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Abstract

This thesis contributes optimization of periodic maintenance using condition monitoring techniques and operational data so that maintenance can be performed before critical equipment fails. Periodic maintenance is carried out at regular intervals based on equipment's failure history. In this case, the maintenance interval is not scheduled in terms of the actual deteriorating condition of equipment. Therefore, either over-maintenance or under-maintenance could be performed. This will cause overstocking of spareparts, high maintenance cost and unnecessary downtime

By using Condition monitoring techniques such as vibration analysis, ultrasonic, oil analysis, infrared thermography, etc, the actual equipment condition can be monitored either continuously or periodically. By integrating the actual failure data acquired from condition monitoring techniques with historical (event) data, the current health condition and the remaining useful life of the equipment will be evaluated. Therefore, a suitable maintenance action can be scheduled and performed based on the current condition and projected remaining life of equipment. A procedure of condition monitoring is suggested in this thesis.

Even though optimizing periodic maintenance using condition monitoring techniques leads to many benefits, there will be initial costs that may discourage the maintenance managers. This thesis presents a cost-benefit-analysis of condition based maintenance that helps the decision makers to decide the need of condition based maintenance to the given system.

The last part of this thesis is to develop a methodology on how to select suitable equipment for condition based maintenance. Different criteria such as, criticality analysis, technical feasibility, economical analysis and others are considered for the selection process.

Acknowledgments

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I would like to express my deepest gratitude to my supervisor at the University of Stavanger, Professor Tore Markeset for his valuable guidance. I would also like to thank Maurina Andriana from Apply Sørco for the availability of data and for the helpful technical discussion during this thesis work.

Finally, I would like to thank my wife for supporting me the whole time.

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List of abbreviations

CBM: condition based maintenance

MTBF: Mean-time-between-failures

MTTF: Mean-time-to-failures

FMECA: Failure mode, effects and criticality analysis

FMEA: Failure mode and Effect Analysis

CA: Criticality Analysis

RPN: Risk Priority Number

PV_C: present value of condition monitoring cost

PV_b: present value of condition monitoring benefit

NPV: Net Present Value

PV_x: Present value of additional cost

PV_y: Present value of additional benefit

1. Introduction

1.1 Background

As British Standards8210 (1986), defined maintenance as*:" A combination of all technical and administrative actions carried out to retain an item in, or restore it to a state in which it can perform its required function".*

Proper maintenance of equipment can improve production performance and reduce overall operating costs. There are several maintenance strategies that have been implemented in various fields and manufacturing industries to improve production performance over the past few years. Periodic maintenance is one of the most common types of maintenance strategies used in different industries to prevent equipment from breakdown. The maintenance actives (inspection, repair, replacement, etc) are performed at regular intervals. The intervals can be based on fixed number of operation cycles, fixed cumulative outputs, calendar- based (may be in weeks, months or years) or number of operating hours (run time based) (Kelly,1997).

Periodic maintenance is scheduled based on the estimated statistical values of mean-time to failure from the equipment failure data collected on the past. Since, the values of mean-time to failure is not quantified based on the actual condition of equipment, over maintenance (periodic maintenance is performed at more frequent than it is necessary) or under maintenance (maintenance is performed too long intervals) can be performed. Therefore, periodic maintenance has to be optimized based on the actual equipment failure data so that maintenance can be carried out on the right time. The actual failure data can be obtained by using condition monitoring techniques to the system.

The use of condition monitoring techniques to optimize periodic maintenance management has been increased rapidly over the past few decades. Performing maintenance actions based on the actual condition of the machine could maximize system availability, safety, improve equipment reliability, and minimize operational and technical maintenance costs, etc. By monitoring the underlying deteriorating processes of the equipment, the periodic maintenance interval can be optimized and the expected maintenance action will be carried out only when it is needed.

1.2 Problem formulation/project description

Optimizing periodic maintenance management using condition monitoring techniques is not a simple task. It utilizes a combination of different types of sensors (measuring instruments) and skilled personnel to acquire and process condition monitoring data so that the appropriate maintenance action with optimum intervals can be decided.

Before condition based maintenance is decided to the system, it is important to analyze the feasibility of the investment and develop a cost-benefit analysis. In addition to this, only equipment which is critical and suitable for condition monitoring techniques is going to be selected for a condition based maintenance program. There are different criteria going to be considered on the selection processes. Introducing condition monitoring techniques to the system will be a challenge since it is going to change the culture on how maintenance is performed in the organization and this will change the organization's system.

1.3 Main objective

The main objective of this thesis is to increase the knowledge on how to optimize periodic maintenance management using condition monitoring techniques and operational data.

1.4 Sub-objective

The sub-objectives of this thesis are,

- Identify periodic maintenance definition and procedures
- Identify different types of condition monitoring techniques and their working principles.
- Develop a procedurefor condition based maintenance.
- Perform cost-benefit analysis of condition based maintenance.
- Formulate a methdology on the selection of suitable equipment for condition based maintenance in the plant

1.5 Methodology

To carry out this project, relevant information from different sources will be collected and analyzed. The information might be from Journals, presentations, internet databases and academic literatures at University of Stavanger. Some information is also collected from Apply Sørco documentation. There will be through discussions with my supervisor at the University of Stavanger.

1.6 Delimitations

This thesis will be focusing on the basic concepts of optimizing periodic maintenance management using condition monitoring techniques and operational data. The cost-benefit analysis will be a part of the project. Other Types of maintenance strategies will not be covered in detail.

1.7 Project Activities

Some of the activies which are going to be carried on this thesis are,

1. There will be a literature review to understand the basic concepts of periodic maintenance strategy and develop a methodology on how to optimize periodicmaintenance management using condition monitoring techniques. In this part, a model will be proposed to integrate condition monitoring data and equipment failure data to improve maintenance program continuously.
2. The working principle of condition based maintenance will be covered. Failure mode mechanisms and measuring parameters could be identified and a condition monitoring techniques related to the failure mechanisms will be proposedto detect the actual deterioration process.
3. The cost-benefit analysis of condition based maintenance will be discused in detail.

2. Periodic Maintenance

2.1 Introduction

The idea of periodic maintenance is performing maintenance activities at regular intervals before a critical system is failed. In periodic maintenance strategy process the failure characteristics of the machine (MTBF/MTTF and failure trends) will be calculated and analyzed from the failure time data set which is stored in the maintenance database (Ahmad& Kamaruddin, 2012). Different types of mathematical modeling such as Weibull distribution model, Normal distribution model, and lognormal distribution model are used to analyze the failure data and predict the failure characteristics of the machine. Procedures of periodic maintenance processes are illustrated on Figure2-1 bellow.

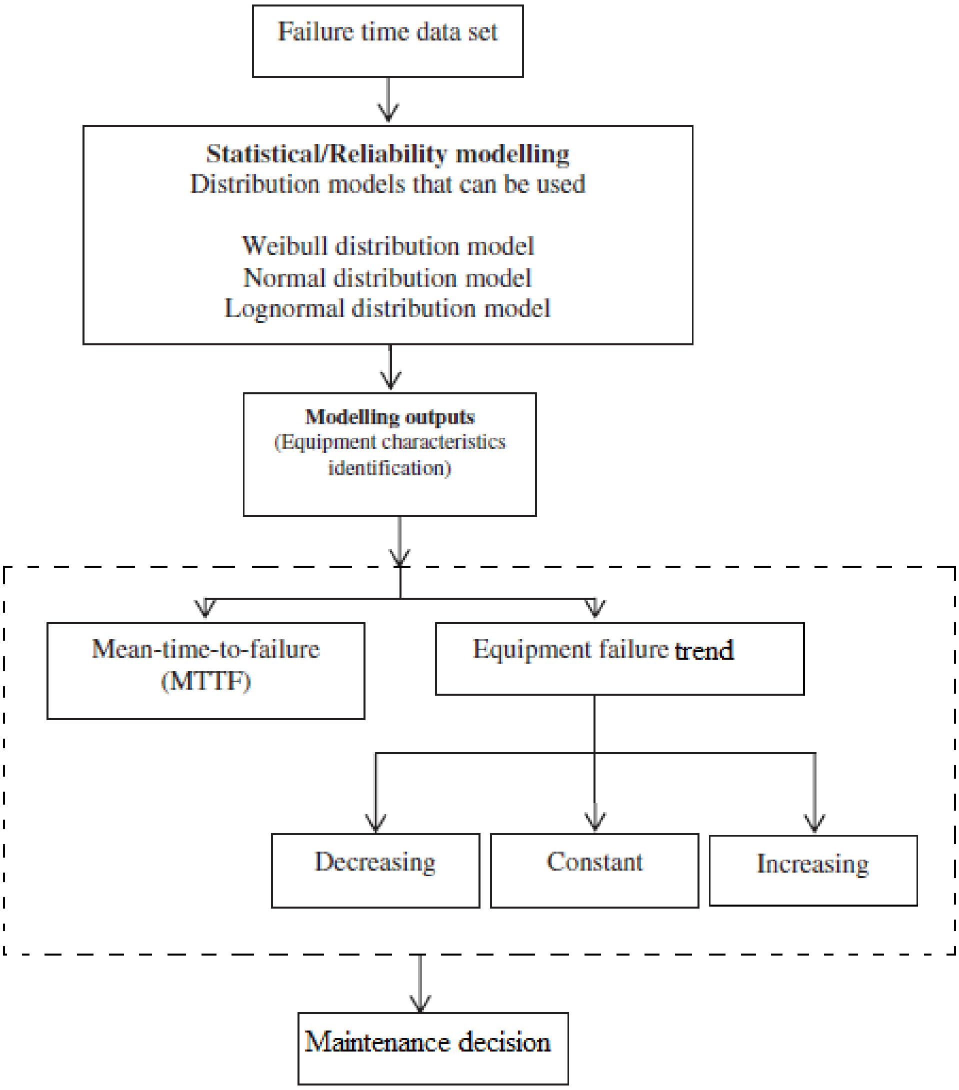


Figure 2-1: Procedures of periodic maintenance processes (Ahmad& Kamaruddin, 2012).

After the value of mean time between failures (MTBF) and equipment failure trends are estimated, the maintenance action will be decided. Periodic maintenance improves system reliability, production efficiency and safety by keeping the machines in a good operating condition.

2.2 Field data collection

Enough amounts of field data with detail information should be collected so that a reasonable value of MTBF/MTTF can be estimated. Different types of information such as, basic system information, operation context, environmental context, etc, should be gathered with the failure data. This additional information will help the maintenance personnel to decide the right maintenance strategy with optimum maintenance intervals. Accuracy in the data collection will affect the value of reliability parameters (failure rate, MTBF/MTTF) so as the periodic maintenance intervals (Troyer, 2009).

2.3 Failure rate

Failure rate is the frequency in which components or machines failed over a specified period of time. The failure rate of a complex system is affected by component`s failure rates within the system. As we see on Figure 2-2 below, components are having a random failure rate. Therefore, the overall system failure rate distribution will be a combination of each failure trends in the system and it is having a bathtub curve shape (Figure 2-2).Equipment may fail in the early stage, useful life period or wear-out period (Troyer, 2009).

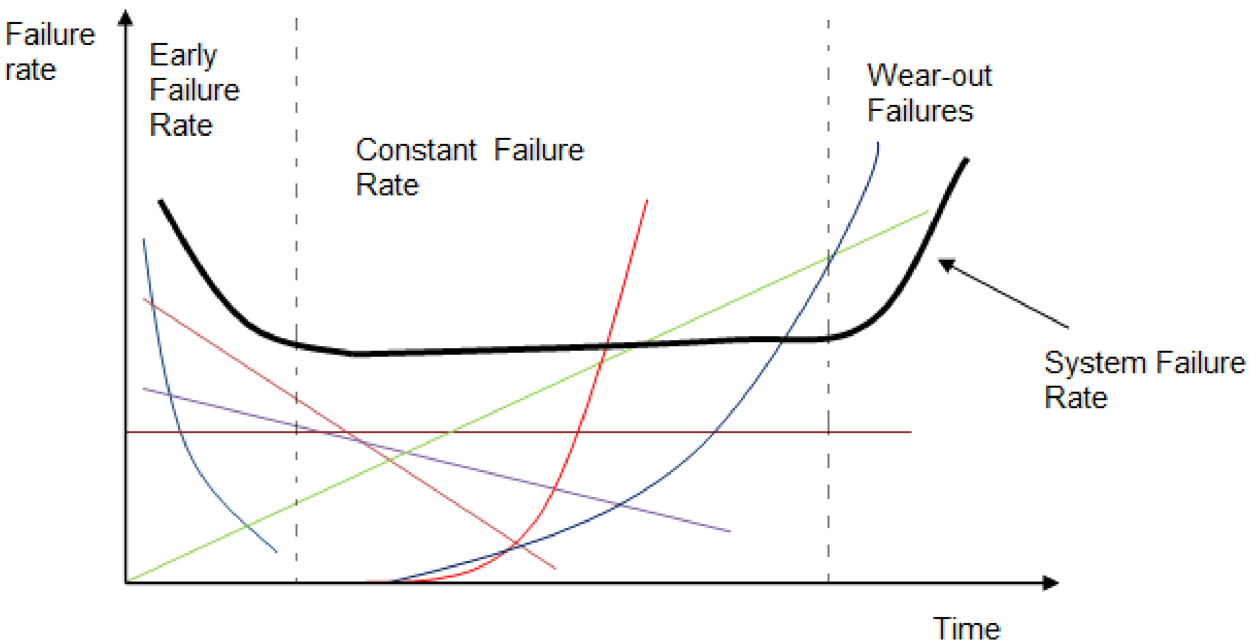


Figure 2-2: System and Component failure rate vs. Time (Troyer, 2009)

The bathtub curve on Figure 2-2 describes the failure rate of the entire population of components in the system over time. The three types of failure rate trends on the bathtub curve over the entire time are,

- **Early failure rate**:the intial period of the bathtab curve is starting with a high failure rate and deacreses with time. Therefore, it hasa decreasing failure rate trend. The reason of early equipment failure is usually because of design problem, manufacturing defects, incorrectly assembled, or lack of proper control on the operation processeand use of low standard components.One of the methods used to reduce infant mortality (early failure) is controling the quality of components before installations (quality control)(Reliability Analytics Corporation, 2011).

