands to decide what kind of superior CBM-regime to implement and build upon. According to [23] a general list of stakeholders and examples of requirements for a large company could be:

- Authorities: Lots of general safety requirements.
- Owners: profit, HSEQ
- Management: profit, availability of equipment, HSEQ
- Customers: regularity.
- Competitors: unknown.
- Alliance partners: regularity.
- Environment: HSEQ
- Employees: Work environment, regularity with respect to work-agreements and salaries.
- Financial institutions: regularity with respect to capability of paying loans etc.
- Suppliers: Regularity.

All these stakeholders have their requirements and wishes for the company. How to perform a stakeholder analysis will be presented later on in this report. [23]

Regardless of what kind of maintenance strategy a company has, it is necessary to develop measurement parameters and control parameters for maintenance. Such parameters could be availability and technical condition of equipment, MTTR (mean time to repair, i.e. the average repair time), rate of postponed maintenance etc. In addition it is important to develop long-and short term safety-related goals, and specification regarding incidents required to be reported. [2], [5]

Specific activities related to CM could be goals for how large parts of the plant to perform online monitoring on (continuously monitoring) vs. offline monitoring and periodically inspections. Sometimes the management also may have requirements for specific CM methods. An example for this can be that all rotating equipment shall be monitored with vibration monitoring, or that for instance 70 percent of the plant/production facility have to be maintained through CM methods. There should also be requirements for how to perform the maintenance actions, and safety procedures related to the specific type of CM method based on risk analyses. For instance there are different safety aspects to take into consideration when performing Gamma monitoring then when performing Acoustic monitoring or oil analysis because of gamma radiation.

In addition to goal and demands related to safety and the technical condition of equipment it is always important for a company to keep the maintenance costs at a moderate level. Costs should always be seen in a life cycle perspective, but often high cost over a short period of time can be a problem. Investing in a lot of expensive monitoring equipment at the same time can be problematic for companies with limited investing possibilities. Probably the owners will set different goals and requirements for cost saved with CM compared to the old strategy for a given period of time to reduce the total maintenance costs.

The goals and demands are principally on a superior level, and specific goal and demands for all levels will not be focused on. However the head of the maintenance organization can state superior requirements for the processes in the loop. This could for instance be that all information related to the condition based maintenance must be implemented in SAP (common term for ERP programs delivered by the German company SAP). Gathering all data and information in SAP solutions with a user-friendly interface will generally ease the work related to trending, analysis and decision making. A goal towards the maintenance organization can for instance be that 80 percent of the CM work should be performed by the company's own personnel, to secure competence within the company. [2], [5]

Summed up the main activities within this process will be:

Main activity: To decide a superior CM-regime according to goals and requirements.

- Gain insight on goals and demands from related stakeholders.
- Developing superior measurements and control parameters for technical condition, safety, availability, and costs.
- Risk classification of systems and equipment to decide which systems that needs to be focused most upon related to CM.
- Cost-benefit
- Developing and distribute superior goals and requirements for other processes in the loop.

4.2 Maintenance Program

This part of the MM loop focus on work processes for development, updates and improvements regarding programs for preventive maintenance, inspections and condition monitoring etc. The main purpose with the maintenance program is to organize the maintenance work and find the best possible "road" for fulfilling the goals and demands.

In this context development of condition based maintenance (CBM) program will be focused on. To be able to develop an effective CBM program a lot of important processes and activities needs to be put efforts on. A CBM program usually consists of online continuous monitoring, offline condition monitoring, periodically inspections and corrective maintenance actions. There should be systematic criticality classifications based on risk analyses to separate critical systems and equipment from uncritical to decide which systems or equipment that needs the highest degree of CM. Since full RCM analysis on all equipment will be very demanding and expensive, the company should be able to develop methods and instructions for identifications of equipment that needs full RCM.

The company needs to make clear which equipment types that will be object for continuous online monitoring and which that will be object for offline CM and periodically inspections. Decisions regarding suitable CM methods for different equipment should also be made based on analyses on the most critical degradation mechanisms. [2], [5], [9]

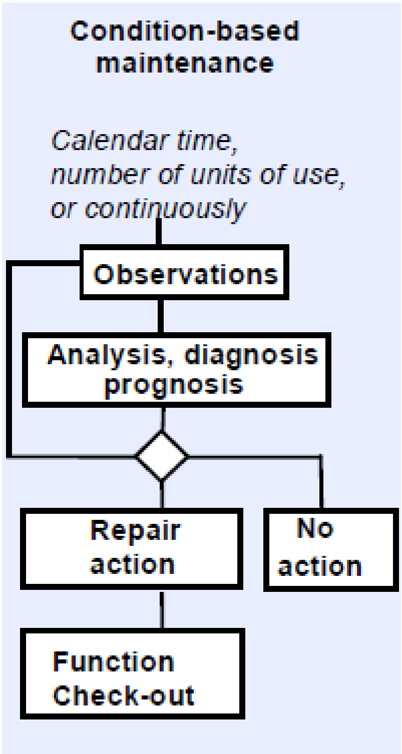

Figure 5 CBM [20]

In addition a CBM program should include a distribution of resources (competence, time, tools etc.), procedures for registration of failure-data and trending, program for preservation of equipment, areas of responsibilities, handling of updates and quality-checks of the program. [2]

Summed up the main activities regarding the Maintenance program will be:

- Further Risk classification of equipment and systems.
- Decisions regarding CM methods to use for various equipment types.
- Decide intervals for CM, inspections etc.
- Provide as accurate as possible the logistic needs related to CM actions and inspections.
- Preliminary scheduling of CM actions with related distribution of resources.
- Develop procedures and documentation for the CM activities based on the goals and requirements.
- Programs for preservation of equipment out of operation etc.
- Continuously evaluation and updating of existing CM- and inspection programs.

4.3 Planning

Planning is an essential process that needs to be done properly in all parts of an organization. The reason for planning maintenance activities are among others to make the maintenance activities as safe as possible, control of the resources and equipment and to get an overview on costs related to different activities. There are three main groups of planning of maintenance activities: Long term planning (2-5 years), short term planning (months and weeks), and coordination of work orders and daily operation.

The range of the long term maintenance planning is usually 2-5 years. It's important that the maintenance units get involved in the company's superior long term planning. In a CM perspective there are many activities in long term planning:

- Planning according to the maintenance strategy. How to implement the decided CM methods on different equipment types and optimal intervals for CM actions and inspections.
- Planning of distribution of resources needed, and budgeting of coming maintenance activities based on a life-cycle perspective.
- Prioritizing of systems/equipment to focus on based on risk levels and time limitations.
- Integration between the disciplines to schedule against constrains and handle possible resource conflicts. A plan that shows the number of hours of CM actions in all parts of a plant over a certain time span will give the responsible personnel for the production time to schedule to reach the production demands.
- Planning of how to collect, handle and analyze the CM data in accordance to the CBM program.
- Areas of responsibility.

The short term plans are basically revised versions of the long term plans. Here the tasks are to update with more accurate information about the CM work, since the maintenance crew usually can't depend totally on the original long term plan because of different unforeseen events. Work orders are too specific to prepare in the long term plans because of lack of limited information about the specific case. Therefore they have to be prepared more closely to the point of maintenance action. On a short term basis the activities related to CM are among others:

- Detailed planning of when to perform CM actions, time consume and ranking of priorities.
- Detailed planning of the personnel, tools and resources needed for the respective maintenance actions.
- Preparation of work orders. Create a detailed description of what to be done in the specific task included the risks involved (Safe job analysis) and related documentation.
- Distribution of responsibilities. [24], [2], [25]

4.4 Execution

The execution of the CM work will be different dependent on what kind of action to be done. For equipment types that are object for online condition monitoring data are collected continuously by sensors into a database. The work load here is mainly to analyze the data collected over a certain period, analyze the trends and decide when to make a preventive or corrective action.

Equipment object for offline CM will require more human interaction when performing the CM. Here the system or at least parts of the system often needs to be shut down during the CM action. An offline data collector is mainly used here, which is basically a portable computer storing data. Then the data is being collected from a sensor on the item or the data collector itself has sensors mounted. Then the workloads consist mainly of analyzing the trends of the measurement parameters, and schedule preventive or corrective actions.

Equipment object for inspections are often the most labor-intensive within CM. Inspections usually requires more preparations, work hours and after work than both online and offline CM. How much work there is related to inspection depend on the equipment and the inspection method to use. Usually the equipment and at least parts of the system needs to be shut down during the inspection. Preparations for an inspection can for instance be stripping of fire-insulation when performing Neutron backscatter on a pressure vessel, and safety preparations when performing Gamma Monitoring. Then the inspection is performed, data collected and compared against data from earlier inspections, and a decision regarding what to be done in a preventive or corrective action perform is made based on analyses.

Generally for a CM action or inspection which requires preparations and human interaction, the activities to be done are:

- Going through the procedures and documentation.
- Going through risks involved and perform Safe job Analysis.
- Prepare the work areas for the CM action, and prepare all needed equipment and resources.
- Perform the work (mount the monitoring equipment and start CM or inspection)
- Clean area, mount dismounted parts and make the equipment ready for operation.
- Analyze data and decide equipment status. Schedule ideal time for preventive or corrective maintenance. [2], [5], [10]

4.5 Reporting

After all CM work or inspections there must be procedures for reporting of the results. The reports from the CM actions or inspections should include:

- The equipments operating status and availability including component availability.
- A work list based on priority. It should include completed work, work in progress and work pending.
- Definitions of satisfactory, marginal and critical status.
- A summary of each components operating status from the uncritical components to critical.
- Individual reports for the most critical equipment.
- Recommendation on possible intervention, and when it should be done based on criticality. [20], [2]

Work orders for preventive or corrective maintenance actions are thereafter developed on the basis of the performed CM activities. After each repair reporting of what that have been done, time consume, costs and any incidents or unexpected events among others should be performed.

All production plants should provide periodic reports on the Condition based maintenance. The periods should be at least once a year. The primary functions for this periodic report are to all involved (maintenance, engineering and operations) in addition to showing the impact of condition based maintenance to the upper management. According to [20] the condition based periodic report should include:

- *Management summary*: Highlights of the activities performed during the period.
- *Equipment performance*: List of equipment that indicates degraded or abnormal behavior. Here there are often used alert or watch lists.
- *Information sharing*: A section used by the condition based maintenance personnel for explanations regarding the program.
- *Cost-benefit*: Cost savings associated to CBM activities.
- *Continuous improvement and operating experience*: Discussions on new technologies, training activities and experiences that have or should be implemented in the program. [20]

4.6 Analysis

This process is about analyzing the outcomes of the CM work written in the reports. Here the essential part is to understand the reasons for unsatisfactory results to start the improvement process. Activities here can be:

- Analyzing the measurement parameters when goals and demands for risk level, regularity and safety are not fulfilled. Investigate the decision basis used when taking decisions with respect to maintenance and logistics, and check the correlation between predicted technical conditions on critical equipment against actual technical condition. Here is important to check the reliability of the predicted P-F intervals.
- Cost-benefit: Do the benefits from CM activities justify possible extra costs? Analyzing what that can be done to decrease cost level.
- Analyzing reported unwanted incidents or accidents.
- Analyzing lines for communication, distribution of responsibilities, and availability of reports and user friendliness of the maintenance database system.
- Evaluate the company's "toolbox" for various analyses.
- More efficient distribution of resources. [2]

4.7 Improving Action

Focus on work processes for initiating, carrying out and follow up improvement efforts. The improvement efforts are mainly based on the analyses performed in the Analysis-process described above in addition to problems detected in the overall supervision process. The activities here can be:

- First concentrate on the most critical problems from the analyses. These are often critical measurement parameters for the technical conditions of different equipment. Usually the analysis process has detected causality for the problems or degradation mechanisms, and now it's time to investigate how it's practically possible to reach improvements.
- Create a plan for improvements including distribution of responsibilities and resources. This can be in a long term perspective or near future.
- Carrying on with the improvement work.
- Following up the improvement work trough further monitoring and control. [2]

4.8 Supervision

Work processes for planning and carrying out supervision with respect to own organization, contractors, owners of the installation, and suppliers etc. Control tasks included in the maintenance management's responsibility for daily operation are not included in the supervision. Types of supervision can be revisions, verification, inspections and self evaluations etc. Activities here can be:

- Establish or following up established goal and demands for supervision towards the maintenance function. This includes extent and frequencies of revisions of the MM system and technical systems.
- Create a balance between technical - and system related supervision. [2]

5 Tools for analyses

Here the report will discuss various tools for analyses connected to the processes in the maintenance management loop. The purpose with the analyses is to support the activities in each process and ease the work with decision-making.