- **Constant failure rate:** this zone is characterised by a constant failure rate trend. In this area components are usually failed by chance. Exponential failure distribution is apllied for a constatnt failure distribution.There are different reasons why components are failed during this time. Some of the reasons are limitations of component strength for the given operating stress (overload), accidents due to poor maintenance activities, etc.

- **Wear-out failures:** is characterized by increasing failure rate with time. Failures in this period are caused by material detrioration or fatigue with age. The only way to prevent wear out failure is to give approprate maintenance on time before failure has happened(Reliability Analytics Corporation, 2011).

As we can see from equation 2.1, Failure rate can be calculated from the statistical failure data over a specified period of investigation time. Failure rate can be expressed in different ways such as (Antony, 2008),

- Number of of failures per year, hour or minuts
- Number of of failures per mile (in automated field) or
- It can be expressed in terms of per operating cycles like Number of of failures per one million revolutions.

$$Failurerate = \frac{totalnumberoffailureswit \quad hint hepopulation}{totalrunningtimeduringt \quad heperiodofinvestigation} 2.1$$

The failure rate for new equipment is predicted from the historical failure data of similar equipment.

Among the mathematical model used to analyze statistical data and describe (model) the probability density function of equipment failures, Weibull distribution is best for a system of having a bathtub curve failure rate distribution. The probability density function for each type of failure rate trend will have a curve with different types of shapes with different values of shape factor, β (Figure 2-3).

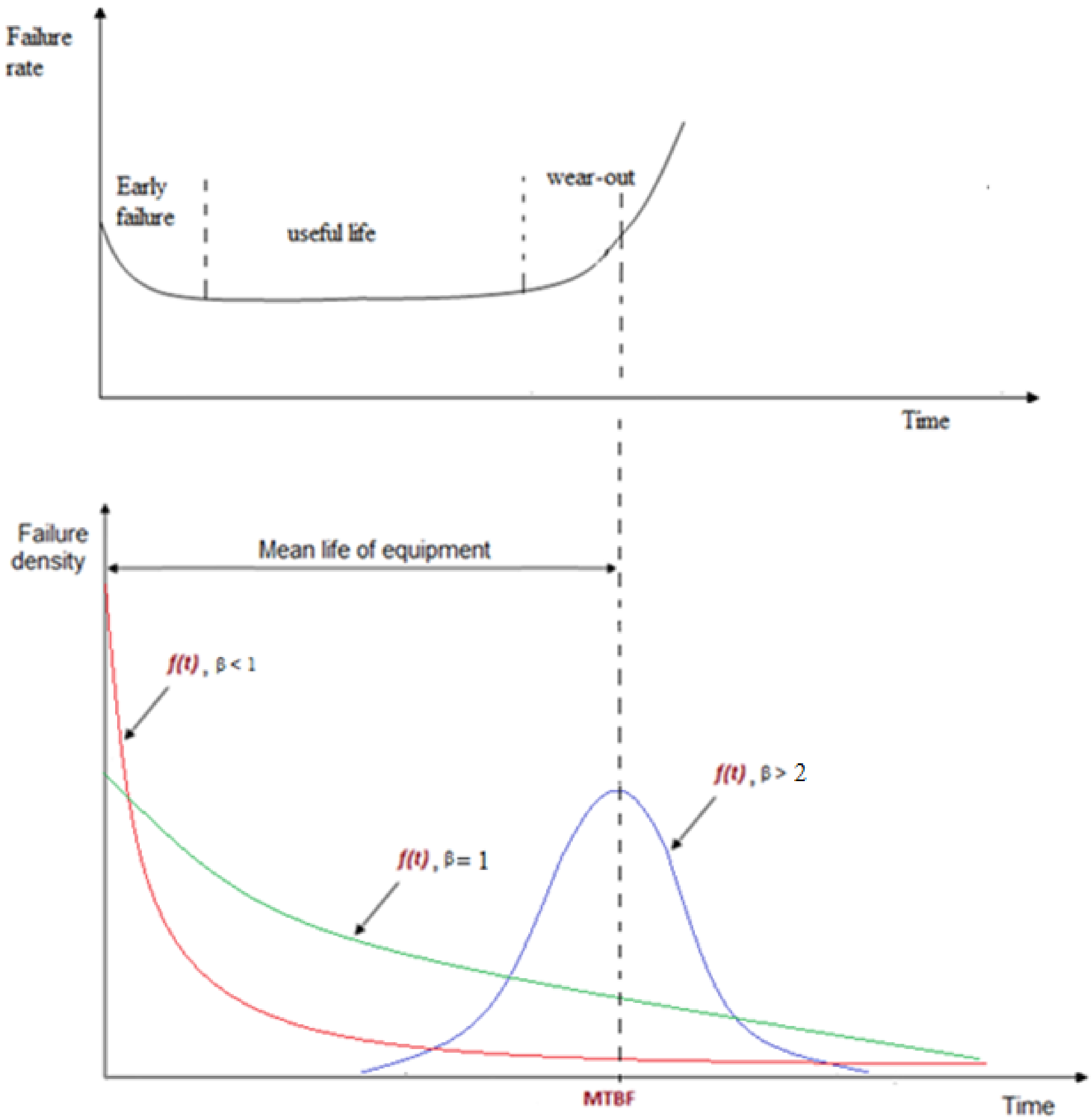


Figure 2-3: Failure probability density function for different values of β (Kelly, 1997)

The value of the shape factor, β depends on the type of failure rate distribution (early failure distribution, useful life, or wear out failures). The mathematical equation of a two parameter Weibull distribution to express the failure probability density functions of equipment, $f(t)$is given by (Troyer, 2009):

$$f(t) = \beta ⅄^{\beta}(t)^{\beta-1}e^{-(t⅄)^{\beta}} \quad 2.2$$

Where: β = the slope of distribution curve (shape factor)
⅄ = *Failure rate*

The values of the shape factor, β in three different failure characteristic areas on the bathtub curve are,

i. When the value of β< 1, weibull distribution describes the failure probability density function of early componentfailures (infant mortality failures). For this case, failure rate dicreases with time.The failure probabilty density function is having hyper-exponential or running-in probabilty density function(Kelly, 1997).
ii. When the value of β = 1, weibull distribution describes the failure probability density function of usfull life of equipment. In this case, failure rate is constant. The failure probability density function is having an exponential distribution function (Figure 2-3) and is given by:

$$f(t) = ⅄e^{-⅄t} \quad 2.3$$

Where: ⅄ = failure rate (constant)

f (t)= probability density function

iii. When the value of β>2, weibull distribution describes the failure probability density function of wear out failures.As the value of β raises above 2 the probability density function is having a normal distribution. The only way to prevent wear out failure is by performing a preventive maintenance action at regular time intervals(Kelly, 1997).

Limit should be considered to describe the uncertainty when we estimate reliability parameters (MTBF and failure rates). The uncertainty limit depends on the sample size and amount of failure data considered to estimate the parameters (Antony, 2008).

For example, when there is no enough statistical data are available, there will be a high uncertainty to the estimated parameters (MTBF and failure rates). In this case the probability density function will be more dispersed and more difficult to justify the time to perform preventive maintenance actions (Figure 2-4).

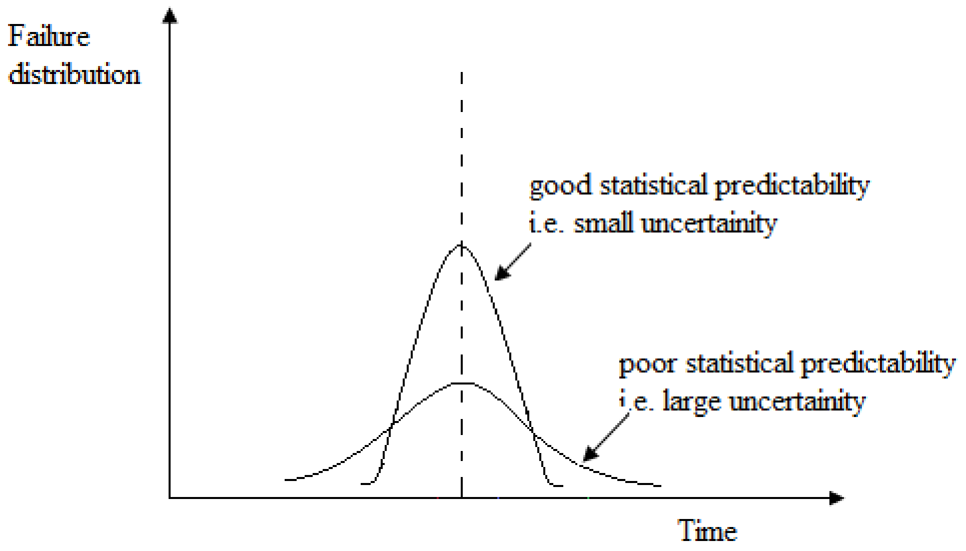


Figure 2-4: statistical predictability (Kelly, 1997).

Most engineering equipment is failed in the region of some mean operating ages (Mean time between failures). Depending on the operating condition of the machine, the value of mean time between failures (operating ages) and failure rate distribution with time will be different. For example, the machine which is operating under extreme condition will not have the same values of mean time between failures and failure rate distribution than when it is operating under a good operating condition. Therefore, equipment's operating condition must be considered when we evaluate the reliability parameters. As shown on Figure 2-5, there are three different types of probability density functions with different mean time between failure values, MTBF1, MTBF2, and MTBF3.

i. Case one shows a probability density function of statistical failure data when equipment is working under similar and extreme condition like, corrosive environment, extreme temperature condition (High or freezing), excessive contamination level, strong magnetic field, tropical environments, etc. therefore, equipment will have a shorter life (MTBF 1) than its normal life.
ii. For the second case, the probability density function is aresult of statistical failure data taken from equipment operating under different conditions. This will give us a wrong estimation of mean time between failures to determine a preventive maintenance time. Equipment may break down before maintenance is performed or earlier maintenance will be carried out when it is not really needed. Therefore, it is important that statistical failure data should be collected and analyzed with detail information.

iii. The third case shows the probability density function of statistical failure data taken from equipment working undersimilar and good operating condition.

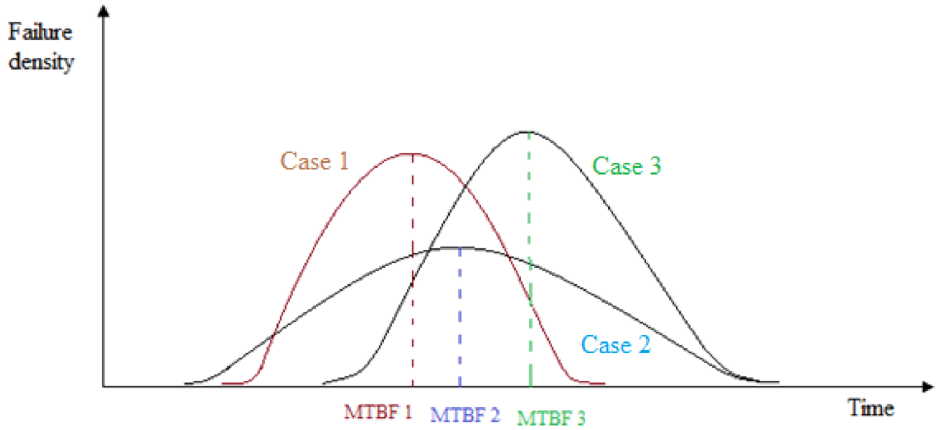


Figure 2-5: Failure rate density function under different operating conditions

2.4 Mean-time-between-failure (MTBF)

Mean time between failures (MTBF) is the estimated time between two consecutive equipment failures. In reliability engineering, MTBF is a common measure of describing the reliability characteristics of reparable system. MTBF is commonly estimated from the historical failure data of the machine recorded on a maintenance database. As we see it on Table 2-1 below, the value of MTBF is calculated for equipment under the main functions of a three stage gas compression system. The estimated values of MTBF and failure rate per million hours listed on Table 2-1 are for the main functions of the first stage gas compression processes (only some of the equipment is listed). The value of MTBF is simply a reciprocal value of the failure rate (see equation 2-3) (Troyer, 2009).

$$\text{MTBF} = \frac{1}{\text{Failure}} = \frac{\text{total running time during the period of investigation}}{\text{total number of failures with in the population}} \qquad 2.4$$

Since MTBF = 1/λ, the failure probability density function, $f(t)$becomes,

$$f(t) = \beta \frac{(t)^{\beta-1}}{MTBF^{\beta}} e^{-(\frac{t}{MTBF})^{\beta}} \qquad 2.5$$

Table 2-1: Failure rate and MTBF for main equipment in the first stage of gas compression processes (Apply Sørco, 2012)

Main Function	Name of Main Function	Comments/ Description	Main Equipment	Failure Mode	Number of failures pr 1000000hr	OREDA all modes failure pr 1000000hr (MTBF)
2302	Cooling of gas by cooler from 2nd stage separator 20VA002	These are plate coolers and cools from 74 to 30C with the cooling medium as sea water	23HB101A 23HB101B 23HB201A 23HB201B	Internal/ External leakage, structural damage	17	Critical failure M = 6,8 Years
2303	Circulating seawater for cooling	Globe valve	23TV0101 23TV0201 23TV0301 23TV0401	Fail to open/close on demand Plugged	3	critical failure M = 42,8 Years
2304	Scrubbing of cooled gas in first stage scrubbers 23VG101 and 23VG201	Vertically mounted two-phases separator. Level indicating controller: High alarm 78%. Low alarm 45% Level safety transmitter: High High alarm/trip 94% Low alarm/trip 30%	23VG101 23VG201	Blocked inlet or outlet. External leakage	23	Critical failure M = 4,97 Years
2307	Compression of gas in export compressors 27KA101 and 27KA201	Suction Pressure High alarm trip: 1,5 barg Low alarm trip 0,05 barg. Discharge Pressure High alarm trip: 8 barg. Low alarm trip 2,7 barg. Temperature high alarm	23KA101 23KA201 23PST0151 PSD 23S0026 23S0467 23PST0152 PSD 23TST0153 PSD	Breakdown Overheating Plugged Seal leakage	176	Critical failure M = 0,65 Years
2309	Pumping of condensed liquid from first stage scrubber to 2nd stage separator in system 20	Centrifugal pump, electrical driven. Pressure low low alarm trip 1 barg. Flow low low alarm trip 2,5m3/hr	23PA101A 23PA101B 23PA201A 23PA201B 23PST0152 PSD 23TST0153 PSD 23S0045	Fail to start/stop on command Spurious stop Plugged	50	Critical failure M = 2,3 Years

2.4.1 Misconception of Estimating the Value of MTBF

There is a misconception when we estimate the value of MTBF. Mostly, the values of MTBF is calculated based on equipment failure data collected for a certain period of time, may be when the machine/equipment was operating under a good conditions or normal life. During this time they have the lowest failure rate. For example, let us take a sample of 20,000 people and all of them are 20 years old on a sample population. Within one year period, the data is collected on failures (death) from this population.

- Operational life of the population is, 20,000*1 year= 20,000years
- Let us say, from the data collected 100 people are failed (died). Therefore, the failure rate, FR = 100/20,000=0.005/year

Therefore, MTBF= 1/0.005 = 200 years, which is unrealistic.

The only true way to calculate MTBF that would evaluate the service life of an item is from the data which is collected for the entire population from their normal life to their end of life (Torell&Averal, 2004).

2.4.2 Methods used to determine the value of Mean Time betweenFailures (MTBF)

By far, there are two methods of determining the value of MTBF(Jamaluddin et al., 2009).

a. **Estimate MTBF**: estimating the value of MTBF when we have enough historical maintenance data

b. **Predict MTBF**: when we don't have enough historical data, for example, for the case of Space Shuttle or new product designs, we are going to use historical data of similar products to predict MTBF or calculate the value of meantime time between failure based on system reliability design.

2.5 Periodic MaintenanceWeakness

Since periodic maintenance is performed based on the mean time between failures (MTBF) which is estimated from the historical equipment failure data available, it has the following weakness.

i. The maintenance activities may be performed after the machine breakdowns in service, orwhile the machine is under a normal operating condition. Performing unnecessary maintenance activities will cause overstocking of spareparts, high maintenance cost and unnecessary downtime.

ii. During the estimation of the value of MTBF, loading variation on equipment and working environment are not usually considered.this will lead to the wrong estimated valuse of MTBF.
iii. Disassembling the whole system for inspection, repair or replacement purpose will cause further system failure (Williams et al., 1994).

3. A Procedure for Condition Based Maintenance

Condition monitoring is a maintenance process used to collect and evaluate a real time data to identify changes in the operating condition of the system or items within the system. Well designed condition monitoring system improves system reliability and reduces unexpected production losses. Unexpected downtime will cost organization in millions of dollars. Some of the reasons to implement condition monitoring program to the system are surmised below (Sondalini, 2004),

- It is used to identify any changes on the operating conditions of the machine/equipmentby measuring parameters chosen for condition monitoring.
- Reduce production cost by eliminating unnecessary downtime and number of maintenance service. Every period of time when periodic maintenance is performed based on equipment's failure history, critical equipment will be shutdown and disassembled fully or partially for repair, replacement or inspection purpose. During this time production will stop. Therefore, if the parameters chosen for monitoring the system operating conditions are properly measured and analyzed, there will be valuable information to optimize periodic maintenance intervals so that the maintenance action can be carried out when it is necessary.
- To improve system reliability by verifying if there is a design problem or production defects.
- Improving product quality by improving maintenance quality.
- Improve safety: saftey can be improved by performing periodic maintenance at regular bases before the machine breakdowns and cause harm to the people and environment.

Depending on the criticality of equipment, condition monitoring is taking place either periodically (time-based monitoring) or continuously (real-time data).There are different ways of monitoring equipment such as, (Butcher, 2000).

- Using different types of sensors which can be installed on the operating equipment and monitoring it continuously (online), or
- Using portable sensors that can measure any changes on the condition of equipment, or
- Using manual gauges or instruments to perform time based inspection

As illustrated on figure 3-1, by integrating condition monitoring data with historical data, periodic maintenance can be effectively scheduled. As a result, the availability and reliability of the system will increase and so as the production performance.

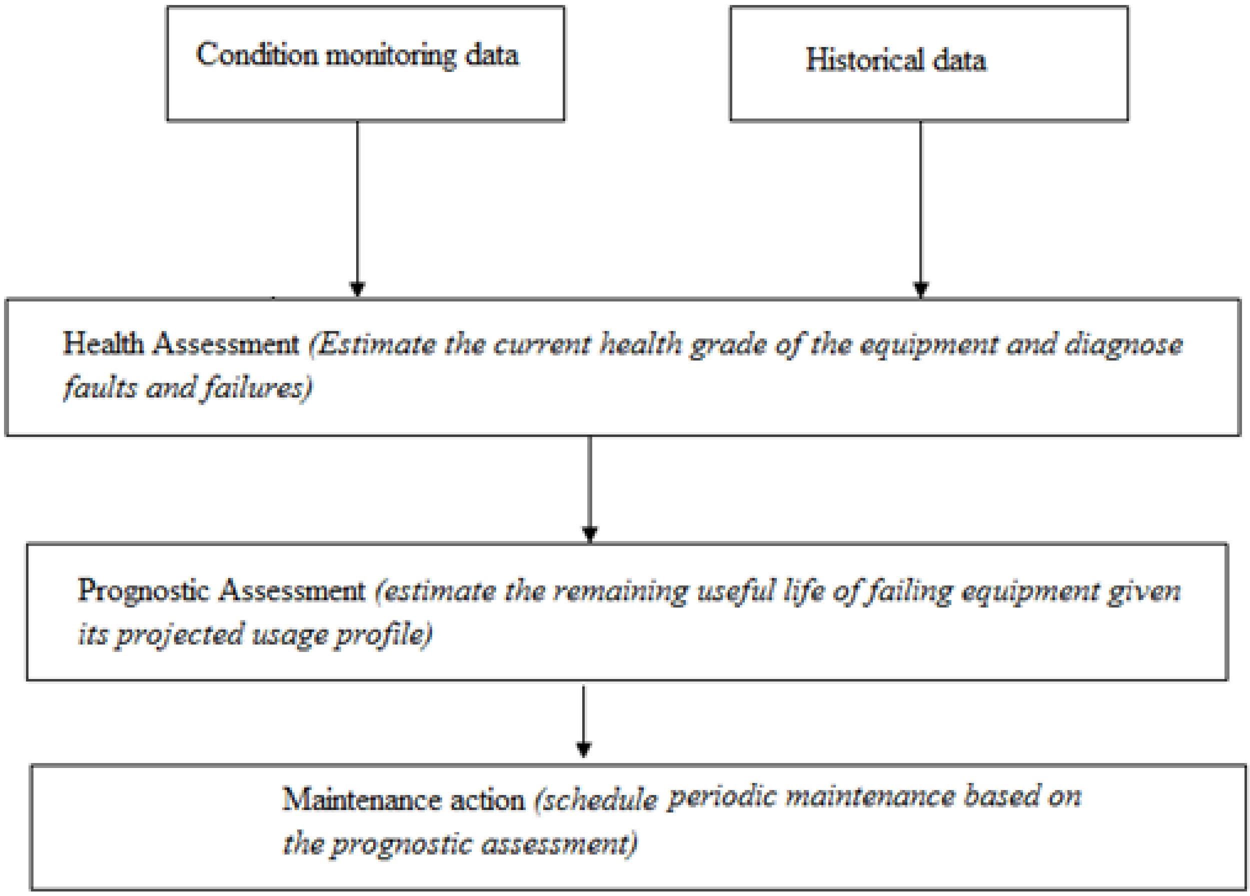


Figure 3-1: Integration of condition monitoring data with historical data to optimize periodic maintenance time interval

Condition based maintenance is performed based on the actual condition of equipment when it is needed. A procedure which will be used when implementing condition based maintenance to the system is summarized on Figure 3-2 below. The key steps are discussed in detail.

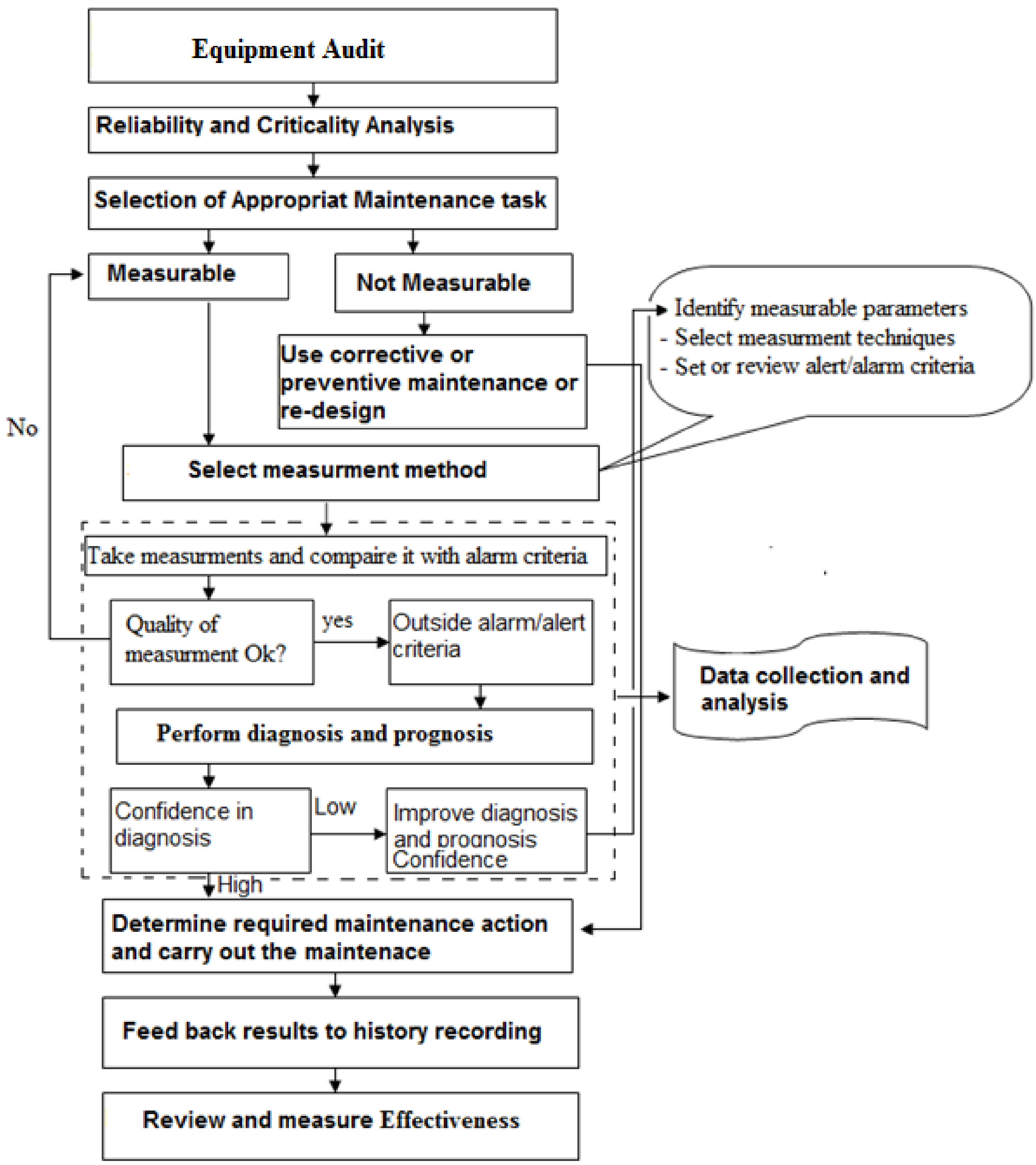


Figure3-2: A procedure for Condition based maintenance (ISO-17359, 2002)

3.1 Equipment Audit

The first step of condition monitoring process is that all assets in the plant should be clearly identified and labeled on the maintenance database. Identify their function (what is the equipment required to do) and operating conditions are also important on this step (ISO-17359, 2011). Some of the activities taking place in this stage are:

- Surveying the plant to identify equipment and their functions
- Discuses the processes diagram if there is and understand the operating process of equipment.

3.2 Reliability and criticality analysis

Some of the activities carried out in this step are produce reliability block diagram, equipment criticality analysis, and FMECA. Reliability and criticality analysis help the maintenance personnel to target the most important asset for condition monitoring program and apply the correct maintenance decision (AV Technology Ltd, 2011).

3.2.1 Produce reliability block diagram

Reliability block diagram is a graphical representation of components in the system and their connections with each other. It is used to define the logical relations between component/equipment failures within the system, how the failure of one equipment/component can affect the others or the whole system. The reliability block diagram can have a series, parallel or series-parallel configurations (ITEM, 2007). When we produce the reliability block diagram lines represent the connection between components and blocks represent the components itself (Figure3-3).

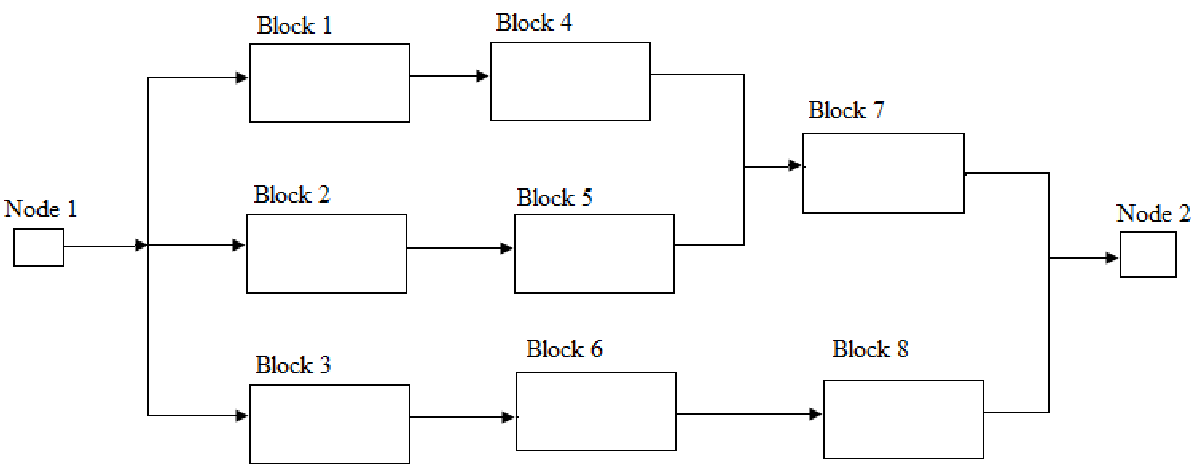


Figure 3-3: Example of Reliability Block Diagram

The reliability of the system can be calculated from the assigned probability of failure for each component in the system.