5.1 Reliability Centered Maintenance (RCM)

5.1.1RCM introduction

According to [9] there are mainly two types of organizational adjustments for maintenance, *Repair-focused organization* and *reliability-focused organization*.

A premise for an efficient maintenance organization is a reliability-focused maintenance organization which has a point of view that equipment failures usually should not occur, and that there is lack with management, strategy and management-focus if failures occur.

A Repair-focused organization on the other hand bases the maintenance management on the view that equipment will fail, and that the organization's main task is to react quickly for repairs. Such focus will provide the maintenance personnel with a lot of repair actions and a minimum of time for investigating causes for equipment failures. A repair-focused organization usually provides lower efficiency in the maintenance work than a reliability-focused organization. [9]

Reliability centered maintenance (RCM) has for a long time been a useful method for the reliability-focused maintenance organization for developing an effective Preventive maintenance (PM) program. RCM was initially developed by the airline industry in the late 1960's. Later in 1984 the Electric Power Research Institute (ERPI) introduced it for the nuclear power industry. The following definition used by ERPI was: "*Reliability centered maintenance (RCM) analysis is a systematic evaluation approach for developing or optimizing a maintenance programme. RCM utilizes a decision logic tree to identify the maintenance requirements of equipment according to the safety and operational consequences of each failure and the degradation mechanism responsible for the failures*". [26]

There are today many versions of RCM with different names. Examples of these are Lean RCM, Streamlined RCM, Reversed RCM, RCM2 and MSG3 (Maintenance Steering Group). The basic principles are more or less the same in all of them, but there are different areas of main focus for the different methods. *Lean RCM* is often used in early design phases when the amount of information is relatively limited, and is done to detect the coarsest shortcomings and provide a preliminary estimate on the extent of maintenance. *Streamlined RCM* and *Reversed RCM* focus on existing plants where a total revision of the maintenance program is desirable. Then the existing maintenance program is used as a basis for further adjustments through the RCM principles. *RCM2* is a general method with standard schemes independent of application area, and MSG3 is the RCM procedures related to the civil aviation industry. [9]

The reason for mentioning RCM here is that it can be seen as a decision tool that can be used through all the processes in the MM loop. In figure 5 below the main steps of an RCM analysis is shown.

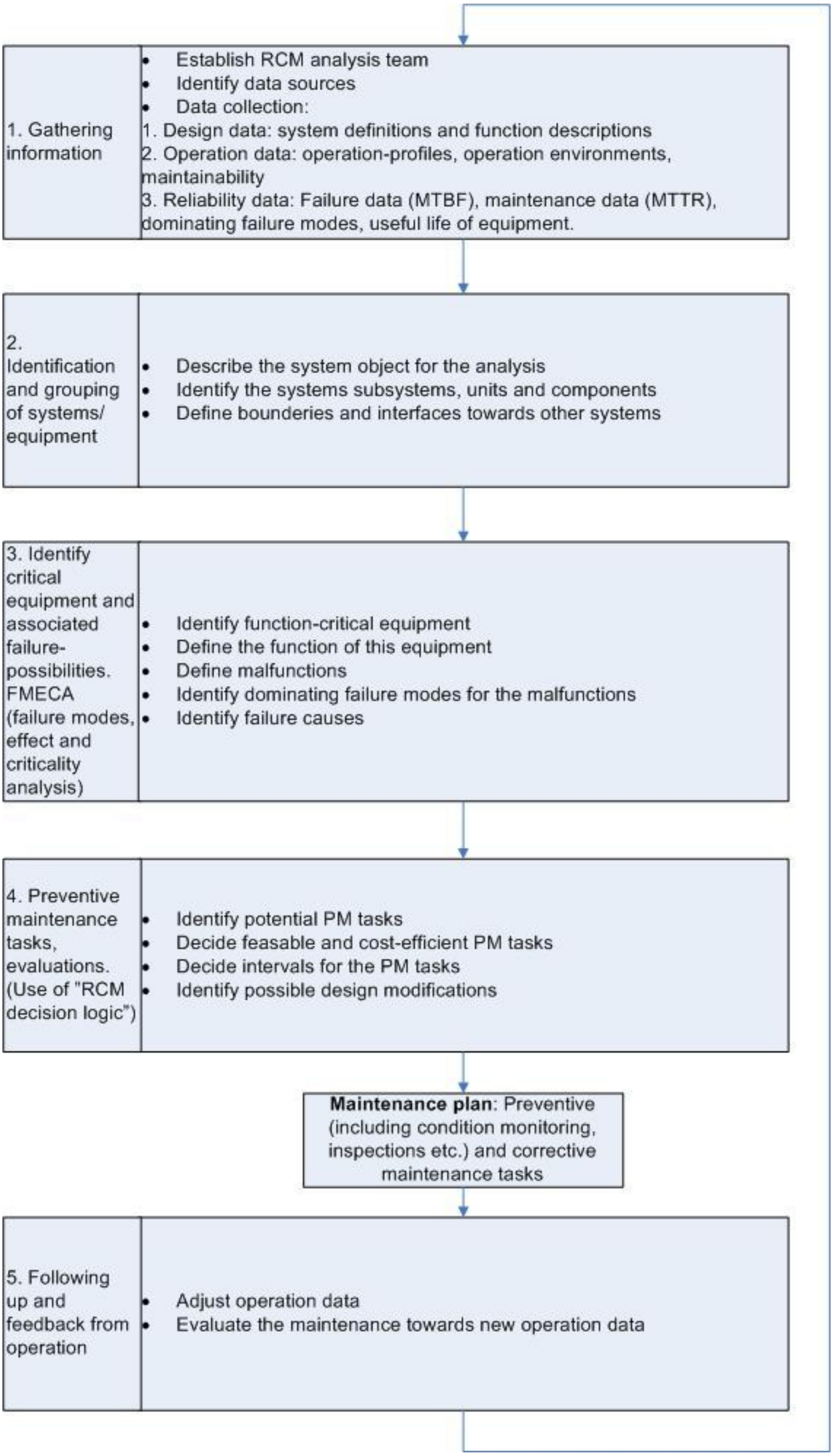

Figure 6 RCM flow [9]

5.1.2 Steps in RCM

Here is a short explanation of the main steps in the RCM analysis. Due to the extent of the report, only a brief explanation will be given.

1. Gathering information

First there should be established a RCM team consisting of both personnel from operation and maintenance to secure a wide extent of knowledge. In general the data that should be collected are design data, operation data and reliability data. Required documentation for carrying on with the activities in figure 4 will vary depending on the system/equipment to be analyzed, but in general system drawings (P&ID's etc.) showing system structures and equipment-function coherences will be necessary. In addition system descriptions and earlier failure data for the system in question will be useful basis for the further work in the RCM analysis. Good system understanding and knowledge regarding the equipments functions, consequences with loss of functions, potential failures, failure causes and how to detect potential failures will be necessary. [9]

2. Identification and grouping of systems/equipment

Data and information collected in step 1 are then worked through for each system. All equipment belonging to a system is then grouped based on predetermined grouping systems for the plant. These grouping systems are usually so-called Tag number systems. Variances in Tag number systems from one company to anther can however cause problems with the data processing from operation. [9]

3. Failure modes, effects and criticality analysis (FMECA)

Originally FMECA was developed by the National Aeronautics and Space Administration (NASA). It was put into use related to space program hardware to improve and verify the reliability. FMECA is in fact two separate analyzes put together, the Failure Mode and Effect Analysis (FMEA) and Criticality Analysis (CA). [27]

The prime goal with an FMECA is to uncover relations between causes and consequences in addition to be able to separate critical equipment failures from uncritical equipment failures. The resulting FMECA gives a set of critical and uncritical equipment failures. One central aspect with an FMECA is risk matrix. A risk matrix is based on criticality which is the product of consequence of an event multiplied with frequency the event. Criticality is usually measured after the following criteria's: safety, environment, availability and costs. Preventive maintenance should be performed on the equipment classified as critical, while uncritical equipment often can be repaired when failures occur (planned corrective maintenance). [9]

Performing a preliminary FMECA already in the design phase of systems will probably be beneficial with respect to decide equipment/systems need for maintenance and support package. The FMECA methodology is shown in the figure below.

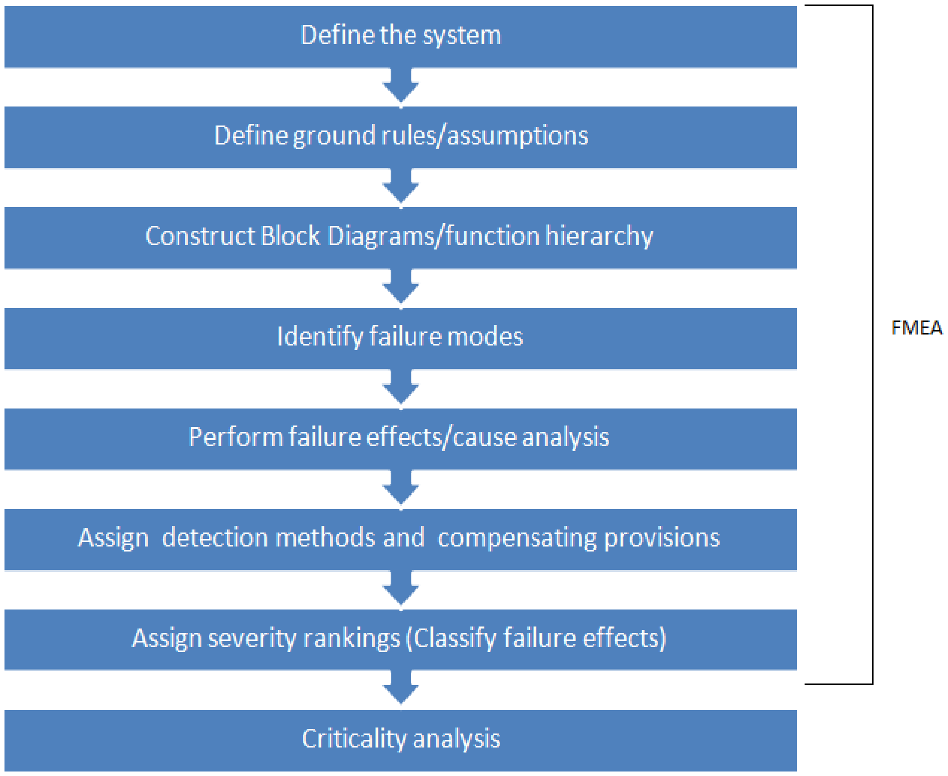

Figure 7 FMECA flow [27]

4. Preventive maintenance tasks and evaluations

Here "RCM decision logic" should be performed on the equipment detected as critical according to one or more of the four criteria's. The decision logic is usually given as a question-answer process where the purpose is to find cost-efficient preventive maintenance methods. Feasible preventive maintenance can be periodic maintenance based on intervals or various condition monitoring methods. If there is not a cost-efficient and feasible preventive maintenance method available for the equipment it can be included in the planned corrective maintenance if the risk can be accepted. If the risk cannot be accepted redesign is often the only solution. Sometimes redesign can be beneficial with respect to reducing costly maintenance and increase the reliability. After this step in RCM a maintenance plan is provided with suitable preventive and corrective maintenance task and intervals. [9]

5. Following up and feedback from operation

This is the last step in the RCM process. Here it's basically just to follow up the decisions made in the maintenance plan and collect new operation data. All documentation affected by changes from the RCM process needs to be updated and adjusted. Then the RCM analysis team needs to evaluate the maintenance towards new operation data to see if the changes made have been beneficial. Then there is given feedback to step 1 and the RCM process can be performed one or more times if needed. [9]

5.2 Relations between RCM and other techniques

There are several methods/techniques in use which have strong relations to RCM. Here a short description of these methods will be presented:

5.2.1 Risk-based Inspection (RBI)

Risk-based Inspection is defined as "a decision making technique for inspection planning based on risk – comprising the probability of failure and consequence of failure" [28]. It is a systematic method for determining inspection-types and intervals of components and structures. The goals are to increase the safety and reliability, and to reduce the costs. The method focuses on the most critical areas, and tries to increase the quality of each inspection to be able to reduce the frequency of inspections without any safety or economical negative consequences. RBI is most popular within the nuclear power industry and the oil industry. RBI is quite similar to RCM in the methodology but focuses on finding the best inspection-strategy, instead of focusing on the overall maintenance strategy. Non-destructive testing (NDT) and Non-intrusive inspection (NII) techniques are central in RBI to provide information on the equipment without causing down-time. [9], [28]