3.2.2 Equipment criticality analysis

Equipment criticality analysis is prioritizing equipment based on their failure consequences mostly on the production, HSE, and costs. In most industries, risk matrix is a common ways of classifying failure consequences. Therefore, risk matrix can be used to classify equipment into different classes of risk level so that equipment can be prioritized for inspection, maintenance, work orders and others. As shown on Table 3-1, there are three categories of consequences (C1, C2 and C3), four categories of probabilities of failure occurrence, and three classes of risk level (High = H, Medium = M, and Low = L). For this case equipment can be grouped into three different classes of risk level. The number of classes can be different from organization to organization (NORSOK STANDARD (Z-008), 2011).

Table 3-1: Example of risk matrix used for prioritizing equipment (NORSOK STANDARD (Z-008), 2011)

Freq. cat.	**Freq. per year (*), (**)**	**Mean time between failure (year)**	**RISK**		
F4	**> 1**	**0 to 1**	M	H	H
F3	**0,3 to 1**	**1 to 3**	M	M	H
F2	**0,1 to 0,3**	**3 to 10**	L	M	H
F1	**< 0,1**	**Long**	L	L	M
			Loss of function leading to:		
Consequence category			**C1**	**C2**	**C3**
Consequence safety			No potential for injuries. No effect on safety systems.	Potential for injuries requiring medical treatment. Limited effect on safety systems.	Potential for serious personnel injuries. Render safety critical systems inoperable.
Consequence containment			Non-flammable media Non toxic media Natural/normal pressure /temperature media	Flammable media below flashpoint Moderately toxic media High pressure/ temperature media (>100 bar/80 °C)	Flammable media above flashpoint Highly toxic media Extremely high pressure /temperature media
Consequence, Environment; restitution time (***)			No potential for pollution (specify limit) < 1 month	Potential for moderate pollution. 1 month – 1 year	Potential for large pollution. > 1 year
Consequence production			No production loss	Delayed effect on production (no effect in x days) or reduced production	Immediate and significant loss of production
Consequence other			No operational or cost consequences	Moderate operational or cost consequences	Significant operational or cost consequences

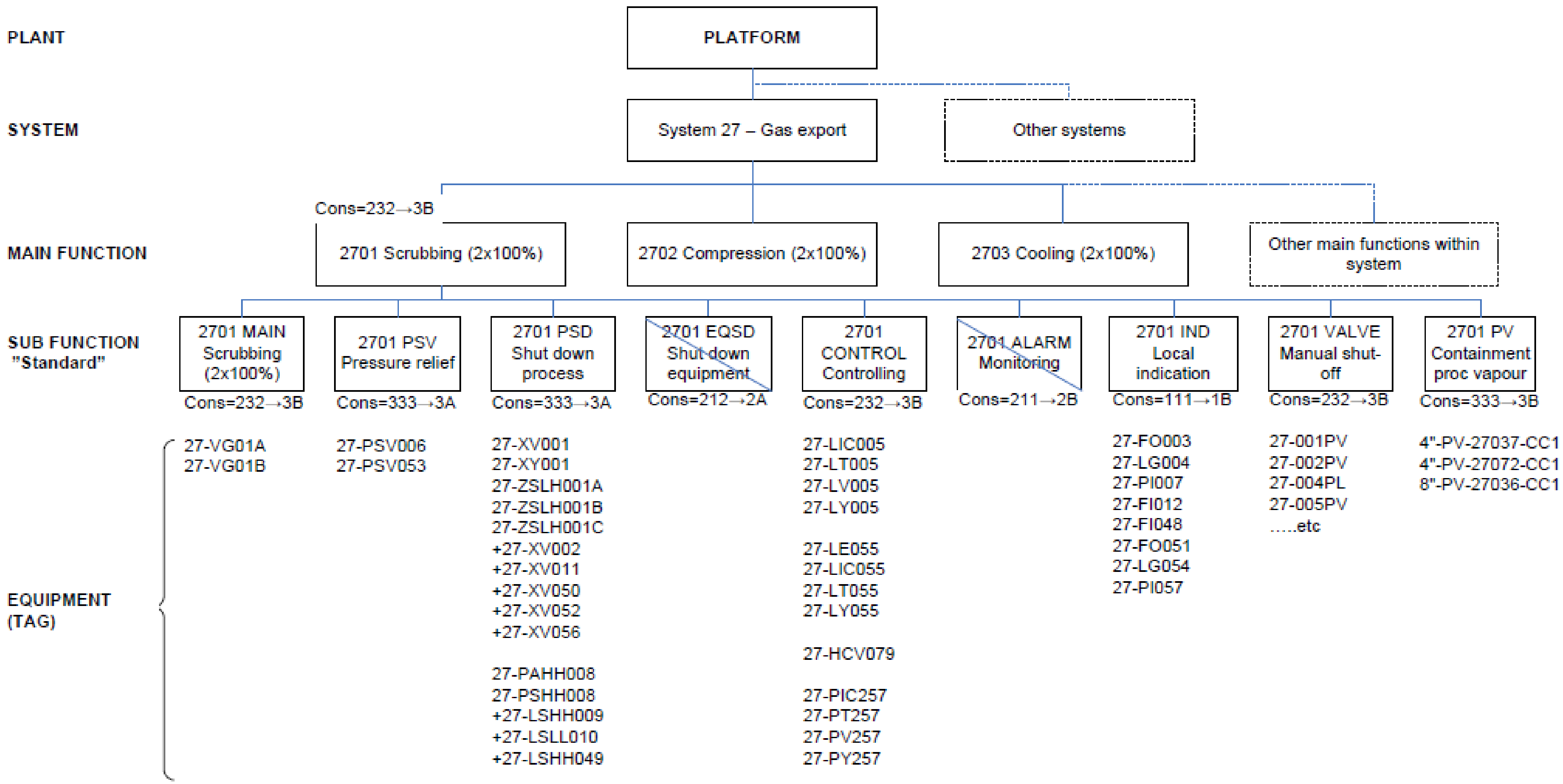
Equipment in the system has two types of hierarch, technical hierarch and functional hierarchy. Technical hierarch gives an overview about how equipment is related to each other technically. Functional hierarch gives an overview about how equipment is interrelated functionally to each other and to the system as a whole. Understanding the functional hierarch of the system helps to identify critical equipment. Functional hierarch may have two or three levels of detail. For example, as illustrated on Figure 3-4, scrubbing is one of the main functions of the gas exporting system (system 27 in the Norwegian continental shelf). Scrubbing is used to remove condensate gases or moistures within the gas to be exported. If the scrubber is not working properly, it will affect the whole system. For example, the gas compressor next to the scrubber will be damaged with time if there is any moisture passing through the compressor with the gas. Under this main function(scrubbing), there are sub functions that includes2701 MAIN Scrubbing (2x100%), Pressure relief(2701 PSV), Shut down process (2701 PSD), Shut down equipment (2701 EQSD), Controlling (2701 CONTROL), Monitoring (2701 ALARM), Local indication (2701 IND), Manual shut-off (2701 VALVE), and Containment process vapour (2701 PV)(NORSOK STANDARD (Z-008), 2011).

A fault which prevents the main function from operating will affect the whole system (the gas exporting system) immediately (with in 0 hour) with a 100% loss of functionality. Under each sub functions there are different types of equipment identified by their tag numbers (Figure 3-4) and faults on this equipment will cause the same consequences on the main function as the sub function. Therefore, equipment under the sub functions has the same classes of consequences with the sub function. Consequence classification of the sub function is shown on Table 3-2 below (NORSOK STANDARD (Z-008), 2011).

Table 3-2: Consequence classification of the sub functions on Figure 3-4(NORSOK STANDARD (Z-008), 2011).

Function	**Description**	**Reduction**	**Crit. time (Hours)**	**Redundancy degree**	**Classification**		
					S	P	C
2701 MAIN	Scrubbing	100 %	0	B	2	3	2
2701 ALARM	Monitoring	0 %	168	B	2	1	1
2701 CONTRO	Controlling	100 %	0	B	2	3	2
2701 IND	Local indication	0 %	720	B	1	1	1
2701 PSD	Shutdown, Process	100 %	0	A	3	3	3
2701 EQSD	Shutdown, Equipment	100 %	0	A	2	1	2
2701 PSV	Pressure relief	100 %	0	A	3	3	3
2701 VALVE	Manual shut-off	100 %	0	B	2	3	2
2701 PV	Containment, Process Vapour	100 %	0	A	3	3	3

Where: S = Safety, P= Production, O = Cost
3 = High, 2 = Medium, 1 = Low
A = No Spare, B = One Spare, C = Two or More Spares



Explanation: Cons = Consequence. Figures: 3=High, 2=Medium, 1=Low HSE, Production and Cost respectively. Last result is a combination of the highest Consequence and Redundancy degree (A – No spare, B – One spare, C – Two or more spares) in operational phase.

Figure 3-4: Functional hierarchy, example with standard sub function and classification (NORSOK STANDARD (Z-008), 2011)

From the result of equipment criticality analysis the following actions must be decided.

- Equipment under high classes of consequences should be either redesign or carried out further FMECA analysis.
- Equipment listed under medium classes of consequences FMECA analysis will be considered.
- For equipment which are classified under low classes of consequences may be corrective maintenance should be considered.

3.2.3 Failure modes, Effects and criticality analysis (FMECA)

A failure mode, effects and criticality analysis is used to identify all possible failure modes and their effects on the system and avoid these failures or reduces the effects on the system.

As it is described in ISO-17359, 2002,*"FMECA analysis is used to identify potential failures, their consequences and parameters used to identify the presence of potential failures"*.

FMECA analysis has two parts; FMEA and critical analysis (CA). FMEA is the part where different types of failure modes and their consequences are identified. It is used to identify possible failures and their effects on the system during design. Criticality analysis is used to prioritize or raking different failure modes based on their severity (on the production, HSE, cost, etc.), rate of occurrence (probability of occurrence), and detectebilitiy. In theory, the combination of these three criteria is used for failure mode criticality analysis and is called risk priority number (RPN). RPN is the overall risk for each type of failure modes (Equation 3.1). But in reality, it doesn't work like this most of the time. One company may give more priority for safety than cost or production, or in the other way around.

RPN = Severity (S) x Probability of occurrences (F) x Detectebilitiy (D) 3.1

An example of FMECA is shown on Table 3-3 for the main functions of a gas compression in the gas exporting system (system 27). Equipment under the main functions has the same criticality rate with the main function. They are listed by their tag numbers.

Table 3-3: FMECA analysis for main equipment in the first stages o f gas compression processes (Apply Sørco, 2012)

Main Function	Name of Main Function	Comments/ Description	Main Equipment	Workshop Results									
				Complete Failure S = Safety/Health, E = Environmental, O = Operational, C = Cost									
				Failure Mode	Consequence S	E	P	C	Complete Failure Frequency	Rationale	System effect	Installation effect	Compensating measures
2306	Flaring of gas to HP flare header		23PSV0110A 23PSV0110B 23PSV0210A 23PSV0310A 23PSV0310B 23PSV0360A 23PSV0360B 23PV0359 23BV0356 ESD 23PSV0410A 23PSV0410B 23BV0456 ESD 23PV0459 23PSV0460A 23PSV0460B	Fail to open/close on demand Plugged	3	1	3	1	5-30 Years	A safety valve plugged will activate safety systems and a failure of a non-safety valve to open on demand can cause reduced flaring.	Failure of safety valves can cause safety hazards to the personnel. Flare system will be required to shutdown	Stop production for more than 12 hours	Isolate the defective PSV and continue to flare through other PSV.
2307	Compression of gas in export compressors 27KA101 and 27KA201	Suction Pressure High alarm trip: 1,5 barg Low alarm trip 0,05 barg. Discharge Pressure High alarm trip: 8 barg. Low alarm trip 2,7 barg. Temperature high alarm trip 124C.	23KA101 23KA201 23PST0151 PSD 23S0026 23S0467 23PST0152 PSD 23TST0153 PSD 23S0045	Breakdown Overheating Plugged Seal leakage	1	1	3	3	5-30 Years	Failure could result in loss of production for more than 12 hours.	A system shutdown will be required for more than 12 hours to restore the function.	A complete function failure will result in installation shutdown for more than 12 hours.	Continue to produce on reduced capacity on partial functional failure.
2308	Sampling of gas		23AP001 23AP003	Plugged/ Choked	1	1	1	1	0-12 months	A blockage in sampling station will have no influence on safety, environment, operation and cost.	No effect on operations.	No influence on rate for the separator.	

Main Function	Name of Main Function	Comments/ Description	Main Equipment	Workshop Results									
				Complete Failure S = Safety/Health, E = Environmental, O = Operational, C = Cost									
				Failure Mode	Consequence				Complete Failure Frequency	Rationale	System effect	Installation effect	Compensating measures
					S	E	P	C					
2306	Flaring of gas to HP flare header		23PSV0110A 23PSV0110B 23PSV0210A 23PSV0310A 23PSV0310B 23PSV0360A 23PSV0360B 23PV0359 23BV0356 ESD 23PSV0410A 23PSV0410B 23BV0456 ESD 23PV0459 23PSV0460A 23PSV0460B	Fail to open/close on demand Plugged	3	1	3	1	5-30 Years	A safety valve plugged will activate safety systems and a failure of a non-safety valve to open on demand can cause reduced flaring.	Failure of safety valves can cause safety hazards to the personnel. Flare system will be required to shutdown	Stop production for more than 12 hours	Isolate the defective PSV and continue to flare through other PSV.
2307	Compression of gas in export compressors 27KA101 and 27KA201	Suction Pressure High alarm trip: 1,5 barg Low alarm trip 0,05 barg. Discharge Pressure High alarm trip: 8 barg. Low alarm trip 2,7 barg. Temperature high alarm trip 124C.	23KA101 23KA201 23PST0151 PSD 23S0026 23S0467 23PST0152 PSD 23TST0153 PSD 23S0045	Breakdown Overheating Plugged Seal leakage	1	1	3	3	5-30 Years	Failure could result in loss of production for more than 12 hours.	A system shutdown will be required for more than 12 hours to restore the function.	A complete function failure will result in installation shutdown for more than 12 hours.	Continue to produce on reduced capacity on partial functional failure.
2308	Sampling of gas		23AP001 23AP003	Plugged/ Choked	1	1	1	1	0-12 months	A blockage in sampling station will have no influence on safety, environment, operation and cost.	No effect on operations.	No influence on rate for the separator.	

3.3 Selection of appropriate maintenance task

Some failure mode symptoms are hard to measure. If the failure mode symptom doesn`t have a measurable parameters, an alternative maintenance strategy (either corrective maintenance or re-design) has to be implemented. If it is measurable, the next step will be carried out (Select measurement method) (ISO-17359, 2002).

3.4 Measurement method

In this part, some of the activities carried out in this stage are identify measurable parameters, select measurement techniques, monitoring interval, and set or review alarm/alert criteria.

- Identify measurable parameters: measuring parameters will be selected based on the type of failure mode symptoms. The parameters can be pressure, temperature, vibration, voltage, resistance, etc.
- Select measurement techniques: approprate measurment techniques should be selected based on the parameter needs to be measured to reveal equipment failures with time. For some types of equipment failures, more than one types measurment teqniques may be required.
- Monitoring intervals: condition monitoring can be either continuous or periodic. Either the type condition monitoring (online or periodic)or monitoring interval will be decided based on the criticality of equipment and failure modes.
- Set or review alarm/alert criteria: the alarm/alert criteria is set or reviewed based on failure history, standards, manufacturer`s guide lines, and experience (ISO-17359, 2002)

3.5 Data collection and analysis

There are different types of technologies, models and algorithms are used for condition monitoring data collection and signal processing. Measurements are taken from different sources and processed to identify equipment failure trends and determine the require maintenance action. Activities carried out in this stage are data acquisition, data manipulation, state detection, health assessment, and prognostic assessment (Andrew et al., 2009). The data collection and analysis a process is summarize on Figure 3-5 below.

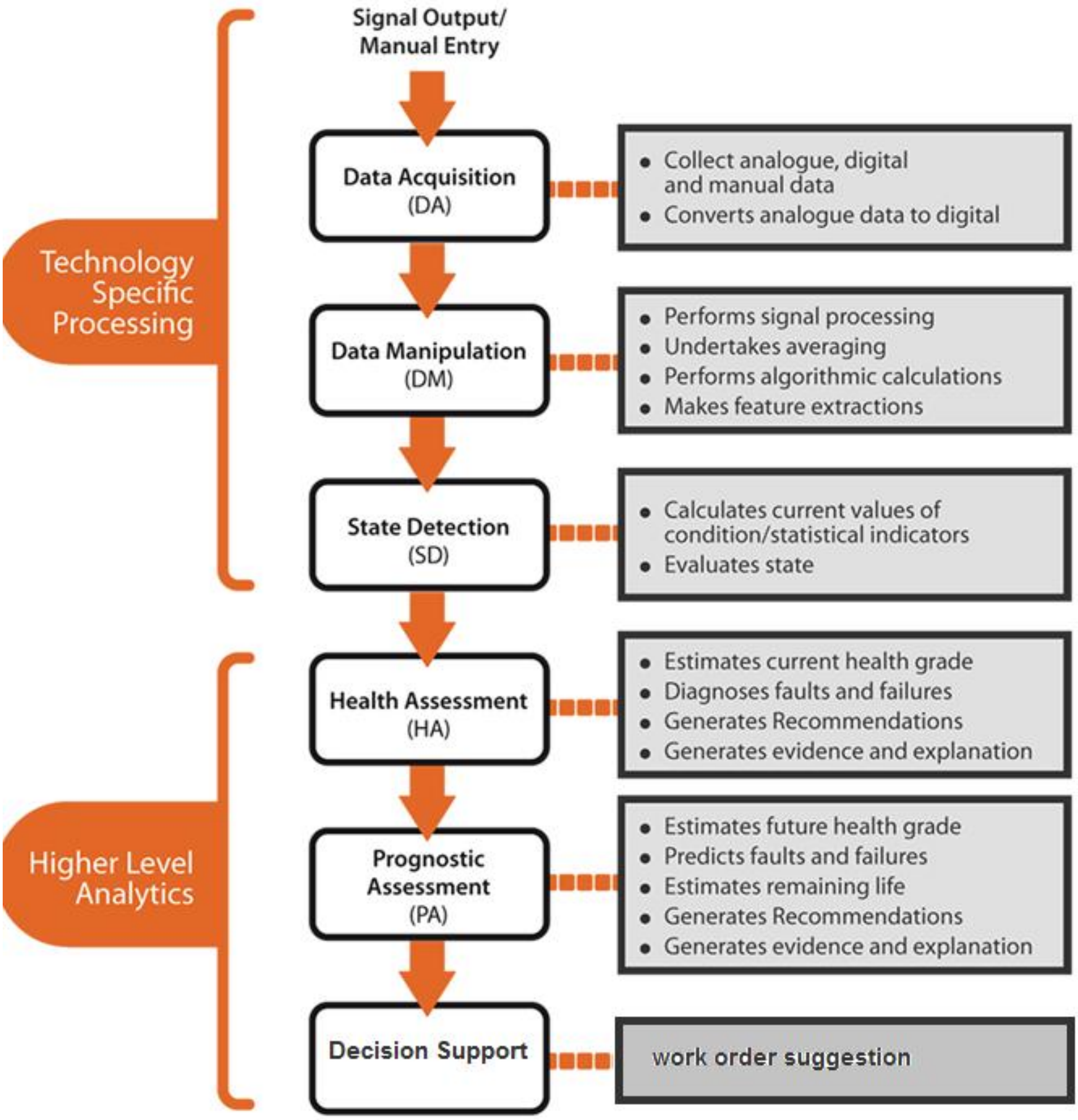


Figure 3-5: Data collection and analysis process block (Schwarzenbachet al., 2010)

3.5.1 Data acquisition (DA)

In the data acquisition stage an input data are collected from different condition monitoring data sources as a form of single value data (temperature, pressure, humidity), wave form data (vibration and acoustic data), or multidimensional data (thermography and x-ray data); and manual entry data which is also called an event data. The event data is all about the information what happened on the past, was there any activities carried out, like some replacement, oil change, etc.? This data will improve our judgment on the interpretation of condition monitoring data on a specific failure mode. Data acquisition block commonly consists of signal conditioning and analog to digital convertor. At the end of data acquisition processes the quality of the data will be identified (bad, good, unknown) and the data will be digitalized (Andrew et al., 2009).

3.5.2 Data manipulation (DM)

As described on ISO 13374-2, 2004, "*data manipulation processes the digital data from the data acquisition block to convert it to a desired form which characterizes specific descriptors (features) of interest in the machine condition monitoring and diagnostic process.*"

In data manipulation block, different types of special processing function such as Fast Fourier Transformation (FFT), wavelets or simple average value over a time interval are used to process the signal.

3.5.3 State detection

The primary function of State detection is to report any deviations from the normal operational conditions by comparing the outputs from data acquisition and data manipulation with a baseline profile values. It is also used to assess the operational state of the machine (for example, high speed operation, normal speed operation or low speed operation). In this stage, the state indicators from the machine will be calculated and helps to generate alert based on the defined condition limits (ISO 13374-2, 2004).

3.5.4 Health Assessment

Estimate the current health grade of the equipment and diagnose faults and failures with associated degree of confidence (likely hood probability) by combining inputs from data acquisition, data manipulation, state detection and other health assessment information like trends in the health history, operational information of the equipment, and others. Therefore, in this stage faulty items will be identified and isolated from the system.

3.5.5 Prognostic Assessment

Prognostic assessment is used to estimate the remaining useful life of failing equipment given its projected failure trends. Prognostic assessment determine the future deteriorating rate of equipment in terms of the current information (health assessment data, state detection data, data manipulation, and data acquisition) , historical failure data, and other external factors by applying prognostic algorithm/model with associated level of likely hood probability distribution(Campos, 2009).

Unlike electrical systems, Prognostic assessment is mostly implemented on the system consists of mechanical and structural components which are deteriorating slowly with time. Assessing equipment failure trend helps to recalculate its remaining useful life. Depending on the relation between individual components within the system or the criticality of components in the system, component level prognostic conclusion will extend to system level decision. (Mathur et al., 1994).

3.6 Determine and carry out the required maintenance action

The main purpose of condition monitoring on periodic maintenance is either to eliminate equipment breakdowns or prolong maintenance intervals. If the current estimated equipment condition reaches or exceeds a predefined failure limit, an appropriate maintenance action will be decided to carry out. If the present condition of the equipment is fine, maintenance action will be scheduled for the near future according to the failure trend analyzed on prognostic assessment (Figure 3-6).

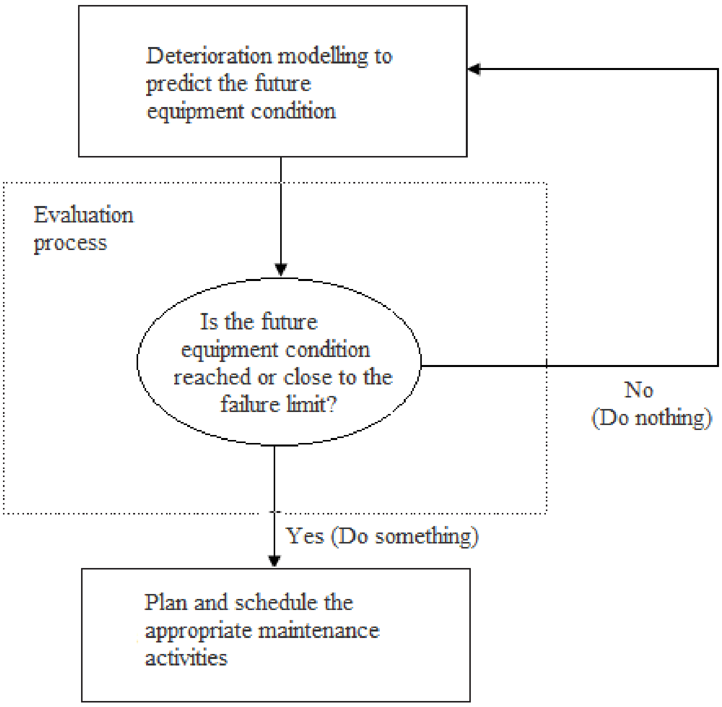


Figure 3-6: Maintenance decision framework

In the end, the condition monitoring process and alarm/alert value should be reviewed. Since the mean-time-to failure is estimated with a high degree of probability of confidence based on both historical data and condition monitoring data, periodic maintenance will be performed when it is necessary.

3.7 Challenges of condition based maintenance

There are several challenges that the organization is going to face when condition based maintenance is introduced to the system. Some of the challenges are (IAEA, 2007),

- High intial cost: since different types instrumentations and technologies are required for condition monitoring data collection and processing, the intial cost will be high. Therefore, it is important to do the cost-benefit analysis before the investment starts.
- False reading from the instruments (sensors): sometimes, instruments used to detect equipment's fault may fail and gives a false indication. Therefore, it is very important to check the sensors whether they are working perfectly or not every time.
- Training is required: a high degree of technologies are usually involved when condition based maintenance is applied to the system. In addition to that, interpreting and processing of condition monitoring date requires skilled personnel. Therefore, training has to be given for maintenance personnel to make sure they are familiar with the technologies and software required for data collection and processing.
- Data management: since condition monitoring data come from different sources in several forms, it will be difficult to manage. Data management process includes data acquisition, data manipulation, state detection, health assessment, and prognostic assessment. It is a new and unfamiliar tasks.

4. Condition Monitoring Techniques

This day, different type of condition monitoring techniques such as, vibration analysis, ultrasonic, oil analysis, infrared thermography, etc. are implemented in different industries to monitor equipment condition. For each type of monitoring techniques there are different types of parameters which need to be measured and evaluated. Change of these parameters from the normal value indicates machine failure (Wang & Gao, 2006). Examples of condition monitoring parameters for a pump, industrial gas turbine, and electric motor are listed on Table 4-1 below.

Table 4-1: Example of condition monitoring parameters (ISO-17359, 2011)

parameters	**Machine type**		
	Pump	**Industrial gas turbine**	**Electric motor**
	Condition monitoring measurement techniques	*Condition monitoring measurement techniques*	*Condition monitoring measurement techniques*
Temperature	•	•	•
Pressure	•	•	
Pressure (head)	•		
Pressure ratio		•	
Pressure (vacuum)	•		
Air flow		•	
Fuel flow		•	
Fluid flow	•		
Current			•
Electrical phase			•
Input power	•		•
Output power		•	•
Noise	•	•	•
Vibration	•	•	•
Acoustic emission	•	•	•
Ultrasonic	•	•	•
Oil pressure	•	•	•
Oil consumption	•	•	•
Oil(tribology)	•	•	•
Thermography	•	•	•
Torque	•	•	•
Speed	•	•	•
Efficiency (derived)	•	•	
Where: • = *Condition monitoring measurement techniques are applicable*			

4.1 Vibration Analysis

Vibration analysis is commonly used for rotating machineries to diagnose any changes of machine's operating condition (mostly mechanical problems). Some of the mechanical problems that can be revealed by vibration analysis are unbalance, looseness, misalignment, gear teeth defects, bearing defects, impeller and blade defects etc. (Hamernick, 2006).

There are three types of vibration transducers which are installed on the appropriate location of the machine to measure different types of vibration parameters (displacement, velocity and acceleration). As shown in the Table 4-2 below, each type of transducers is responded to different vibration parameters.

Table 4-2: Types of Vibration Transducers and their corresponding measuring parameters (Markeset& Carstensen, 2011)

Name:	**Sensitive To:**
Proximity Probe	Displacement
Velocity Probe	Velocity
Accelerometer	Acceleration

Equipment's vibration signature will not change over time until something happened on equipment's operating condition. When this happened, the amplitude may increase or decrease from the normal value. Vibration signal data can be acquired and displayed in two different formats, time-domain or frequency-domain. At the begging of vibration analysis process the analyst uses a time-domain data to diagnose equipment conditions. During this time it is difficult to separate individual frequencies and events in a complex wave form. For equipment having specific timing events (linear and reciprocating motion equipment) have to be analyzed using time-domain data format. Frequency-domain data is obtained from time domain data by using Fast Fourier Transformation (FFT) (Mobley, 1999).