5.2.2 Fault tree Analysis (FTA)

A fault tree analysis is a technique developed for reliability evaluations of complex systems. This failure analysis is a top-down approach initiated by a top event which usually is a hazard event/accident detected during the FMECA step in RCM. Also block diagrams like event trees from the FMECA step is essential input. The analysis determines how the top event can be caused by lower level events through logic gates. Since the fault tree analysis is a very deep going and time-consuming process it should only be used on the most critical and complex structures. [9], [29]

5.2.3 Reliability, Availability and maintainability (RAM) analyses

RAM analyses are often used early in design phases for evaluation of various technical solutions/systems to implement. Input parameters for a RAM analysis can be among others capabilities, failure rates, consequences of failure, spares, mobilization times, supplies of utilities and resources and system operating rules. The outcomes of a RAM analysis are usually estimates for productiveness, spare part consumption, repair resource requirements and repair strategies etc. [9], [30]

5.2.4 Life Cycle Costs (LCC) Analyses

Life cycle cost calculations are often utilized when evaluations and ranking of priorities are about to be done in design-phases. Getting accurate data foundation, and especially accurate maintenance needs, for LCC analysis can often be a challenge. By applying the RCM method in combination with LCC analysis, results from RCM can be utilized directly in LCC evaluations securing cost-efficient decisions to be made. More information regarding LLC directed towards maintenance management and condition monitoring will be given later in the project. [9]

5.3 RCM and CM

Related to CM RCM can be a useful tool to provide efficient utilization of CM methods. It was revealed from [31] that CM in many cases in the industry is treated as an end product rather than a possible function preservation tool. One example on this involved a plant that used large fans during their production process. The maintenance engineers on the plant told that they used vibration analysis to tell them when the fans need cleaning. Still the fans where shut down every 6 months to clean them. This is a good example of "double work" which plants should try to avoid. There were detected four key questions regarding CM that RCM may provide an analytical answer on:

1. "How does one decide which of the many CM technologies to use?"
2. "How often should a CM technology be applied? "
3. "Is continuous CM worth the investment? "
4. "How good are the CM technologies at detecting the onset of failure?" [31]

According to [31] the Society of Automotive Engineers Surface Vehicle/Aerospace has provides a RCM standard, SAE JA1011, which gives following criteria for technical feasibility of a CM task:

1. "There shall exist a clearly defined potential failure".
2. "There shall exist an identifiable P-F interval".
3. "The task interval shall be less than the shortest likely P-F interval".
4. "It shall be physically possible to do the task at intervals less than P-F interval".
5. "The shortest time between the discovery of a potential failure and the occurrence of the functional failure (the degradation interval minus the task interval) shall be long enough for predetermined action to be take to avoid, eliminate, or minimize consequences of the failure mode" [31]

5.4 Goals and Requirements

The main activities detected here are:

1. Decide superior CM-regime

- Gain insight on goals and demands from related stakeholders.
- Developing superior measurements and control parameters for technical condition, safety, availability, and costs.
- Risk classification of systems and equipment to decide what systems that needs to be focused most upon related to CM, and evaluation of suitable CM methods.
- Cost-benefit
- Developing and distribute superior goals and requirements for other processes in the loop.

The main activities here will be to decide superior CM regime according to goals and demands from stakeholders in addition results from the other activities mentioned above, and develop and distribute superior goals and requirements for the other processes in the loop.

5.4.1 Stakeholder Analysis

A stakeholder analysis is a good way to start for gaining insight on the stakeholders related to the maintenance function. The purpose with a stakeholder analysis seen from a maintenance point of view is to map the various stakeholders and transform paramount goals and requirements into maintenance related goals. A stakeholder analysis is important to classify the stakeholders according to their possibility for influence and importance. [23]

A process for stakeholder management is shown in the figure below.

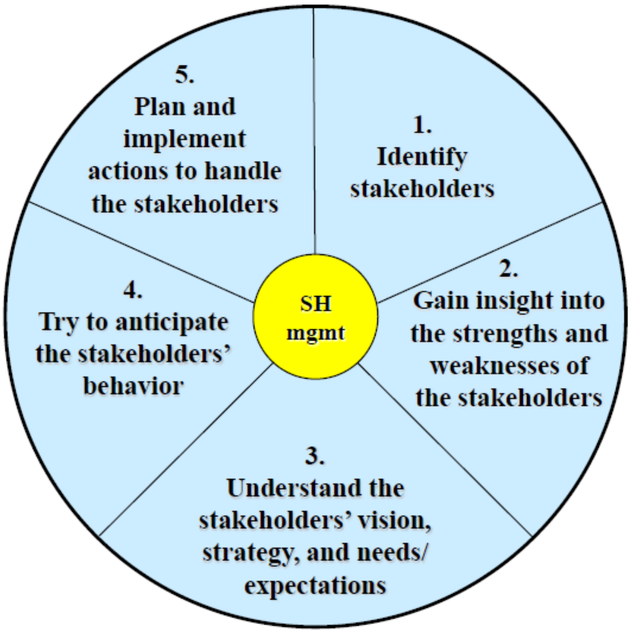

Figure 8 Stakeholder Management [32]

A useful tool when it comes to stakeholder analysis is to use a so-called stakeholder classification matrix to get an overview on which stakeholders the company should put most efforts to satisfy. This matrix consists of potential for cooperation on the vertical axis and potential to impact the organization on the horizontal axis. The stakeholders can be labeled into these four categories with the following suitable strategies for treatment:

2. Supportive: involve the stakeholder in relevant discussions and decisions.
3. Marginal: simply monitoring of the stakeholder.
4. Non-supportive: Use of a defensive strategy. Dependency of these stakeholders should be minimized.
5. Mixed blessing: handle through cooperation. [23]

		Potential to impact the organization	
		High	Low
Potential for cooperation with the organization	High	Mixed blessing	Supportive
	Low	Nonsupportive	Marginal

Figure 9 Stakeholder Matrix [23]

A tool that can be used for awareness of the different stakeholders expectations and to be to classify them into the categories above is the Kano model. This model can be seen as an awareness-creating diagram that shows different levels of wishes and requirements.

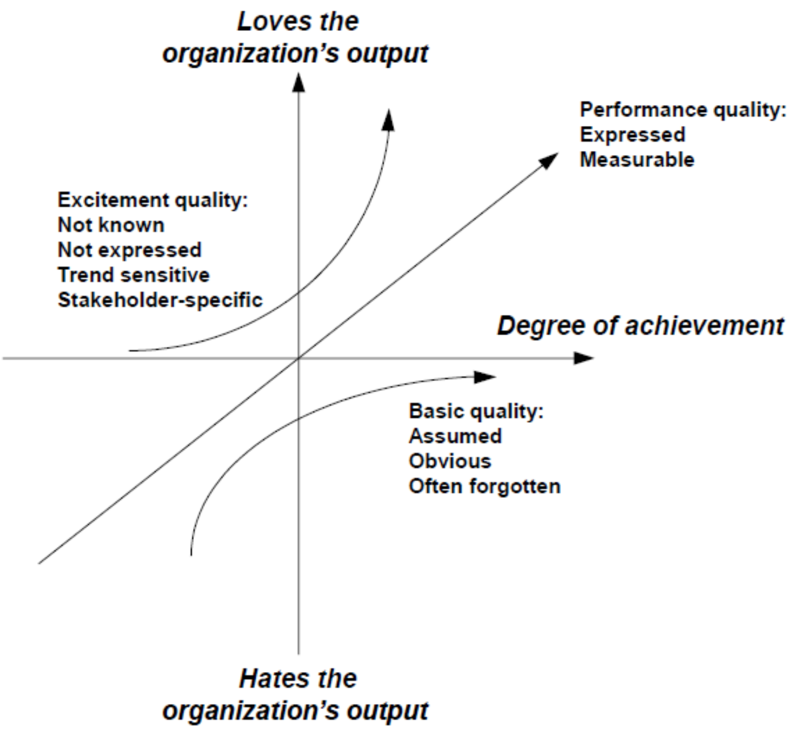

Figure 10 Kano model [32]

In this model three types of requirements are described. Performance requirements are the measureable clear requirements that the stakeholder will remember and describe for instance in the beginning of a project. Basic requirements are the requirements that the stakeholders often only will notice if they are not fulfilled. As the figure shows these requirements alone could never create a positive attitude from the stakeholders. In addition there are a set of requirements that the stakeholder does not expect but which create excitement when they are fulfilled.

A stakeholder analysis should provide an overview on:

- Absolute requirements: this can be safety related requirements regarding work environment from government or owners of the company.
- Requirements that are not absolute but still will lead to consequences if they are not fulfilled. This can be for instance be upper limits for availability and costs, or regarding the maintenance management system.
- Short- and long term goals that often are quite optimistic but that gives the company something to work towards. [23]

5.4.2 SWOT Analysis

To be able to develop superior measurements and control parameters for technical condition, safety, availability, and costs etc. related to the CM activities a SWOT analysis can be a helpful tool. A SWOT analysis is a strategic tool for identifying strengths, weaknesses, opportunities and threats. A SWOT analysis is technically quite simple to conduct since it mainly entails brainstorming within these four categories. However being able to come up with the relevant elements for continuous improvement work can be hard and takes training. [23]

When performing a SWOT analysis for CM activities the team should take earlier results regarding CM as a basis. For instance an annual condition based report could be worked through for detecting which results that are good, average and poor compared to the goals and demands last year. Probably going through earlier CBM reports will mainly detect strengths and weaknesses, so opportunities and threats the team have to brainstorm and discuss during this process. An example of a very basic version of a SWOT analysis for CM activities is shown below.

	INTERNAL	EXTERNAL
POSITIVE	**STRENGTHS** Increased operating time for rotating equipment through vibration analysis increase in early detections of failures. Less downtime for critical equipment.	**OPPORTUNITIES** Intensification of training More focus on qualifying data
NEGATIVE	**WEAKNESSES** Large costs over a short period because of investing in expensive CM equipment Limited number of personnel with satisfactory knowledge regarding CM work. Lead to more outsourcing. A relative high amount of unused data for some equipment types	**THREATS** Increased level of outsourcing can lead to lack of competence within the company. New CM equipment available that will be expensive to invest in.

Figure 11 SWOT Analysis

5.4.3 Risk Classification and evaluation of CM methods

Risk classification of systems and equipment to decide what systems that needs to be focused most upon related to CM. *The RCM* process is as earlier described a well-proven tool for risk classification and contribute with establishing a maintenance program. Probably the RCM process will be run more or less continuously through most of the steps in the PTIL MM-loop. The first four steps in the RCM process will provide a basis for detecting the most critical equipment and systems to focus on, in addition to feasible CM methods to apply. If the plant is well-established, most data and information available including system descriptions and equipment-groups will probably be gathered into the company's database system. This will ease the job with the first two steps in RCM.

A Preliminary FMECA will be the most important step to identify the most critical equipment/systems that needs to be focused upon, and which failure modes that needs to be avoided to fulfill the superior requirements from the stakeholders. Step 4 in the RCM should provide an evaluation of the feasibility CM tasks. Now the most critical systems are detected. RCM decision logic can be applied to investigate result from the existing use of CM from SWOT, and investigate how the existing CM use corresponds to the criteria's for technical feasibility of a CM task mentioned in chapter 5.3. After these four first steps of RCM in addition to cost-benefit evaluations, the maintenance crew should be able to provide preliminary answers on the four questions regarding RCM and CM in chapter 5.3.

5.4.4 Life Cycle cost and Cost –benefit

"Life cycle costs (LCC) are cradle to grave costs summarized as an economics model of evaluating alternatives for equipment and projects" [33]. LCC is a decision tool focusing on facts, money and time feasible for solving these typical problems and conflicts observed in many companies [33]:

- Project engineering: Focus on minimizing capital costs.
- Maintenance engineering: Focus on minimizing repair hours.
- Production: Focus on maximizing uptime hours.
- Reliability Engineering: Focus on avoiding failures.
- Accounting: Focus on maximizing project net present value.
- Shareholders: Focus on increasing the stockholder wealth.

Typical life cycle costs for a system for a company may include:

- Acquisition costs (also design and development costs in some cases)
- Operating costs: This includes cost of failures, repairs, spares, downtime and loss of production.
- Disposal costs.
- Other costs (financial elements such as discount rates, interest rates, depreciation, present value of money etc.) [34]

Cost-benefit analysis is closely related to the LCC analysis since most companies want to find the system which gives the greatest benefits to the lowest possible costs. A preliminary cost-benefit analysis will provide an estimation of costs and benefits related to possible systems to implement. Therefore performing a preliminary cost-benefit analysis already in the start phase will be a good support when deciding a superior CM regime. However the results this early cannot be completely trusted since there will be a considerable degree of uncertainty regarding both costs and possible benefits during the systems life time.