As stated on Mobley, 1990*"The real advantage of frequency-domain analysis is the ability to normalize each Vibration component so that a complex machine-train spectrum can be divided into discrete components"*.

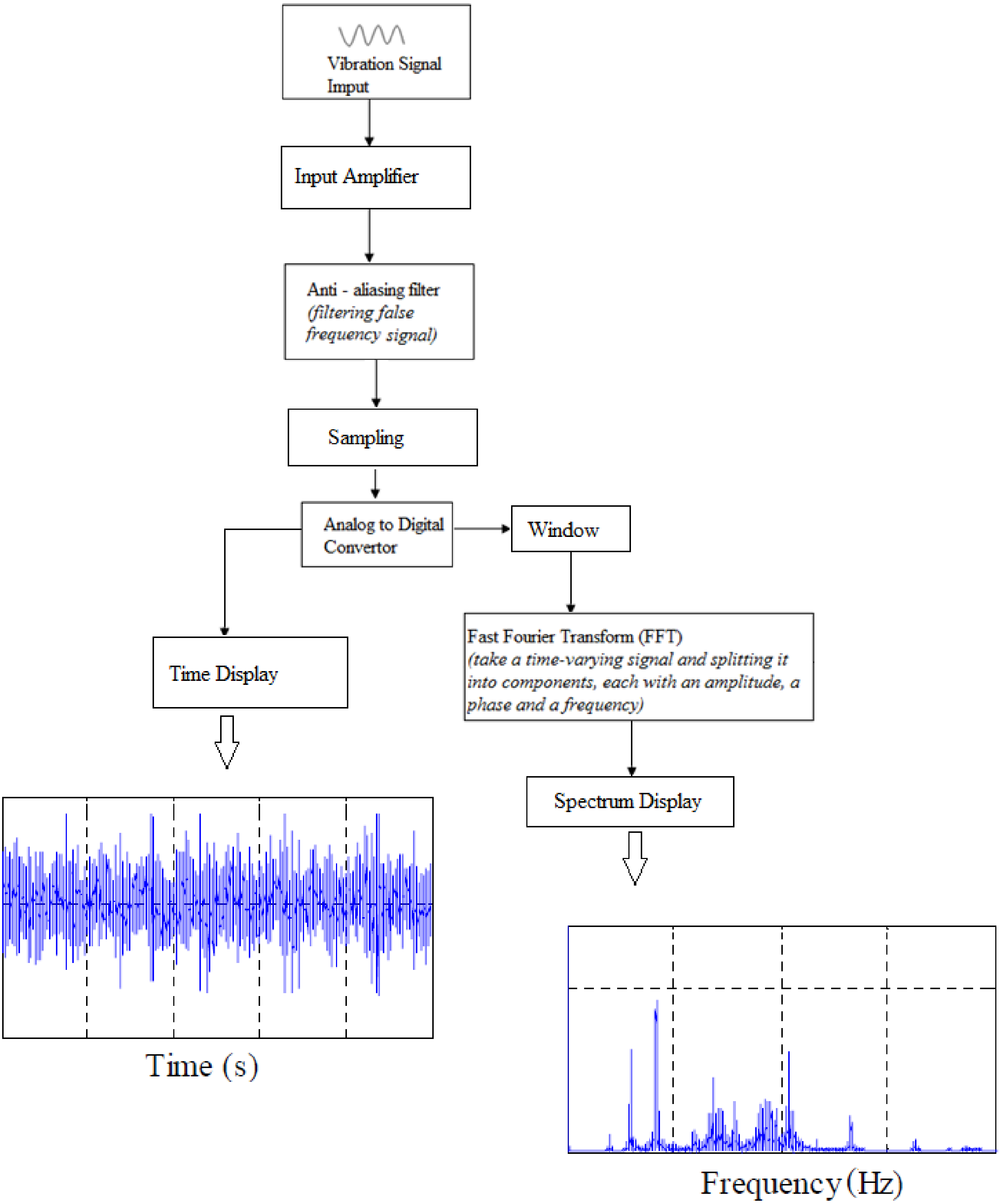


Figure 4-1: Simplified block diagram of an FFT spectrum

It is difficult to separate individual frequency from the time-domain wave form. As shown on Figure 4-1, events which are not cleared and overlapped in the time-domain (time display) are separated into individual components in the frequency-domain (Spectrum) display (Markeset& Carstensen, 2011).

After the input signal is amplified, it passes through an anti-aliasing filter so that the false signals can be removed. Then, the analog signal is converted to digital signals in the A/D convertor. Window function is applied to remove errors and it is then further processed using Fast Fourier Transform (figure 4-1). Fast Fourier Transform take a time varying signal and breaking down it in to components each with amplitude, a phase and a frequency (Shreve, 1995).

4.2 Ultrasounic

Ultrasonic condition monitoring techniques is a simple method used to detect mechanical equipment failures, such as bearing failure, lack of lubrication, over lubrication, early wear, leakage, etc. by translating a high frequency machine sound to a low frequency signal. Therefore, operators or inspectors can hear the sound of equipment defects (Bandes, 2009).

Once ultrasonic signal from the machine during its normal operating condition is registered as a benchmark the future reading will be compared to this value to determine the status of the machine. By using advanced digital technology, the operator can read the DB(ultrasonic level meter) level overtime or recording the signal which is received from ultrasonic receiver sensors installed on the machine and analyze it with specialized software (Wright, 2010).

4.3 Oil analysis

Oil analysis includes fluid property analysis (fluid viscosity, additive level, oxidation properties and specific gravity), fluid contamination analysis (moisture, metallic particles, coolant and air) and wear debris analysis. Fluid property and contamination analysis is used to analysis the quality of oil so that we can change the oil when it is necessary. These analyses are telling you about the condition of the oil itself (Rosales, 2006).

Wear debris analysis is becoming a common use of condition monitoring techniques to give insights into equipment's operating condition (health) by analyzing the content of debris in the lubrication and hydraulic oil samples. The analysis is based on understanding wear particle types, wear particle size, wear particle shape and concentration of wear particles in the lubrication oil. A procedure of oil analysis is shown on Figure 4-2 below.

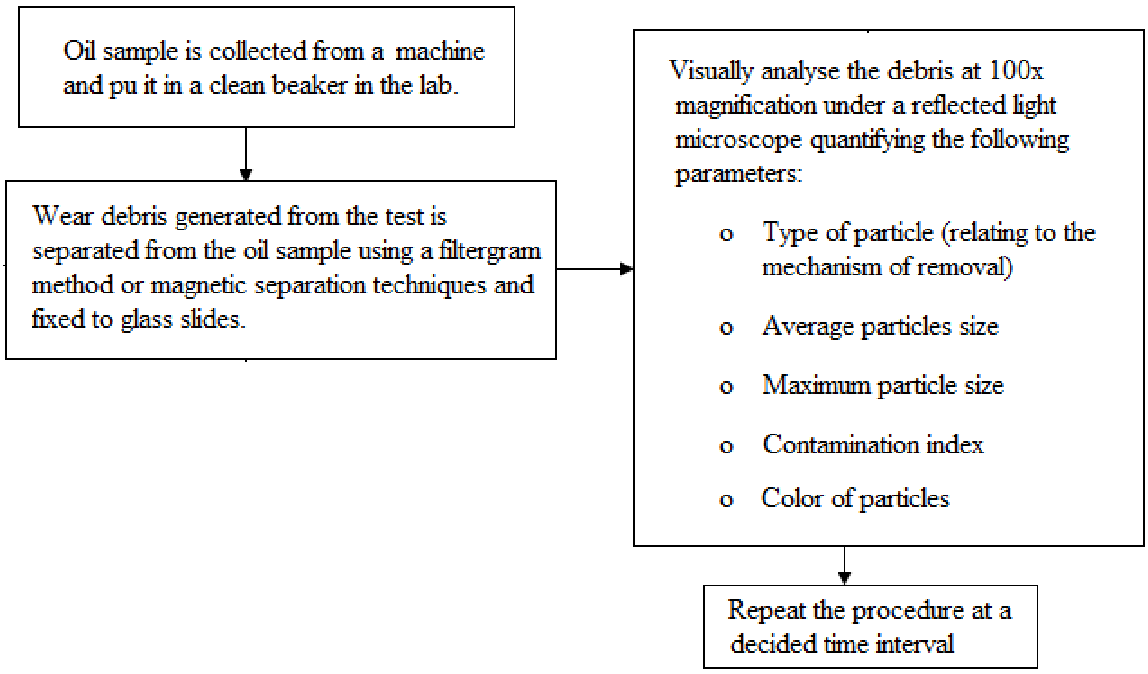


Figure 4-2: A procedure of oil analysis

4.4 Infrared Thermography

Infrared Thermography is a two dimensional real time condition monitoring techniques used to assess the operating condition of a machine by measuring the relative temperature or intensity of emitted radiation (measured as a form of temperature). As we see on Figure 4-3 below, the infrared energy emitted from the object is received by a non-contact remote device and converted it to electrical signal. This signal is amplified and further processed into a visible image and displayed on the monitor as a thermograph. Then after, the temperature calculation will be performed (Shreve, 2003)

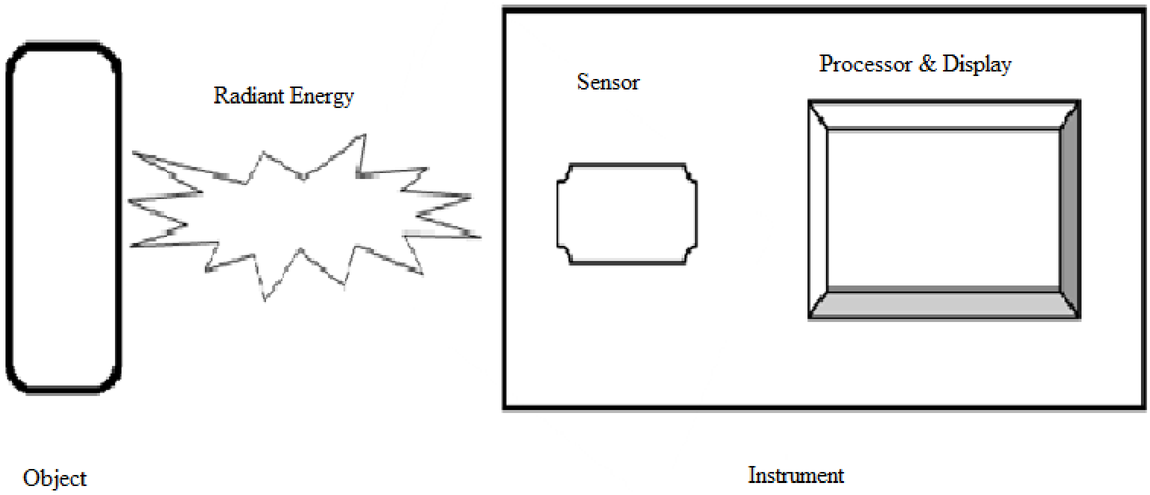


Figure 4-3: Thermography condition monitoring technique

Infrared thermography identifies a hot spot which is created because of load imbalance, loose connection, corrosion, increase in impedance to current, etc.An example of a thermal image taken on a motor and jaw coupling showing a misalignment is illustrated on Figure 4-4 below (Lim, 2009).

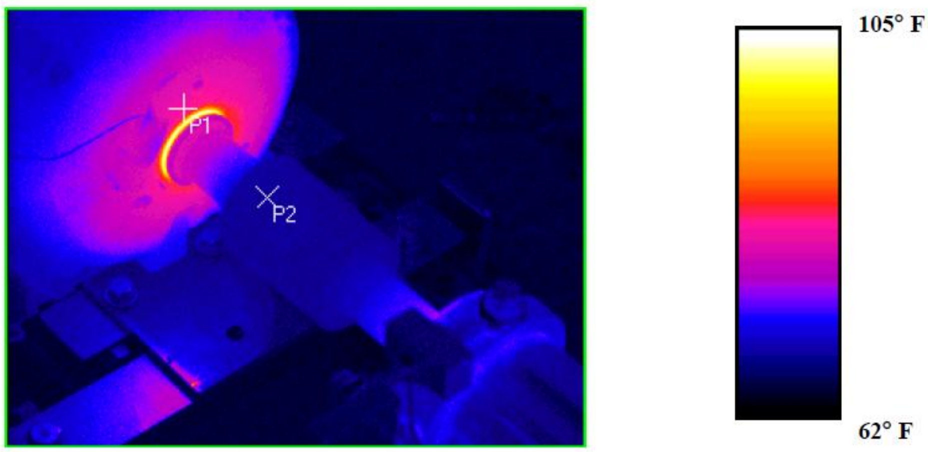


Figure 4-4: Example of thermograph (Shreve, 2003).