5.5 Maintenance Program

The main activities detected here are:

- Further Risk classification of equipment and systems.
- Decisions regarding CM methods to use for various equipment types.
- Decide intervals for CM, inspections etc.
- Provide as accurate as possible the logistic needs related to CM actions and inspections.
- Preliminary scheduling of CM actions with related distribution of resources.
- Develop procedures and documentation for the CM activities based on the goals and requirements.

- Programs for preservation of equipment out of operation etc.
- Continuously evaluation and updating of existing CM- and inspection programs.

5.5.1 Continued Risk classification and CM evaluations

For the activities in the first two points the results from the preliminary RCM analysis should be taken more closely into consideration. Now the most critical equipment/systems have been detected, and a preliminary evaluation of the existing CM methods has been done. For the systems/equipment classified as most critical a full RCM analysis should be provided [2].A few critical systems with a complex structure should in addition be object for fault tree analysis [9]. For equipment object for inspections, Risk based Inspection (RBI) can be applied. According to [35] a limitation with RCM is that it does not give sufficient support for optimizing the maintenance intervals. There is proposed a quantitative analysis in form of *remaining useful life estimation* as an additive to RCM.

A presumption has been made regarding the company's experience with CM technologies when discussing the application of SWOT analysis for detecting strengths, weaknesses, opportunities and threats. In addition *benchmarking* could be a useful supplement when making decisions regarding the use of CM methods.

5.5.2 Benchmarking

Benchmarking as a verb can be defined the following way: "Benchmarking is the practice of being humble enough to admit that someone else is better at something, and being wise enough to learn how to match them and even surpass them at it" [23]. For companies with more than one production plant, these plants can be benchmarked against each other for CM performance. However, establishing a benchmarking partnership with one or more of other companies will probably be most beneficial since it can provide the company with new information and other perspectives on problems. A complete benchmarking study includes the following activities:

- Study and understand own processes.
- Find benchmarking partners.
- Study the benchmarking partner's processes.
- Analyze the differences between own and benchmarking partner's processes.
- Implement improvements based on what was learned from benchmarking partners. [23]

5.5.3 Logistic needs and distribution of resources

It has been assumed that charting of logistic needs for the various CM actions and inspections are mainly done on basis of the company's earlier experiences. Still it is necessary with interaction with Logistic Support when developing a maintenance program, especially for highly complex systems. Logistic support is probably run in parallel with the activities in Maintenance management loop, and continuously receives input from the disciplines and departments. A logistic support analysis (LSA) is a very extensive process. Due to the constraints of this thesis it will only be mentioned briefly. Main inputs for LSA are typically:

- LSA Plan: documents regarding tasks to be completed, when and by whom.
- Supportability Issues: Supportability requirements with related constraints and recommendations.
- Customer data: May also include use study, maintenance concept and required data elements.

- Subcontractor data: analysis, data elements, drawings, product maintenance recommendations etc.
- Engineering data: FMEA/FMECA, maintainability data, hardware breakdowns, etc. [36]

LSA is one of the key elements for integrated logistic support (ILS). ILS was originally developed for management of logistic disciplines in the military, but is also applied in the private sector. Approximately all areas within a company can be input for ILS with the purpose to reduce costs and increase return on investments during the whole lifetime of systems. [36], [37]

Maintenance data will in other words be essential input factors for LSA, and the logistic support department. At the same time logistic support will highly influence maintenance work, especially if spare parts arrives to late or wrong parts have been ordered etc. As mentioned earlier in the report the key ”winning factor” with CM is to be able to detect beginning failures earlier to increase the time available for logistic planning and purchasing, and thereby the quality of this process.

It’s important to amplify that these both LSA and ILS are wide areas that includes much more than just maintenance. LSA will be an important aspect with closely connections to the maintenance program, and maintenance management in general. MM will be important input for LSA and vice versa. However, the field of logistics is too large and the amount of analyses within the field is too high to provide a further insight into on these in this thesis.

Also Integrated planning (IPL) should be involved during the development of a maintenance program. Even though IPL will not be defined as an analysis tool, it is worth mentioning in the correlation with the CM actions and related distribution of resources. Also IPL receives input from the disciplines. The main objective of IPL is to provide plan execution support, scheduling of tasks and handling deviations and conflicts related to the plans. IPL will be presented further in the CM processing chapter. [25]

5.6 Planning

When the MM loop has arrived at this point most feasible analysis tools that may be performed have been mentioned. The maintenance program has now been established, and there is no need for specific tools as far as the author knows of. Various versions of planning may be seen as “analysis tools” themselves, but except from that no tools will be proposed for this process.

5.7 Execution

Also this process will be almost exempted for analysis tools. Most documents related to the specific CM tasks will be prepared in advance of this process. Now the maintenance personnel related to the job mainly need to gather and go through the procedures and documentations.

5.7.1 Safe Job Analysis

Especially safe job analysis (SJA) will be important to go through. SJA can be defined as “a systematic and stepwise review of all risk factors prior to a given work activity or operation, so that steps can be taken to eliminate or control the identified risk factors during preparation and execution of the work activity or operation” [38]

Not all maintenance actions require SJA. According to [38] SJA is required when risk factors are present or may arise, and relevant procedures and work permits is not sufficient itself for performing the work in a safest possible manner.

For CM actions and inspections SJA is probably only needed for larger actions where systems have to be shut down and secured, dismounting of equipment or contact will gas/chemicals etc. It will probably be more common with use of SJA when preventive or corrective maintenance actions are about to be performed on basis of the condition monitoring. In [38] the need for SJA will be detected when the work order (WO) is finished, which can be seen as after the planning phase is ended. This is maybe a little late, and it could be preferable to place this earlier, for instance in the maintenance program or in the planning phase. It is a little difficult to create clear "dividing lines" between the processes in the MM loop, but it has been decided to place it in the execution box.

When starting preparation of SJA the first step is to put together a SJA group. This group basically consists of all the personnel involved with the work that are about to be performed. One person must always be appointed to be in charge of the SJA. This may be the person in charge of the actual work, an area/operations supervisor or another person closely connected to the specific work. According to [38] a SJA group usually may consist of:

- Person responsible for SJA
- Responsible for execution of the work
- Area/Operations Supervisor or a person appointed by him/her
- Area Technician(s)
- Executing personnel
- Relevant safety delegates
- Personnel with specialist knowledge relevant to the analysis

The recommended work process for planning and performing SJA is shown below. The time it takes for preparation and carrying on with SJA depends highly on the extent of the work that are about to be performed.

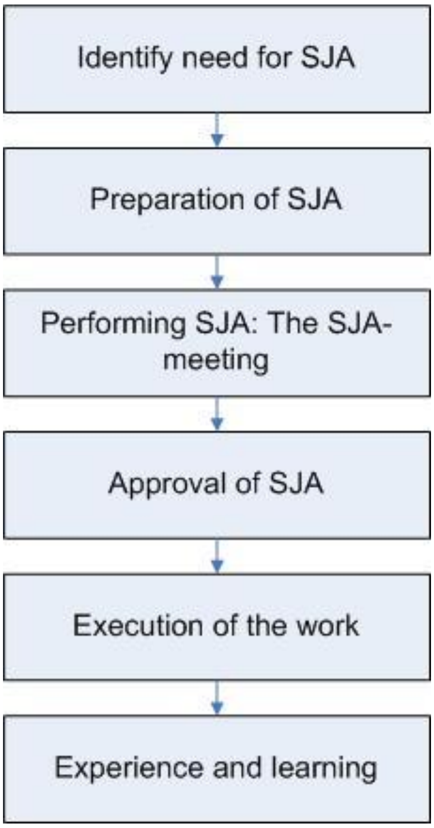

Figure 12 Safe job analysis [38]

5.8 Reporting

Preferably there will not be any specific analysis tools related to this process connected to CM except from the reporting itself. The proposed periodic report on the condition based maintenance should be done at least once a year, and will be based on the results for each year analyzed in the next process.

5.9 Analysis

The clue with this process is to analyze and understand the outcome of the condition monitoring and the condition based maintenance program. If the outcomes are good and satisfactorily according to goals and requirements it will be beneficial to understand which key factors that needs to be focused on for further improvements. If the outcomes are worse than expected it's essential to detect the causes for the dissatisfactory results and improve in the future. The amount of analysis recommended to be performed in this process may vary highly on the extent and complexity of reports from the CM work and inspections. Step five in RCM, following up and feedback from operation will off course be needed to provide a continuous RCM loop. Within this especially evaluation of the maintenance towards new operation data will be important. This may be done through another examination of FMECA in addition to FTA for issues related to particularly complex systems. In addition there should be performed a cost-benefit analysis evaluate if the benefits from CM justifies possible extra costs from monitoring equipment or use of specialist personnel etc. This should be compared against cost-benefit estimations done earlier in the MM-loop.

A reported problem may appear from many possible causes. For instance when a potential failure increases in the criticality before the predicted point of time there can be problems with the measurement parameters. The true cause may also come from the interpretation of the parameters (human errors or system failures), measuring uncertainty with the monitoring equipment or other potential causes.

5.9.1 Root Cause Analysis

A tool that for a long time has been widely used for addressing the true cause/causes of problems is Root cause analysis (RCA). A Root Cause can be defined as "the fundamental breakdown or failure of a process which, when resolved, prevents a recurrence of the problem" [39].

Identifying the true cause of a problem will usually be much more efficient than just temporary fixing of symptoms of the problem. A good analogy on this can be if a person struggles with allergic reactions from an unknown cause. Then it will be much better to detect and remove the true cause of this allergic reaction, for instance a specific type of food, then just "repairing" the allergic symptoms with pills that often creates other problems through various side effects.

Simply said RCA is asking why a problem occurred and continue to ask why until the most likely root cause is detected. For that reason RCA is also known as *why-why chart* or the *five whys analysis* [23]. Most common way to start RCA is to begin with brainstorming. Here fishbone diagram is frequently used to help focusing on various possibilities of causes.

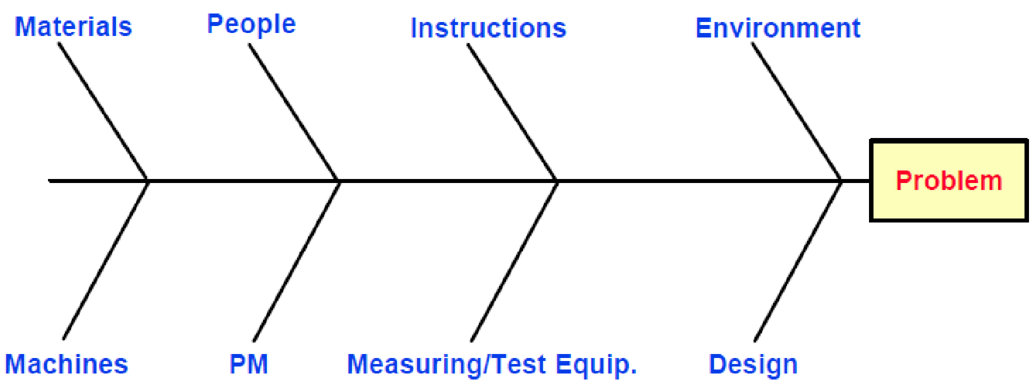

Figure 13 Example of fishbone diagram [39]

Many various sub-tools may be used during the RCA. Among these brainstorming and fishbone diagram are seen as the most valuable ones. In addition Pareto chart, Scatter diagram, flowchart, run chart, histogram, tree diagram and control charts etc. are tools that may be used. [39], [23]

5.9.2 Bottleneck Analysis

For the purpose of analyzing lines for communication, distribution of responsibilities, the maintenance database system, general use of resources etc. a tool that may become useful is bottleneck analysis. The tool is most commonly used related to production optimizing, but may with a little "innovative thinking" be used also related issues effecting the Condition based maintenance system.

The basic in bottleneck analysis is that all resources related to a system can all be classified into two categories: bottleneck or non-bottleneck. A bottleneck means that the specific resource has less capacity than the demand. Non-bottleneck means that the capacity is greater than the demand. The purpose with this analysis is to detect and eliminate the bottlenecks that restrict the "flow" in a system or process. A bottleneck can be eliminated by increasing its capacity or the process may be redesigned to avoid using the bottleneck, but usually another resource will take over as a bottleneck when the fist one is taken care of. Elimination of bottlenecks can therefore be seen a "continual battle".

When a bottleneck is detected, and it's difficult to increase its capacity or divide some of the workload over to another resource, it's very important that the condition of the bottleneck resource is maximized. If for instance a machine or some other equipment is detected as a bottleneck it's essential that the availability and condition of it continuously remains as high as possible. If a human is a bottleneck it's important that this person is motivated and taken good care of and stays healthy etc.

The way of performing a bottleneck analysis starts with modeling and mapping the system through flowcharts or network diagrams. Then it's necessary to identify the demand related to each part of system. Next step is to start from the end of the system flow and determine the capacity need for each resource. This is traditionally done by multiplying the demanded volume by the cycle time for each resource, but will probably be a little more difficult in relation with condition based maintenance. At last all capacity needs should be compared with available capacity which will detect the bottlenecks in the system. [23]

5.10 Improving Action

Improving action will be done on basis of the detections from the analyses that now have been performed. Probably there exists several useful tools for implementing according to the analysis results, but an assumption has been made that improving action can be made through ordinary planning and following up by just following the results and recommendations from the analyses. In other words there will not be recommended any specific tools for this process.

5.11 Supervision

Similarly to the improving action process there will not be recommended any specific tools for this process.

6 CM data processing

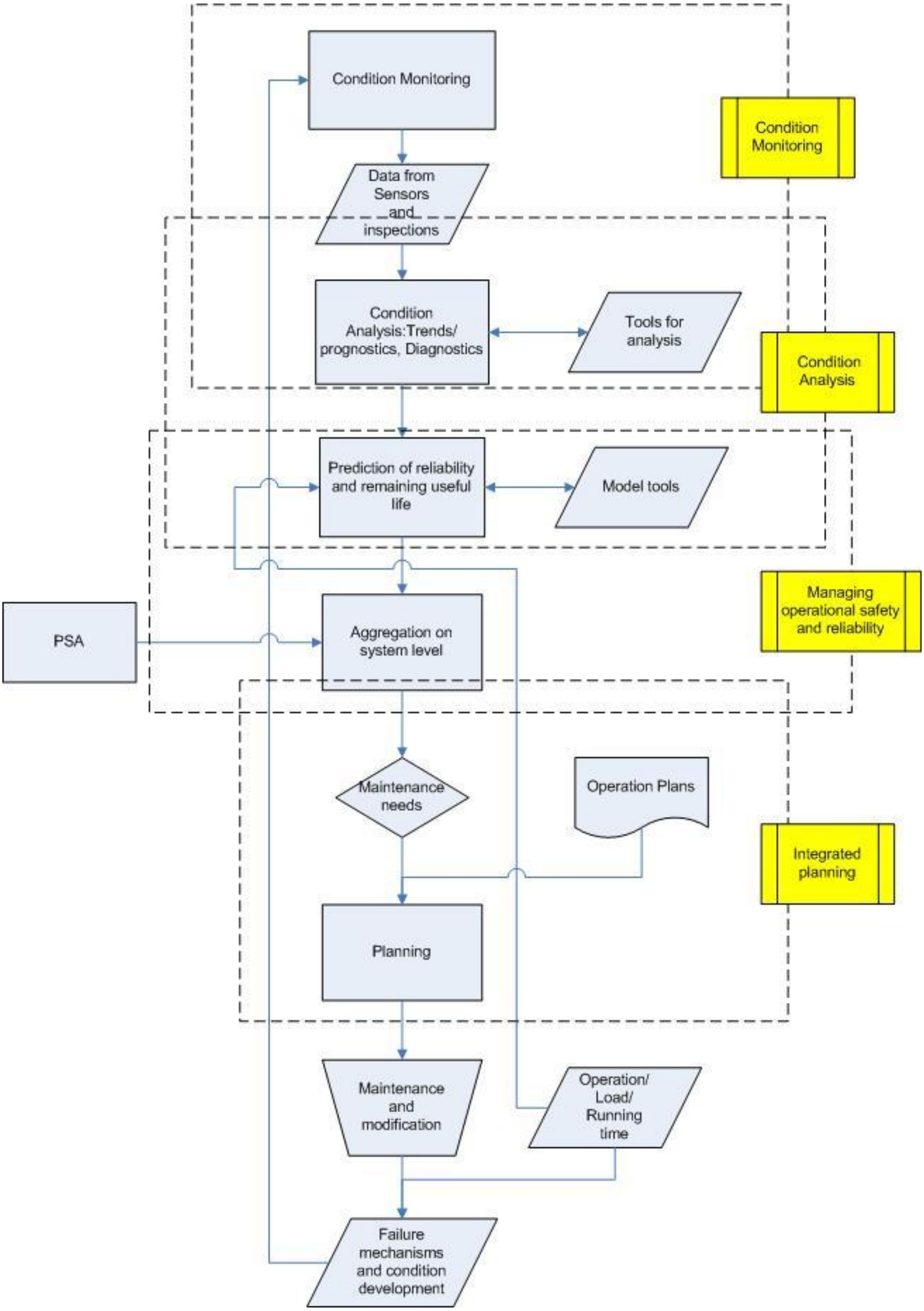

Figure 14 Condition based control of maintenance, availability and safety [40]

This model is based on information received at guidance meetings with supervisors from Marintek. The purpose is to show a possible flow on how CM data should be processed from signal data to trending, prognostics and diagnostics to achieve decision support for maintenance and logistics. The yellow “boxes” with stippled lines are supposed to show the programs within the IO center which deals with the various processes in the figure.

6.1 Condition monitoring

The figure starts with Condition monitoring, i.e. to measure the condition of equipment either through online CM, offline CM or through various inspection methods. This results in a set of measurements and data regarding the equipments technical condition. An example of “raw-data” is shown below in form of a typical frequency spectrum for an industrial fan.

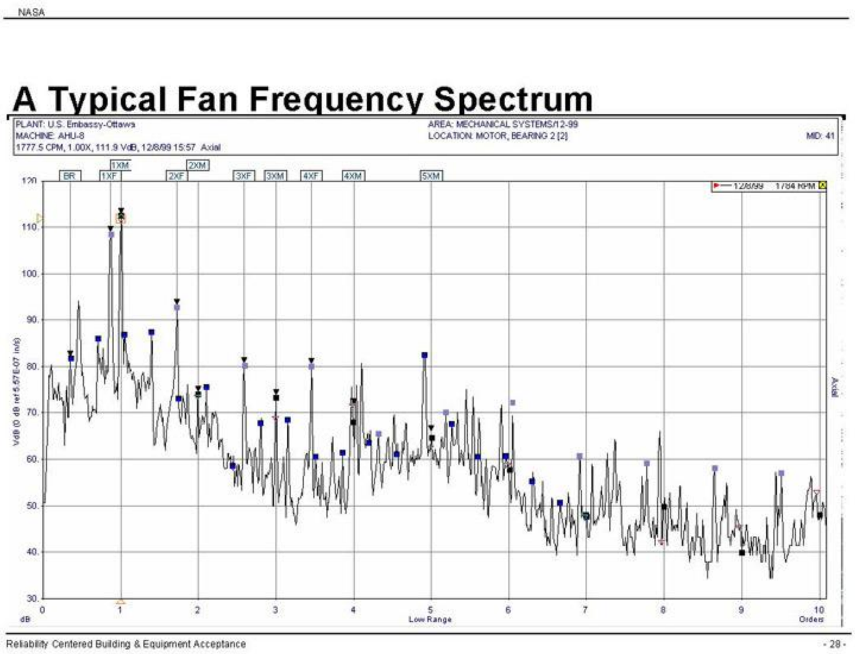

Figure 15 A typical fan frequency spectrum [41]

6.2 Condition Analysis

The next box is condition analysis of the monitoring data. Here trending of CM data is done in combination with various tools for analysis related to prognostics and diagnostics. Trending means to investigate how the measured condition parameter develops over a certain time period.

Diagnostics and prognostics are very important aspects of the CBM program. According to [35] the difference between diagnostics and prognostics is roughly that diagnostics deals with fault processing and prognostics deals with fault prediction. The first can be seen as a post-event analysis while the second as a prior-event analysis. Prognostics will therefore be most efficient for avoiding downtime of equipment, while diagnostics is required when fault prediction fails. Prognostics are usually done on basis of trending and other evaluations. [35]

6.2.1 Mimir

One possible path for condition analysis and prediction of remaining useful life (RUL) is under development within the IO center. This project is called Mimir and the goal is to develop a platform for advanced condition monitoring based on a modular concept. Mimir was developed through an effort to fully modularize the code of existing Halden reactor project (HRP) CM tools. These tools were primarily PEANO and Aladdin. The goal was to embed different techniques into systems available as independent and reusable modules. [42]

The main phases within the Mimir system are to go from pure data through information and knowledge and in the end to intelligence. The "top boxes" in the Mimir system represents intelligence where the following four objects are supposed to be achieved:

- Data validation, Reconstruction and calibration monitoring
- Early fault detection and diagnostics
- Physical degradation monitoring, estimation and prediction
- Lifetime and performance prediction.

The "toolbox" consists of various modules such as data filtering, data normalization, data clustering, statistical analysis, performance analysis, regression estimation, uncertainty estimation and risk optimizing etc. Different paths through these modules can be made dependent on which of the objects mentioned above to be performed. Short said the toolbox takes the user through the information and knowledge phases [42]. Mimir is based on the OSA-CBM standard so many different computer programs can connect to Mimir as long as they use the definition language defined in OSA-CBM. [43]

6.3 Prediction of remaining useful life

A practical explanation of remaining useful life (RUL) can be "The operating hours left on equipment before it has to be down for major repair" [44]. According to [35] there are two dominating ways of "thinking" regarding RUL, and both are considered a little extreme:

- Making an assumption about that RUL is independent of age, i.e. that equipment is seen as "as good as new" after maintenance actions. This way of thinking allows RUL to be determined by CM. Preventive maintenance is required when the CM measurement reaches the predefined threshold value. In that relation setting the correct threshold value is essential, since a too high limit might result in unexpected failures and too low might result in unnecessary preventive maintenance actions. For the time being recommendations from manufacturers of CM equipment will probably result in the best threshold values.
- Aging is the foundation for the second way of thinking. In this way of thinking a non-homogenous Poisson process (NHPP) is used which, and minimal maintenance action is assumed. That means that the system-reliability remains in the same condition after a maintenance action as it was before instead of becoming "as good as new". [35]

One potential tool for estimation of RUL is the Mimir platform described in the above chapter.

6.4 Aggregation on system level

Aggregation means to cluster different maintenance tasks together. After condition analysis and prediction of remaining useful life the equipment and components can be clustered based on the system they belong to and practicability to perform preventive maintenance on several components naturally belonging together. Interacting systems may be object for OBM if the result from the analysis in the steps above allows it. Systems/equipment defined as safety critical, which shows degradation should always be prioritized the highest followed by critical equipment with respect to availability and economy.

In the figure PSA is shown as a box which comes in from the side. PSA's main task is to create acts, regulations and international agreements etc. for activities both on-and offshore in addition to follow up these through supervision. The goal of PSA is to secure technical and operational safety and emergency preparedness, in addition to focusing on working environment. In PSA's terminology safety covers human life, health and welfare, the natural environment, financial investments and operational regularity [45]. The aggregation process is thereby highly influenced by PSA's rules and regulations when prioritizing maintenance actions.

6.5 Planning

Then planning is done based on the decided maintenance needs in combination with operational plans for the plant/facility. The yellow box which combines the maintenance demand with other plans into a common planning process is called integrated planning.

6.5.1 Integrated planning

Integrated planning (IPL) can be defined as "a concept where a cross discipline planning process is established to achieve one integrated operational plan where the objective is to optimize the resource utilization and to overcome bottlenecks of the operations" [46].

IPL is based on planning input from the disciplines. ERP solutions, like SAP, are usually utilized as a task database for requests from the disciplines. The IPL process is run in parallel with Logistic supply support, and activities within IPL are among others:

- Scheduling against known constraints
- Resource leveling
- Resource conflict resolution
- Plan acceptance and dissemination

Central in the IPL process is an Operations support centre (OSC). The purpose with an OSC is to manage the integrated plan, and to be a hub where complex decisions are being made regarding conflicts, deviations and changes in plans. Important tools in the connected to the OSC are extended use of computer technology for net and video meetings and instant messaging. Generally both IPL planners, maintenance planners and logistic planners should be connected to the OSC, in addition to instant access to drilling and production information.

A major strength of OSC is ability to make important decisions from a holistic point of view, i.e. to take decisions that are for the common best for the company as a holistic unit. Especially better handling of plan deviations will be an important contribution to the company through OSC and IPL. [46], [25]

6.6 Maintenance and Modifications

Then maintenance and modification are performed on basis of the decisions made in the planning process. Information regarding operational load and other useful information detected through the maintenance actions are given as feedback into the Condition analysis process and the end result in form of failure mechanisms and condition development. Then feedback from the end result is given to the condition monitoring process for evaluations regarding possible improvements. Both positive and negative results will be valuable contributions for the maintenance organization, either it is to build further on good results or the well-known “learning by burning” experience. Then the loop is closed and ready to be run from the start again.