5. Equipment Selection for Condition Based maintenance

It is not possible to perform condition based maintenance for all systems/equipment in the plant. Therefore, Critical and suitable equipment must be selected for condition based maintenance program. The methodology used for the selection process is illustrated on Figure 5-1. It includes equipment identifications and information gathering, equipment categorization, criticality analysis, technical feasibility study, realization of the Condition Based Maintenance, and economical analysis (Tinga et al., 2010)

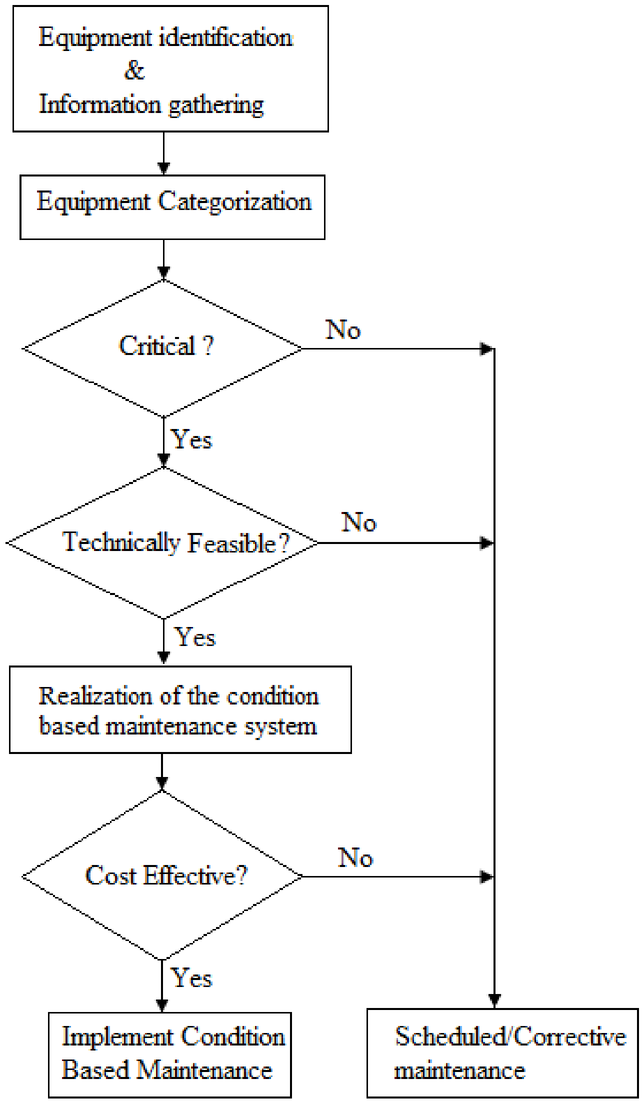


Figure 5-1: A methodology for selecting suitable equipment for condition based maintenance (Modified from Milje, 2011)

5.1 Equipment Identifications and Information Gathering

At the begging of the selection processes all mechanical equipment (rotating or static equipment) such as engine, compressor, generators, pumps, fan, valves, heat exchangers vessels, etc and electrical equipment including motors, circuit breakers, relays, etc in the system must be identified and listed. After the equipment is identified, all the necessary data and information such as maintenance records, equipment locations, failure records, FMECA, functional hierarch of equipment in the system and technical hierarch of equipment in the system, etc will be collected. Sometimes, complete documentation of equipment may not be available. In this case, interview will be conducted with the experienced operators so that equipment's past history can be acquired.

5.2 Equipment categorization

Equipment can be categorized according to their functions in the system. For example, when we see the gas exporting system on chapter 3, it is classified into different main functions such as scrubbing, compression, cooling and others. Each main function has different sub functions. Different types of equipment are placed under each sub functions. Therefore, categorization of equipment based on their functions in the system will help to do criticality analysis and feasibility study for the next stages in the selection processes.

5.3 Criticality analysis

The third stage of the selection process is equipment criticality analysis. As it is discussed in detail on chapter 3, criticality of equipment is usually analyzed based on their failure effects on the production, safety, environment, and cost. In this part of the selection process critical equipment will be identified and prioritized for condition monitoring program. As illustrated on Figure 5-2, equipment is defined as critical if it has significant impacts on safety and environment, or has a great impact on production, or cost.

i. Safety critical equipment: potential for serious personnel injuries or fatalities.
ii. Production critical equipment: cause immediate and significant loss of production.
iii. Cost critical equipment: significant cost consequences

The criticality criteria are different in different organizations. Operators and maintenance personnel judgments are also included on the screening processes. Once the equipment is identified as critical then, it will be evaluated further with other criteria to decide whether it is suitable for condition based maintenance or not.

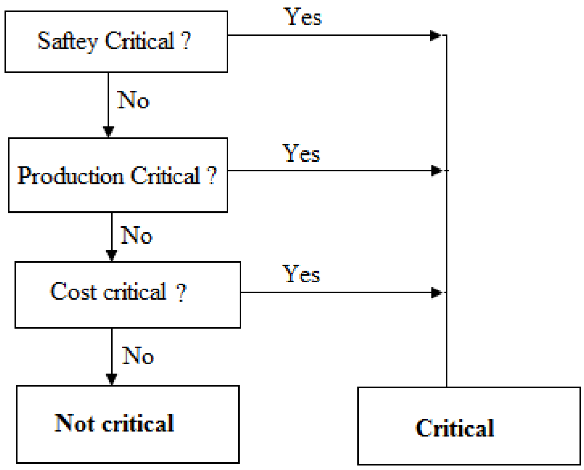


Figure 5-2: Equipment criticality screening (Milje, 2011)

5.4 Technical feasibility study

Technical feasibility is one of the many aspects needs to be considered to choose a suitable equipment for condition based maintenance. Some of the criteria needs to be evaluated to check the technical feasibility of implementing condition based maintenance on particular system/equipment which is shown on Figure 5-3 are,

i. Equipment failures have to be detected and there has to be a condition monitoring parameters that can detect the deterioration in equipment's condition.
ii. The parameter used to identify the deteriorating condition of equipment has to be measured.
iii. After the measured parameter is identified the next step will be assessing whether or not the measured parameter helps to predict equipment failures and estimate maintenance intervals so that the maintenance actions can be performed when it is needed.
iv. Checking P-F intervals. P-F interval is the time between potential failure and functional failure. Condition based maintenance is feasible only when equipment have a sufficiently large P-F intervals so that the failure can be detected and maintenance action can be performed before functional failure has happened. As shown on Figure 5-4, the value of X (monitoring interval) should be less than or equal to one half of P-F intervals ($X \leq 1/2$ P-F intervals) (Moubray, 1997). The time of monitoring interval may be in days, months or years.

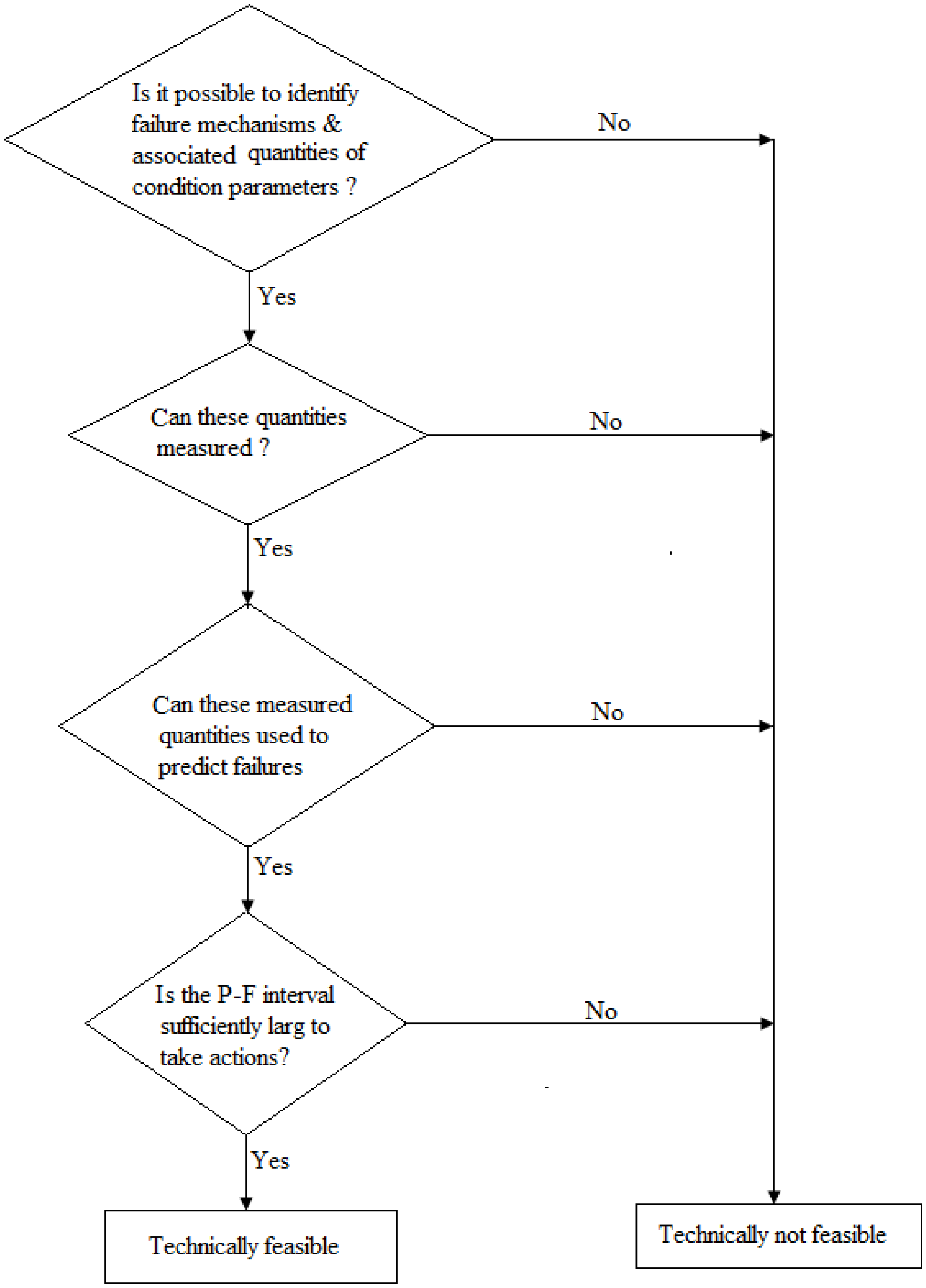


Figure 5-3: Technical feasibility process (Modified from Milje, 2011)

Net P-F interval is the time difference between P-F interval and monitoring intervals (Figure 5-4). Net P-F interval is used to evaluate how much time left for functional failure after equipment failure is detected. Net P-F interval should be long enough to perform the maintenance action before the functional failure of the machine (equation 5.1).

Net P-F interval = P-F interval – Inspection (monitoring) interval (X) 5.1

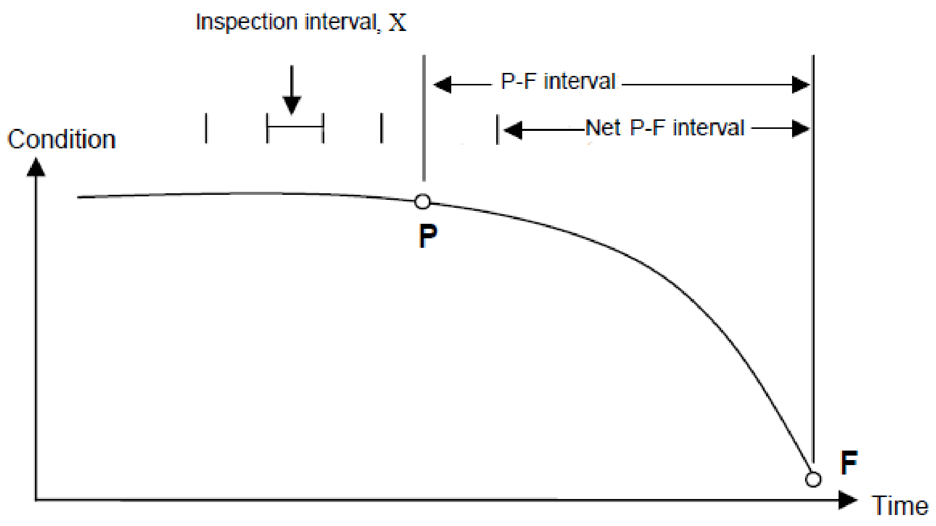


Figure 5-4: P-F interval

5.5 Realization of the Condition Based Maintenance System

Understanding the details of how condition based maintenance system is implemented to the system/equipment will help to do further analysis. To realize the condition based maintenance of the system/equipment the following questions have to be answered (Tinga et al., 2010).

- Is the condition of an equipment assessed directly (wear, cavitations, vibration) or indirectly (performance)?
- Is the right and suitable sensor available to measure the required quantities?
- Is the location of equipment is accessible to measure the required parameters?
- Is data collection possible?
- What will be the monitoring interval (real-time or regular inspections)
- How can the measured parameters be used to evaluate the maintenance intervals?

5.6 Economical analysis

A detailed economical analysis of condition based maintenance on the system/equipment helps the decision makers to decide the need of condition based maintenance. Condition based maintenance has several benefits and costs. Therefore, before deciding the need of condition monitoring program to the system, cost benefit analysis has to be done. There are different types of economic parameters used to do the cost-benefit calculations. The details of cost-benefit analysis will be discussed on chapter 6.

6.Cost-Benefit Analysis

Cost benefit analysis is a maintenance decision tool used to study the economical feasibility of condition based maintenance. When condition monitoring techniques are implemented to the system there will be extra costs that the organization is going to invest. Therefore, Condition based maintenance is like an investment, a benefit is expected from the investment. Cost benefit analysis must be done before the investment (condition based maintenance program) starts. The benefits of periodic maintenance using condition monitoring should be analyzed and quantified financially so that it will be easy to compare the cost with the benefit (Mobley, 2002).

6.1 Costs of condition monitoring periodic maintenance

Costs such as labor cost, spareparts, and other types of costs increase with ages since the components are deteriorating and the amount to be replaced will increase over time. A distribution of maintenance cost with time is illustrated on Figure 6-1.

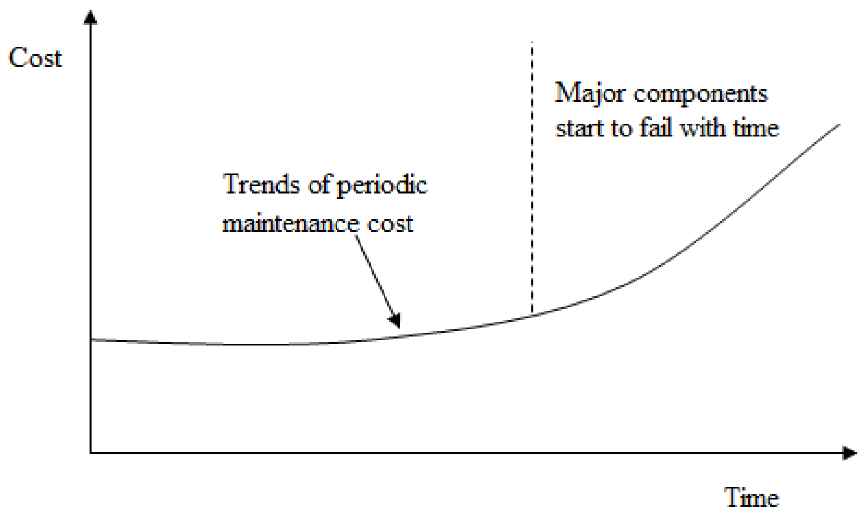


Figure 6-1: periodic maintenance cost with time (Mobley, 2002).

In the case of periodic maintenance strategy that the maintenance interval is estimated based on equipment failure history, there will extra costs the company usually loss because of extra downtime for inspection purpose (may be strip down the whole system), replacement of healthy components, over maintenance, etc. Therefore, it is important to optimize periodic maintenance strategy using condition monitoring techniques. There are two types of costs will be introduced to the system when we implement condition monitoring program.

i. **Initial cost**: includes installation cost, instrumentation price, computers & software (to store and analysis the data).
ii. **Operation cost (running cost)**: includes training cost, labor cost, preventive maintenance cost for monitoring instrumentations, software modification cost, etc.

The cost distribution of condition monitoring program with time is shown on Figure 6-2below.

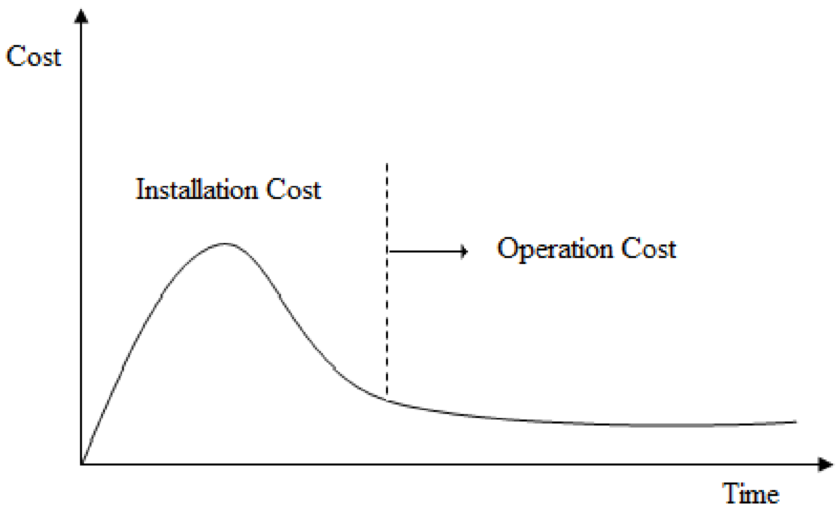


Figure 6-2: Condition monitoring program cost distribution with time (Mobley, 2002).

As shown on Figure 6-2, the maximum cost is at the beginning of the program (initial cost).

6.2 Benefits of condition monitoring periodic maintenance

There are different types of benefits can be derived from condition based maintenance. The benefits can be classified in to two ways (Mobley, 2002).

i. Improved safety: since unscheduled breakdown of the machine is avoided in a condition based periodic maintenance strategy, there will be a safe and smooth operating condition in the plant.
ii. Increased production performance: there are different types of reason why condition based periodic maintenance increases the production performance of the plant. Some of the reasons are,

a. Increase production efficiency by reducing production loseand improves production quality.condition based periodic maintenance identifies the fault in time and plan a maintenance program so that the unnecessary down-time for inspection will be avoided and unexpected breakdown of the machine will be minimized, which are the reasons of production losses.
b. Reduce maintenance cost: since the maintenance work is performed when it is required and the spars are changed based of their conditions, maintenance cost will be reduced and so as the resources required.
c. Improve component's life: when the machine is disassembled for more often, infant mortality will be increased.But, for the case of condition based maintenance,equipment are disassembled for maintenance purpose only when it is necessary.

Figure 6-3, summarizes some of the possible benefits of condition monitoring program in periodic maintenance management.

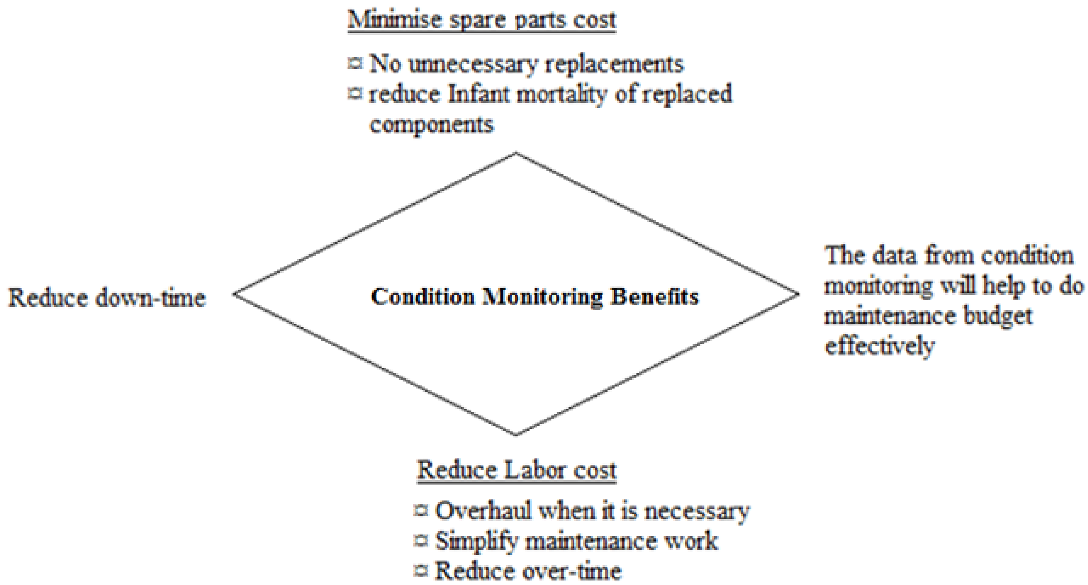


Figure 6-3: Summery of condition monitoring benefits

6.3 Cost-Benefit analysis of condition monitoring program

When we decide to implement condition monitoring program to the existing periodic maintenance strategy, cost benefit analysis has to be done. We have to estimate the future value of the investment by considering the value of money we invest (initial cost) for the program over time (time value of money) and compare it with the future benefits of the program. Therefore, the cash flow of cost and benefits of condition monitoring must be done from year zero (initial investment) to the instrumentation usage life. From the cash flow, the present value of condition monitoring cost (PV_C) and the present value of condition monitoring benefit (PV_b) will be calculated. From these values the Net Present Value (NPV) will be evaluated (see on Table 6-1) (Siyambalapitiya & McLaren, 1990).

Table 6-1: Cash flow of additional costs and benefits of condition based maintenance (Siyambalapitiya & McLaren, 1990)

year	Without condition monitoring		With condition monitoring		Additional costs of monitoring	Additional benefits of monitoring
	Monitoring costs	Repair and downtime cost	Monitoring costs	Repair and downtime cost		
0	X0	Y0	X'0	Y'0	ΔX0	ΔY0
1	X1	Y1	X'1	Y'1	ΔX1	ΔY1
2	X2	Y2	X'2	Y'2	ΔX2	ΔY2
3	X3	Y3	X'3	Y'3	ΔX3	ΔY3
4	X4	Y4	X'4	Y'4	ΔX4	ΔY4
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
K-1	Xk-1	Yk-1	X'k-1	Y'k-1	ΔXk-1	ΔYk-1
K	Xk	Yk	X'k	Y'k	ΔXk	ΔXk

Where:

K= useful life of the machine

$\Delta Xt = X't - Xt$ = additional cost of monitoring

$\Delta Yt = Y\,t - Y't$ = additional benefits because of condition monitoring.

By considering the discount rate (i) of the investment, all additional costs and benefits should be converted to today's money (present value). The formula for converting additional costs to the present value of money is,

$$V_x = \frac{\Delta X_t}{(1+i)^t} \qquad 6.1$$

And

The formula used to convert additional benefits of condition monitoring to the present value is,

$$PV_y = \frac{\Delta Y_t}{(1+i)^t} \qquad 6.2$$

Where: PV_x = present value of additional cost

PV_y = present value of additional benefit

i= annual discount rate

t = year in the future, 0, 1, 2........K-1, K

After both additional costs and benefits are converted to the present values of money, it is possible to add all additional costs and benefits of condition monitoring and come up with a total present value of costs and benefits. The total present value of additional costs is given as,

$$PV_{x,total} = \sum_{t=0}^{K} \frac{\Delta X_t}{(1+i)^t} \quad 6.3$$

And

The total present value of additional benefits is given as,

$$PV_{y,total} = \sum_{t=0}^{K} \frac{\Delta Y_t}{(1+i)^t} \quad 6.4$$

The cash flow of the present value of condition monitoring additional costs and benefits are illustrated on Tale 6-2 below.

Table 6-2: Present Values of additional costs and benefits for condition based maintenance

Year	**present value of additional cost**	**present value of additional benefit**
0	ΔXo	ΔYo
1	$\frac{\Delta X_1}{(1+i)^1}$	$\frac{\Delta Y_1}{(1+i)^1}$
	$\frac{\Delta X_2}{(1+i)^2}$	$\frac{\Delta Y_2}{(1+i)^2}$
3	$\frac{\Delta X_3}{(1+i)^3}$	$\frac{\Delta Y_3}{(1+i)^3}$
4	$\frac{\Delta X_4}{(1+i)^4}$	$\frac{\Delta Y_4}{(1+i)^4}$
.	.	.
.	.	.
K-1		
K	$\frac{\Delta X_k}{(1+i)^k}$	$\frac{\Delta Y_k}{(1+i)^k}$
Total	$PV_{x,total}$	$PV_{y,total}$

After the total present values of condition monitoring additional costs and benefits are calculated, the next step will be calculating the net present value (NPV),

$$\mathrm{NPV} = \mathrm{PV}_{x,total} - \mathrm{PV}_{y,total} \qquad 6.5$$

Therefore, there are criteria used to study the economical feasibility of investing condition monitoring program on the existing periodic maintenance strategy based on the cash flow of additional costs and benefits. These criteria are (Siyambalapitiya & McLaren, 1990),

i. The total present value of benefit should be greater than the total present value of cost

$$\mathrm{PV}_{y,total} > \mathrm{PV}_{x,total} \qquad 6.6$$

ii. The Net Present Value (NPV) should be greater than zero.

$$\mathrm{NPV} = \mathbf{PV}_{x,total} - \mathrm{PV}_{y,total} > 0 \qquad 6.7$$

iii. The cost/benefit ratio must be greater than one

$$\frac{\mathrm{PV}_{y,total}}{\mathrm{PV}_{x,total}} > 1 \qquad 6.8$$

If the cost benefit analysis satisfies the above criteria, it will be ok to invest the condition monitoring program

7. Discussion and Concluding Remarks

Periodic maintenance is performed at regular intervals to prevent critical equipment functional failures. The maintenance interval is estimated from equipment failure time data set collected on the past. As discussed on chapter 2, different types of mathematical models such as Weibull distribution model, Normal distribution model, and Lognormal distribution model are used to analyze the failure data to calculate the mean–time–between-failures (MTBF) and predict equipment failure trends (increasing, constant or decreasing). Therefore, the right maintenance strategy can be decided. The focus of this thesis is how to optimize periodic maintenance intervals based on the actual deteriorating condition of the machine by using condition monitoring techniques and operational data.

Different types of condition monitoring techniques such as vibration analysis, ultrasonic, oil analysis, infrared thermography, etc. are used to monitor equipment's condition so that preventive maintenance can be performed before catastrophic breakdown of the system. Depending on the criticality of equipment, condition monitoring activities will be carried out continuously (real-time data) or periodically (with time intervals). There are different ways of monitoring equipment's condition:

- Using different types of sensors which can be installed on the operating equipment and monitoring it continuously (online);
- Using portable sensors that can measure changes on the condition of equipment; or
- using manual gauges or instruments to perform time based inspection

A Procedure for condition monitoring processes to decide the appropriate maintenance task and to optimize periodic maintenance intervals are discussed on chapter 3.

Examples of equipment criticality analysis and FMECA are documented on this thesis from Apply Sørco. Equipment Criticality analysis is conducted based on their failure consequences on the production, HSE (Health, Safety and Environment) and cost. For critical equipment having measurable parameters condition monitoring program is recommended. Before starting to carry out condition monitoring process, the following activities such as identify measurable parameters, select measurement techniques, and choosing monitoring intervals have to be done. Then, condition monitoring data collection and signal processing will be the next step. Activities carried out in this stage are data acquisition, data manipulation, state detection, health assessment and prognostic assessment. Each of the activities is discussed in detail on chapter 3. In the end, an appropriate maintenance task with optimum intervals will be decided.

The mean-time-between-failure will also be estimated with a high degree of probability of confidence. There are Some challenges such as high initial cost, false instrumentation reading, training, data management, etc, when condition based maintenance is implemented to the system.

Cost benefit analysis has to be done. During the analysis, all the benefits of condition based maintenance are quantified financially and compared to all the costs spending for the program. Since there is no cost-benefit data is available, only the theoretical part is covered in this thesis. Two type costs are introduced in this thesis.

i. Initial costs such as installation cost, instrumentation price, computers & software (to store and analysis the data) and
ii. Operational costs includes training cost, labor cost, preventive maintenance cost for monitoring instrumentations, software modification cost, etc.

As illustrated on Figure 6-2 (condition based maintenance cost distribution) the maximum amount of money is spent at the beginning of the program (initial cost). The benefits of condition based maintenance are also discussed on chapter 6 in to two ways. Benefits related to improving safety and related to improving production performance. In this thesis, the cost-benefit analysis is done by comparing the total present values of the cost with the total present values of the benefit. The net present value should be greater than zero in order to implement condition based maintenance program.

Condition based maintenance is not appropriate for all equipment in the plant. Therefore, equipment which are suitable for condition based maintenance have to be selected. A methodology used for the selection processes is discussed on chapter 5. It includes equipment identifications and information gathering, equipment categorization, criticality analysis, technical feasibility study, realization of the condition based maintenance, and economical analysis.

By integrating condition monitoring data with historical data, periodic maintenance management can be optimized effectively so that the maintenance action can be performed when it is needed. As a result, the availability and reliability of the system and the production performance will increase. Further research is recommended to improve the monitoring result, prediction of maintenance tasks and intervals, and CBM implementation.

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