6.7 CM data processing evaluated against the MM loop

When looking back at the PSA MM loop it’s interesting to evaluate the coherence between the CM data processing figure and the MM loop. The condition monitoring process is seen as a part of the execution box. To be able to evaluate the technical condition, also the condition analysis process and the prediction of reliability and remaining useful life process have to be performed before a result can be seen in the MM loop in form of technical condition.

The results from condition analysis and prediction of RUL should be then being reported. Reporting process is not shown in the figure 14, but should still be included in the flow of CM processing. The aggregation on system level may be performed in a step between the Goals and requirements and maintenance program, or only in the maintenance program box. The decided outcome in form of maintenance needs should thereafter be implemented in the maintenance program.

Information regarding preventive and/or planned corrective maintenance needs is then sent to planning and coordination. This includes the integrated planning process. Maintenance and modification is then performed in the execution box. Results from the preventive and corrective maintenance actions in form of real failure mechanisms and condition development may then be processed through the rest of the MM loop and implemented into the Maintenance program box. This experience data may then be used for improvements and updates of the existing program for condition monitoring. An illustration for explaining this possible way of connecting these two flow schemes is given in the figure below.

For inspections which is not non-intrusive, which means that the maintenance personnel often physically opens up and checks the equipments condition, real failure mechanisms and condition development will often be detected during the inspection itself. This can for instance be to check for internal corrosion or loosen parts inside a pressure vessel. Then the process from detecting failures to the failure is repaired be much faster since the equipment now will be out of operation due to the inspection, and the number one priority will be to get the equipment back in operation as fast as possible. Preferably there will just be reporting of the failure after the inspection, and thereafter emission of a work order to perform the maintenance as fast as possible. [40]

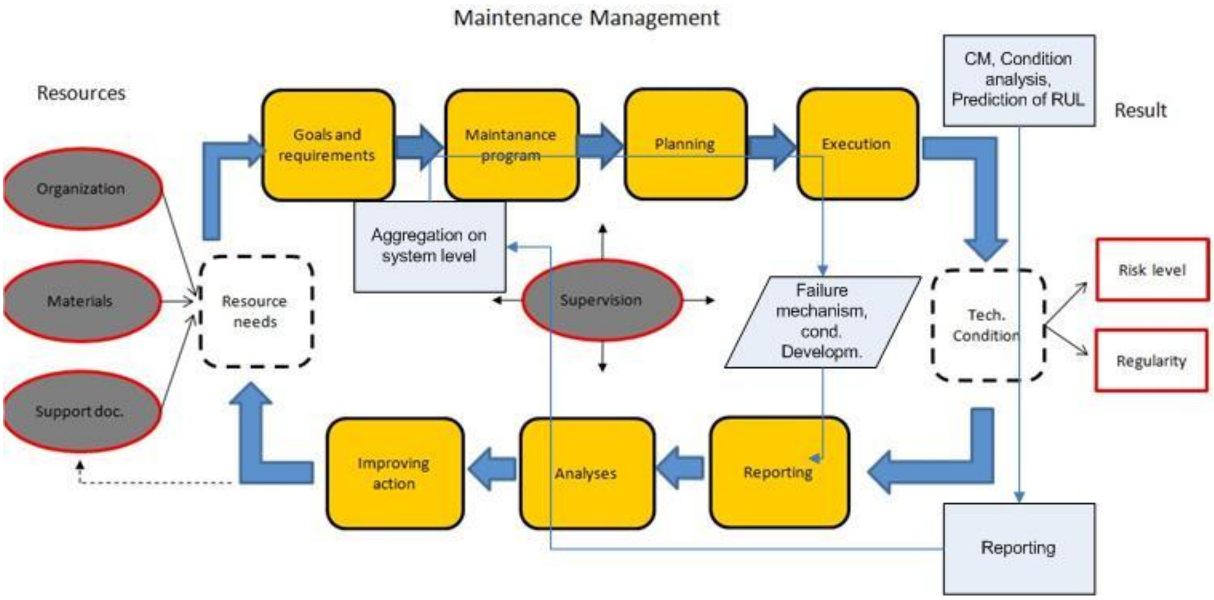

Figure 16 CM data processing evaluated against the MM loop

7 Maintenance regime for separators today

To be able to say something about how a typical maintenance regime are today for offshore O&G separators the author has been in contact with Tom Anders Thorstensen, Principal researcher RCT NDS EP at Statoil ASA. [47]

Today a typical maintenance regime for O&G separators consists mainly of inspections. A maintenance/inspection program for separators depends on the separator's design and external stresses. The two main functions to maintain are the separators integrity (safety due to leakage) and the performance of the separator. The maintenance strategies follow a Risk based inspection (RBI) program.

The inspection program with respect to the integrity requires inspections of the internals and the external parts of the separator. Inspection of the external part of the separator can usually be done during normal operation through different NTD methods etc. Inspection of the internals of a separator on the other hand requires stop in production, pressure relief, N2 inserting and cleaning before entering. This can be very time-and resource demanding.

A maintenance regime for a separator is, according to [47], different for separators/tanks made of carbon-steel than for separators made of more noble materials. At old offshore constructions as for instance Statfjord, separators of carbon-steel in combination with a high level of water production often requires annual inspections. For these separators and tanks in general made of carbon-steel Statoil have a tank-program, a little different from an ordinary inspection program, where planned actions like new coating/painting/cladding are done during these revision stops. At constructions where separators of more noble materials are utilized the inspection-intervals are longer with respect to internal inspections. These internal inspections are mainly done with respect to integrity with a special focus on pitting. The inspection intervals vary often between every three and five years. The operator, in this case Statoil, is in charge of managing the requirements for inspections.

Inspections with respect to performance of the separator are mainly decided based on process-related conditions. The focus here is to avoid "growing" inside the separator caused by sand or naphthenates etc. Also internal mounted equipment, such as hydro cyclones, loosens and falling down to the bottom of the separator can be a problem.

An ordinary inspection program for separators is a combination of intervals for internal and external inspections with respect to integrity. An inspection regarding the performance of the separator is usually done when there is need for it caused by a noticeable degradation, in other words a corrective action.

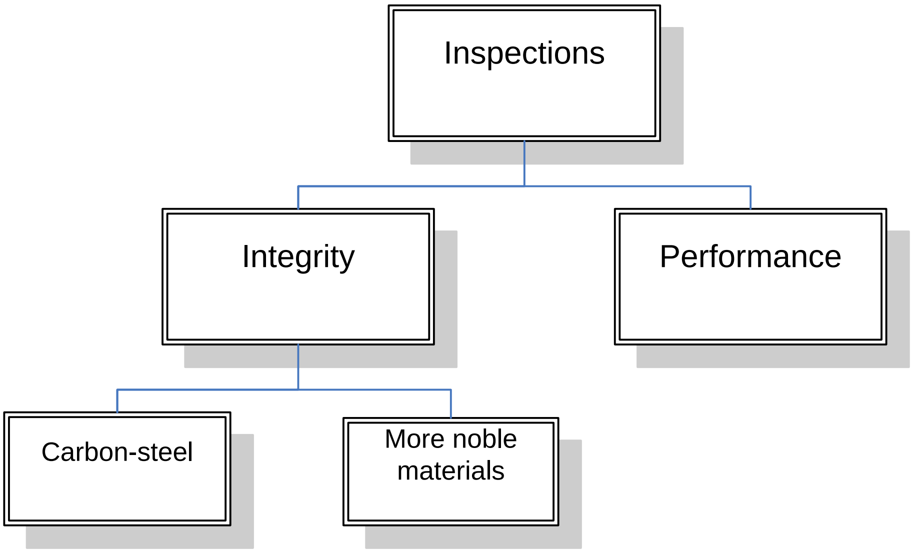

Figure 17 Simplified view on Inspection of separators today [47]

8 Development of tool for optimum maintenance and logistic demand for offshore equipment

When it comes to development of a theoretical tool/guideline that can be used for determination of optimum maintenance and logistic demands for various types of offshore equipment some constraints and choices have been made. As seen in the revised version of the MM loop in the figure below the goal behind such a model is to achieve a best possible result in form of technical condition, and at the same time minimize the resources required to achieve an optimum result.

Choices regarding the area of focus landed on the path from Goals and Requirements to maintenance program. In addition it has to be communication with technical condition and resources. The purpose is that this should be a general theoretical model that can be used for many different types of equipment. The reason for the choice of main focus area is that those to “boxes” in the figure are the essential ones when it comes to development of an efficient maintenance program. This tool/guideline will try to say something about how optimum maintenance and logistic needs can be determined for the equipment of interest only. Coordination, planning in general and integrated planning are themes that justifies for a master thesis themselves so they will not be focused on in this tool/guideline.

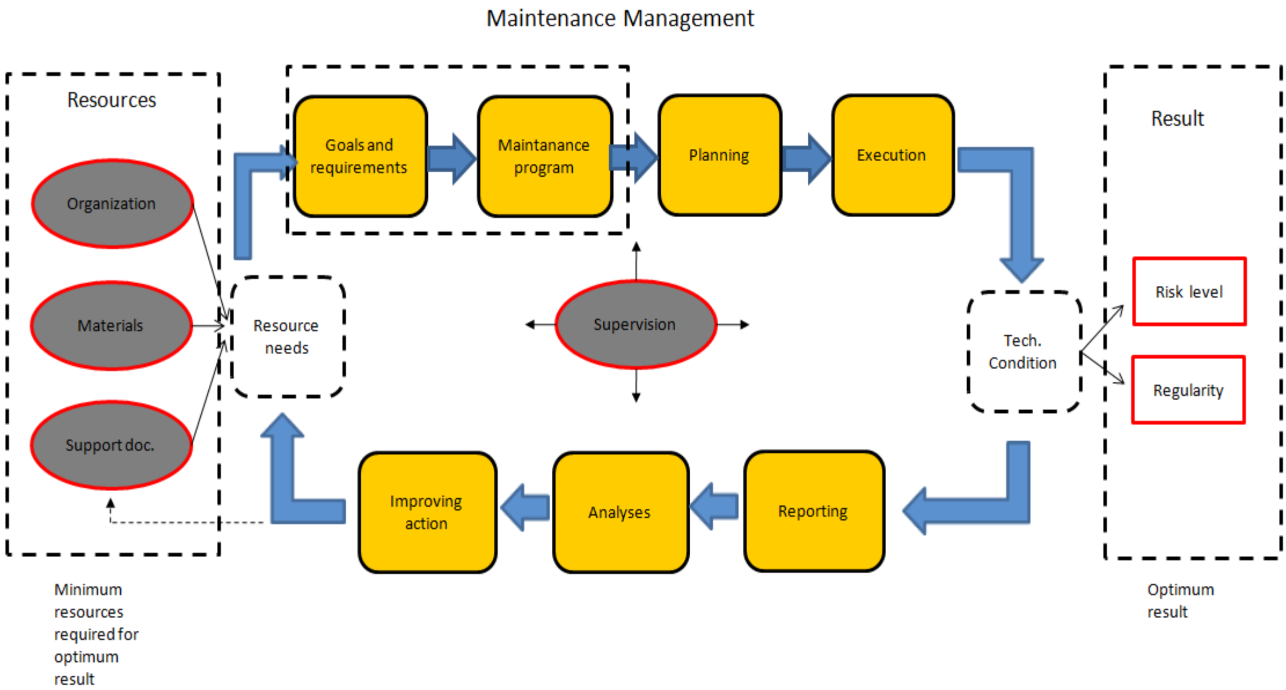

Figure 18 Overview of focus areas of the tool

8.1 From goals and requirements to Maintenance program

Generally for one system or equipment type, the main goals and requirements for that system should be:

- High safety with respect to personnel and environment

- High production availability
- Long mean time to failure/mean time between failure (MTTF/MTBF)
- Minimum costs

The first step in the path from goals and requirements to maintenance program for a random equipment type/system will be to detect the dominating failure modes and the criticality of the system. The criticality is mainly based on QHSE aspects and costs related equipment out of operation. This is usually taken care of through RCM/FMECA.

For critical equipment there is basically a choice between CM (on-line, off-line or inspections), periodic preventive maintenance (see figure 2) or various combinations. Which strategy to use depends on many factors that will be tried to go further into trough this model.

Then there have to be done evaluations regarding CM as an applicable maintenance concept for detecting the critical and dominating failure modes, and in that case which of the CM or inspection methods that will detect the failure modes and be feasible to fulfill goals and requirements. For this purpose the earlier mentioned decision diagram within RCM can be useful.

From figure 19 [9] it can be seen that both criticality, possibility for detection and failure characteristic will be significant when deciding maintenance action. For critical equipment with the non-hidden failures and detectable degradation there should be checked for an applicable and cost-efficient CM method.

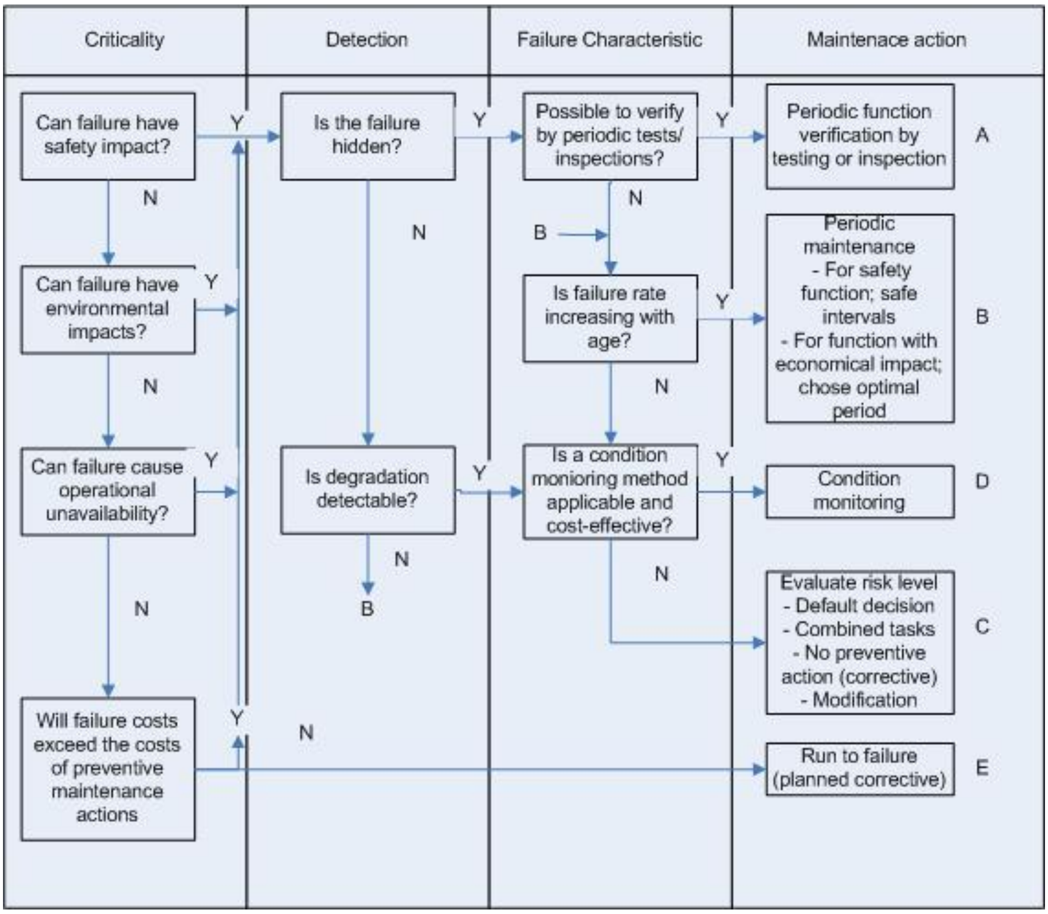

Figure 19 Decision diagram for maintenance tasks [9]

8.2 Decision tool

This tool/guideline can be seen as a revised version of the RCM decision diagram in figure 14 with more focus on CM and Criteria's for CM to be applicable. It has been tried to take both technical feasibility requirements in addition to cost aspects into consideration. In the figure there has been set a division between "path flow" and "information flow" by respectively solid and stippled lines.

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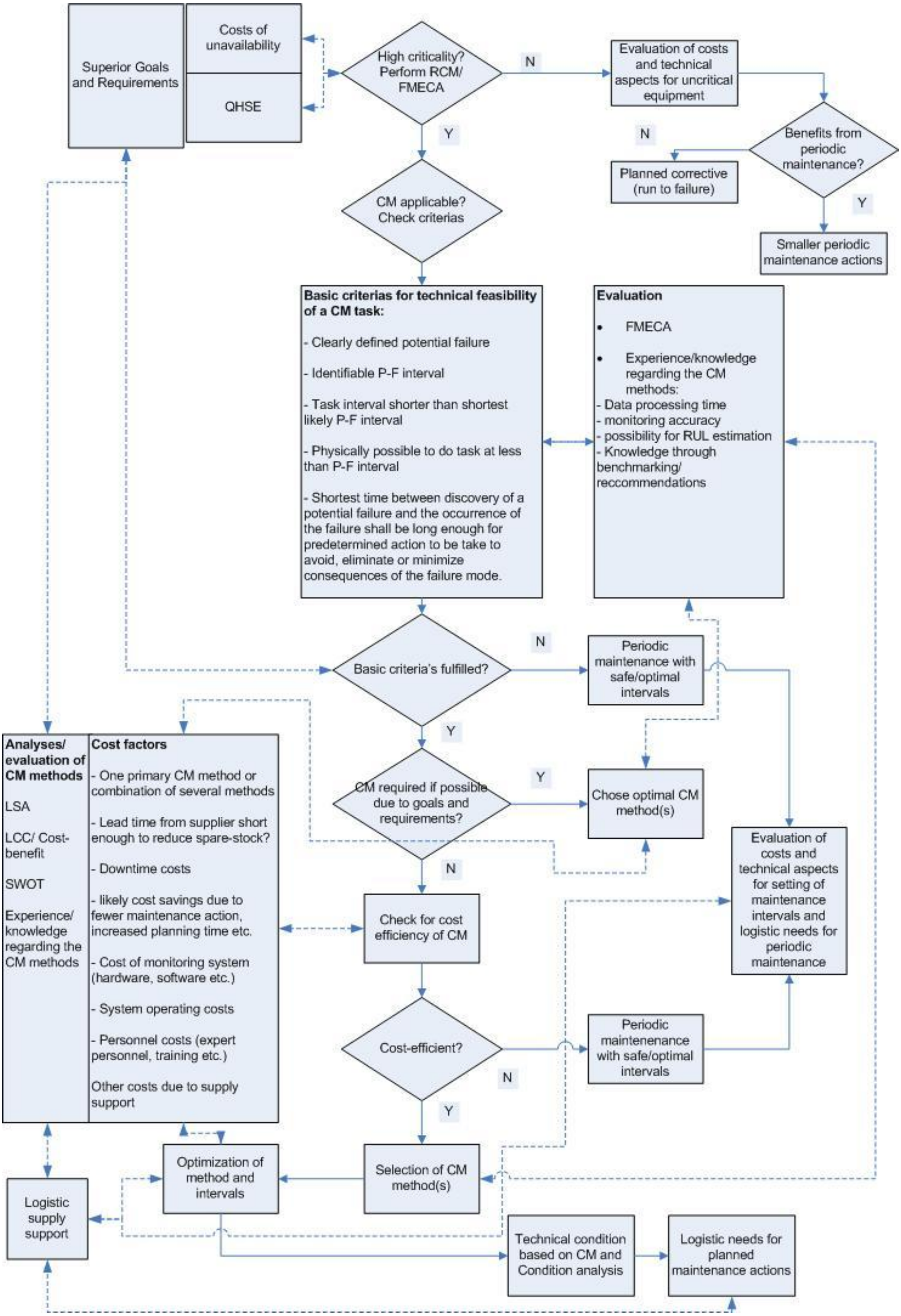

Figure 20 Decision tool for maintenance and logistic demand

8.3.1 Explanation of the decision tool

Similar to the RCM decision diagram the process starts with RCM/FMECA for detecting the criticality of function failures due to HSEQ aspects and costs of unavailability. If the criticality is high there should be checked towards the criteria's for technical feasibility of a CM tasks from standard SAE JA1011 described in chapter 5.3. These are seen as the basic premises to be fulfilled for CM to be technical possible without focusing on costs. If the criticality is low there should be an evaluation of costs and technical aspects for uncritical equipment, resulting in either planned corrective maintenance (run to failure) or smaller preventive maintenance tasks.

The evaluation process for technical feasibility of CM starts with results from the FMECA where the critical failure modes to avoid is clearly defined. The next step is to investigate among others if there is an identifiable P-F interval through the various CM methods under evaluation, and the length of the P-F intervals compared to task intervals. This evaluation will be mainly based on experience and knowledge regarding the various CM methods, either from own experience, from benchmarking partners, procedures and recommendations or hired-in experts. Needed technical data here will be information regarding time period of data processing, i.e. the time required for condition analysis and prediction of RUL described in chapter 6, and if RUL is possible to predict with a certain degree of accuracy.

If the basic criteria's for CM are not fulfilled periodic maintenance with safe/optimal intervals should be implemented. Then there should be an evaluation process regarding costs and technical aspects for setting maintenance intervals and logistic needs for the periodic maintenance actions on critical equipment. If the basic criteria's are fulfilled the process with evaluating CM goes further. In some cases there may be requirements saying that CM should be implemented if it's technical possible due to safety etc. This may for instance apply for safety critical equipment such as safety valves etc. In that case the optimal CM method should be chosen from a safety perspective. If there is more than one feasible method there should also be cost evaluation involved. The stippled lines show this communication.

If CM is not required if the technical foundation allows it, there should be checked for cost-efficiency of the various methods. Here there are many cost factors to take into consideration when evaluating if one or more methods will provide financial benefits compared to periodic maintenance. For instance it will probably be more expensive to combine several CM methods than using only one. All costs related to the specific CM method for evaluation will include among others acquisition costs of the monitoring system, system operating costs, personnel costs and other costs due to supply support. This should be evaluated against likely cost savings due to fewer maintenance actions, increased planning time for maintenance actions, and reduced downtime costs etc. One important likely benefit from CM is to be able to reduce the spare-stock, especially offshore where storing costs are high. For this purpose it will be necessary to investigate the lead time from supplier and compare it with the length of the P-F interval. Analyses connected to cost evaluations may be LSA, LCC and cost-benefit evaluations. In addition SWOT and general experience/knowledge may be used for comparing various applicable methods against each other. The results from cost evaluations should fulfill the preset goals and requirements for the CM methods to be seen as cost-efficient.

If the applicable CM method or combination of CM methods is not considered cost-efficient, periodic maintenance should be chosen. If CM is considered cost-efficient the method should be selected.

Thereafter it is an optimization regarding the method and intervals for CM with communication with logistic supply support, cost factors and the technical evaluation process. Then the chosen CM method will be implemented and technical condition and RUL will be analyzed according to the process described in figure 14. Logistic demand for preventive or corrective maintenance actions will thereafter be detected through the selected CM method with continuous communication with logistic supply support.

8.3.2 Discussing the tool

This tool/guideline has been an attempt at creating a best possible general model for determination of maintenance method focusing mainly on the factors that will set the terms for CM to be applicable and cost-effective. According to the task description of this M.sc. thesis, determination of logistic demand should also be an integrated part of the model but this part has been put less focus on. Here the logistic demand related to implantation and performing CM is seen as the most important aspect. The logistic demand related to planned maintenance actions have to be based on the detections from CM and can with that not be detected before condition analysis and RUL estimation have been performed. If the system/equipment ends up with periodic maintenance instead of CM it is assumed that logistic demand related to the periodic maintenance actions are known through experience with the specific equipment.

The actual decision process for CM or not may also often be simpler and mainly based on knowledge and experience. When evaluating if a condition monitoring method is applicable and cost-effective there should be a division between equipment that could be object for well proven CM technologies for the dominating failure modes, and equipment with more uncertain benefits of CM.

For instance vibration monitoring for rotating mechanical equipment/machinery has been used for a long period of time. From the 1960's the US Navy, petrochemical and nuclear electric power industries started to invest in monitoring equipment based on noise or vibrations. Now advanced microprocessor technology systems makes the monitoring process much more automated. Data acquisition is simplified, and automated data management minimizes the need for vibration experts for interpretation of data. Any degradation of plant machinery can in theory be detected through vibration monitoring techniques [13].Another argument for implementing vibration monitoring on rotation equipment is that surveys have shown that 70 percent of the failures on rotating equipment are introduced by maintenance activities [10], which implies that reducing physical maintenance actions here will give great benefits. For rotating equipment it has for a long time been accepted that vibration monitoring will be a better solution than periodic maintenance. Combining vibration monitoring with oil analysis will usually provide the best for the time being solution for machine control. This combination will give the maintenance personnel the opportunity to detect all the "big five" root causes of machine failures; balance, alignment, looseness, lubricant quality and contamination. [48], [49]

For other static mechanical equipment the choice of implementing CM or not will probably not be as easy as choosing CM for rotating equipment. Here it may often be a more difficult trade-off between costs of implementing CM and likely benefits, but many condition monitoring and inspection techniques also here can be done both automatic and non-intrusive giving the possibilities of detecting a wide range of failures without causing downtime of equipment [10]. Costs of implementing CM will probably vary a lot depending on which monitoring techniques to use. If the plant already has invested in a system for CM including hardware, software and sensors etc. it will be easier and less costly to add more sensors and equipment into the system, than starting from scratch.

8.4 Testing the tool related to a separator case

When testing the decision tool to determine the maintenance and logistic demand for an offshore separator as a case it has been decided to use the detections from M.Sc. thesis of Jørgen Houmstuen [10] as a basis since these thesis have done a deep investigation into failure modes and CM methods feasible for separators.

The first evaluation in the decision tool is regarding the criticality of the equipment, in this case a first stage production separator located at the Draugen platform in the North Sea. The application of this separator is to separate oil, gas and water. According to the decision tool the separator will be considered for CM if it is detected as critical during FMECA.

8.4.1 FMECA

Central in the FMECA is the use of risk matrix. The risk matrix shows the criticality as a product of probability/frequency of failure and consequence of failure. Probability/frequency classes, consequence classification and the risk matrix used by [10] in the FMECA are shown below.

Frequency classes	Quantification
Very unlikely	Once per 1000 years or more rarely
Remote	Once per 100-1000 years
Occasional	Once per 10-100 years
Probable	Once per 1-10 years
Frequent	More often than once per year

Table 2 Frequency classes in [10]

Consequence	Safety	Environment	Production
Catastrophic	Complete plant meltdown	Large uncontrollable spillage > 100 m^3	Complete plant shutdown
Critical	Injury to personnel, death to personnel in close proximity	Spillage < 100 m^3	Risk of downtime, severely reduced capacity
Major	Injury to personnel in close proximity	Spillage < 10 m^3	No downtime, reduced capacity
Minor	No safety risk	No spillage	No downtime, negligible capacity reduction

Table 3 Consequence of failure classification in [10]

Frequency		Consequence			
		Minor	Major	Critical	Catastrophic
	Frequent	4	5	6	7
	Probable	3	4	5	6
	Occational	2	3	4	5
	Remote	1	2	3	4
	Very unlikely	0	1	2	3

Table 4 Risk matrix in [10]

Figure 21 shows the resulting FMECA of [10]. The color codes in the FMECA are:

- Red: critical failure. Such failure causes immediate and complete loss of the system's capability of providing its output.
- Yellow: Degraded. This failure mode is not critical, but it prevents the system from providing its outputs within specifications. Such failure may develop into a critical failure in time.
- Green: Incipient. This failure will not immediately cause loss of a system's capability of providing its output, but could result in degraded or critical failure if it's not attended to.

As the FMECA shows there four failure modes classified as critical and therefore unacceptable. Abnormal instrument reading has been detected to be critical both with respect to safety and production. The other two failure modes detected as critical are external leakage and Plugged/choked (from excessive sand/scale), both with respect to production. In addition there is several failure modes classified as degraded which should follow the ALARP principle. ALARP means "as low as reasonably practicable" and states that there should be performed efforts to reduce the risk unless the cost-differential is to high between implementing the effort and the expected benefits.

Abnormal instrument readings were detected to be the most serious concern with a rate of 60 percent of the total recorded failures in OREDA. 80 percent of the instrument failures were connected to level measurement. External leakage of the process medium was seen as the second most common critical failure with a rate of 8 percent of total recorded failures in OREDA. [10]

Failure mode, effect and criticality analysis

Function: Separate oil/gas/water

Equipment: Separator

Failure mode	Failure Cause or mechanism	Failure rate [per 10^5 Hr]	Effect on system	Resulting state	Criticality Safety	Environment	Production
Abnormal instrument reading	Instrument/ sensor failure	14,03	critical	Shutdown	5	4	5
External leakage	Corrosion/ erosion	9,55	critical	Shutdown	4	4	4
Plugged/ choked	Improper design/ Excessive sand and scale	4,05	critical	Shutdown	4	3	4
Abnormal instrument reading	Instrument/ sensor failure	24,96	degraded	Degraded	3	4	4
External leakage	Corrosion/ erosion	15,61	degraded	Shutdown	4	4	5
Plugged/ choked	Improper design/ Excessive sand and scale	29,68	degraded	Degraded	3	4	5
Abnormal instrument reading	Instrument/ sensor failure	252,3	incipient	Degraded	4	4	4
External leakage	Corrosion/ erosion	23,71	incipient	Degraded	3	4	4
Parameter deviation		21,68	incipient	Degraded	3	3	3
Plugged/ choked	Improper design/ Excessive sand and scale	15,42	incipient	Degraded	3	3	4

Figure 21 Resulting FMECA in [10]

Looking back at the decision tool in figure 19 the answer on the question regarding criticality of a separator must be that the criticality is high enough to be considered further for CM.

8.4.2 Check for technical feasibility of a CM task

The first criteria are that there must be one or more clearly defined failures. These are described in the above chapter. In addition main failure modes for separators according to [50] are damaged and/or broke-off cyclones and, loose bolts and other equipment loosen and falling down to the bottom of the separator due to fatigue, stress, vibration and the general harsh environment inside the separator. Gamma radiation and microwaves were mentioned as the most “hopeful” failure detection methods with respect to internal presence detection and positioning of internal equipment [50].

It will in other words be necessary to monitor the process inside the separator for being able to monitor the most critical potential failure modes. The methods that were detected as feasible for separator in [10] are given here:

- Internals presence detection: Passive acoustic monitoring, Gamma monitoring, IR Thermometry.
- Internals condition: Passive acoustic monitoring, IR Thermometry.
- Wall defects: Ultrasonic monitoring, Gamma monitoring, IR Thermometry.
- Level measurement: Neutron backscatter, Gamma monitoring, Microwave monitoring, IR Thermometry.
- Foam detection: Neutron backscatter, Gamma monitoring, Microwave monitoring. [10]

For specific information regarding the CM methods there will be referred to [10] or [5].

Regarding the other criteria's for technical feasibilities of a CM task it has not been time for investigation of length of P-F intervals, CM processing time and monitoring accuracy etc. for separators. It is assumed that the methods presented in [10] are feasible for their area of monitoring showed above. The monitoring areas that were detected as most important were Level measurement, internals presence detection, wall defects and internals condition. The methods covering most of these areas were IR thermometry and Gamma monitoring. Other methods may also be combined with one of these for even better monitoring capability [10]. According to the decision model basic criteria's basic are fulfilled and the methods will be object for further evaluation.

8.4.3 CM required if technical possible due to goals and requirements

On the question if CM is required if possible due to goals and requirements it is hard to know the question on this. This will probably be decided on top level in the maintenance organization. For most oil companies separators will probably be among the most critical equipment classes. As long as the required safety level is ensured, the "path" for achieving this safety level will probably be up to the company to decide. This may be achieved either through various CM methods, traditional revision stops or a combination. It is still common for companies to run revision stops for separators periodically with respect to internals condition as described in chapter 7. An assumption regarding this question for separators will therefore be no, and the separator is evaluated further for Cost-efficiency of CM.

8.4.4 Evaluation of Cost-efficiency

The cost-efficiency of a CM system depends on all costs that can be related to the system and the calculated/estimated costs savings from the system. This is a very comprehensive process and the estimated/calculated costs and benefits will probably nearly almost deviate from the real results due to uncertainty, changes in the market and assumptions etc. Therefore also this evaluation process should be highly influenced by expert knowledge and experience regarding the CM methods and not only quantitative measures.

However, quantitative cost evaluations will be necessary for convincing the top management that a CM system should be implemented.

The CM method that was calculated as most cost-efficient alone according to the LCC analysis in [10] was Infra Red (IR) Thermometry. The IR solution that was analyzed was an automatic continuous online method utilizing cameras in the cost range from 30 000 NOK to several hundred thousand. Results on IR was a net benefit of 73 511 000 NOK with a Net benefit/LCC ratio on 15,19. The best overall solution that was detected was IR combined with Passive Acoustic monitoring with a Net benefit on 76 305 000. This solution however was calculated as more costly with a Net benefit/LCC ratio on 9,09 [10].

Choosing to trust these results the answer with respect to cost-efficiency must be yes.

8.4.5 Selection of CM method(s)

Based on the cost evaluations performed in [10] the company should select either IR alone, or a combination of IR and Passive Acoustic. It was recommended to implement the combined solution if the investment budget allows it [10].

8.4.6 Optimization of method and intervals

Assuming that the company will chose the best solution the combined solution is sent for optimization. The IR solution in question was an automatic method, so this will of course be operated continuously without intervals. Also the passive acoustic solution that was evaluated is an online solution. This solution consists of a set of wireless sensors including energy generating devices. The sensors are supposed to be glued on various areas of the separator. [10]

Since both these solutions are online solutions there is no need for optimization of intervals. There could on the other hand be an optimization of costs. If the budget is low the implementation of the combined solution could be less costly if the number of sensors is reduced. In [10] it was estimated that the cost of one IR camera was 100 000 NOK and the results relies on this estimation. Since the cameras could vary from 30 000 to several hundred, maybe cameras to a price of 70 000 for instance could do almost the same job. However, this process is an optimization between costs and the technical aspects, and there are no benefits from reducing the investment costs marginally if the ability of monitoring is degraded or harmed because of that.

8.4.7 Discussion on maintenance and logistics demand for a separator

A CM system is decided and implemented if the CM system manages to fulfill the technical requirements and in addition will be cost efficient. Maintenance demand is this relation is interpret to be that a CM system is able to detect the critical failure modes that would had been taken care of through standard physical inspections else. In this case an online solution of IR combined with passive acoustic will provide the basic maintenance demand for a given period if the solution is able to maintain the required monitoring level with respect to the failure modes described earlier. Preventive or corrective maintenance needs will be based on results of CM, and is therefore not possible to detect in advance unless a periodic maintenance solution is chosen instead of CM.

Also the logistic needs for a CM system will be essential input before choosing a CM solution due to cost evaluations. In other words does this decision model only take care of logistic demand related to the CM method(s), in this case IR and passive acoustic. Logistic needs related to preventive and/or corrective actions will be detected from CM with continuous correspondence with Logistic support.

If control of the internal parts of a separator is maintained through CM there will not be need for periodic revision stops and physically opening up the separator for inspection. Today most inspections of the external part of a separator are taken care of during normal operation [47]. If also the condition of the internal parts of the separator can be monitored during operation, there will only be need for stops in production when a failure mode is detected. If the P-F interval for the failure mode is long there will be better time for planning and detection of logistic supply for repairing the specific failure mode. In general this increased planning time should provide a shorter stop in production for fixing the problem, than it would if a critical failure suddenly appears with limited warning time. A long warning time for a failure would also probably give the maintenance personnel an opportunity for OBM. Then the stop in production can be done when a minimum of economical or safety related damage is inflicted on the company.

9 Conclusion

With CM as a basis for a predictive maintenance strategy, many benefits should be obtained for a company in the offshore industry today both with respect to maintenance and logistics. The greatest likely benefit from CM is to be able to detect and analyze a failure at the earliest possible stage. This will provide the company the opportunity to repair the failure before it gets critical.

Early detections of a potential failure give the company a longer planning interval with respect to determining repair parts, tools and labor skills needed for the repair. This will provide a minimum of down-time for the repair to be done. The probability of introducing new failures through unnecessary maintenance actions and corrective "rush jobs" will also be reduced since maintenance actions will only be done when it's needed based on the equipments condition. A long P-F interval may give the opportunity of ordering spare parts after a potential failure is detected. Especially on offshore platforms where the storing costs are high compared to land based industry the opportunity of reducing the number of spares stored offshore will be important.

The various activities and related analysis tools for the processes in the MM loop are just proposals and cannot be seen as clear facts. It has been tried to detect activities and related analysis tools that focus on decisions regarding CM in every part of the MM loop.

The decision tool developed is based on the RCM decision logic from [9]. It was decided to first consider technical feasibility for CM and thereafter cost aspects. It has been tried to consider all aspects on a superior level that needs to be taken into consideration when developing a maintenance program for offshore equipment in general. The purpose is to find the best possible maintenance regime with respect to technical feasibility and costs that fulfills the goals and requirements.

Since no FMECA, LCC analysis or similar analysis have been performed in this thesis, it was necessary to use results from others when testing the decision tool in a separator case. Results from [10] has mainly been utilized in that case. To be able to conclude with more certainty that the chosen CM methods are the most beneficial for an offshore separator, there should have been performed quantitative analyses also in this thesis.

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