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Use Risk-based Method to Develop a Foundation for Quantitatively Assessing the Contribution of Maintenance activities in Offshore Petroleum Oil and Gas Industry

Masters Thesis by

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Thesis submitted in partial fulfillment of
the requirements for the degree of
Master of Engineering

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ABSTRACT

As the world market becomes more benefit-oriented, increasingly companies and organizations are becoming aware of the maintenance's contribution to value generation, as well as its contribution to risk reduction. Maintenance is considered as an important business process that could contribute to overall profitability. However, many companies find it difficult to quantify contribution of maintenance in value creation and risk reduction. Therefore, these companies are not able to effectively plan maintenance management as well as decide resource allocation for maintenance activities.

The aim of this research study is to suggest a methodology to quantitatively assess the contribution of maintenance activities in reducing overall risk with respect to HSE and ensuring production regularity. Such kind of quantitative assessment provides a valuable decision-making basis to the managers to appropriately plan maintenance activities and allocate optimal resources.

In this thesis, a risk-based methodology is proposed to quantitatively assess the value of maintenance activities. The value of maintenance activities is expressed as the risk reduction values that could be achieved by performing a particular maintenance activity.

Keywords: *Risk value, Contribution of maintenance, maintenance cost, production regularity, maintenance management, fault, failure modes, etc.*

NOTATION AND ABBREVIATION

F_i	Frequency of failures
P_i	Probability of accidents
C_i	Consequence of accidents
CBM	Condition based maintenance
CED	Cause and effect diagrams
CFC	Clean-up and fine cost of oil leakage
CM	Corrective maintenance
CMM	Corrective maintenance man-hours
CMSP	Corrective maintenance spare parts
DL	Downtime loss
ETA	Event tree analysis
FME(C)A	Failure mode effects (and critical) analysis
FTA	Fault tree analysis
LO	Lost oil cost
MFTT	Mean function test time
MTBF	Mean time between failures
MTTR	Mean time to repair
OREDA	Offshore Reliability Data
OEM	Original equipment manufacturer
PdM	Predictive maintenance
PDL	Production degradation loss
PM	Preventive maintenance
QA	Qualitative risk assessment
QRA	Quantified risk assessment
RBD	Reliability block diagrams
RC	Repair cost
SQA	Semi-quantitative assessment
TBF	Time between failures
TBM	Time based maintenance
TTR	Time to repair

CONTENTS

1 INTRODUCTION

This chapter is aimed to introduce the background and the aim of this thesis. The contributions and limitations are also explained.

1.1 Background

Companies and organizations in all industries are increasingly becoming aware of the maintenance contribution to risk reduction as well as business success. Maintenance spending in many of the companies goes to up to 40% of the operating budgets. According to a study, in U.K. the maintenance spending of manufacturing companies is between 12 to 23% of the operating costs. In oil and gas industry in Norway, companies are increasingly realizing importance of maintenance. A large number of service companies have established that provide knowledge and technology based services to improve maintenance management effectiveness and efficiency.

With the advances in technology, the Norwegian O&G industry is increasingly becoming dependant on advanced, complex and integrated machinery and equipment. This high complexity increases the interdependencies between different components, and brings more uncertainties to the system. In this case, even a small failure can lead to a catastrophic accident: injury, loss of life and uncountable loss of money. Recall the Pipeline Alfa accident, the whole accident only took place in 22 minutes, but caused death of 167 people. Such large accident was just initiated by a broken pump.

Besides risk reduction, maintenance can generate value by reducing downtime, increasing equipment life, etc.. Some years ago, maintenance was and considered as a "Necessary evil", and it was believed that "Nothing can be done to improve maintenance costs."(Mobley, 1990) However, the development of modern maintenance techniques such as condition monitoring, computer based maintenance management changed the paradigm. Both the research results and the practical applications show that the successful maintenance programs can greatly improve the value generation by reducing the machine failures, reducing repair time, reducing spare parts costs, and increasing the machine life as well as productivity

Even though there is a increased focus on maintenance management and almost 40% of the total costs are spent on maintenance in the O&G industry, the recent surveys indicated that one third of all maintenance costs is wasted as the result of unnecessary or improperly carried out maintenance (Mobley, 1990). In U.S.A, the result of ineffective maintenance management represents a loss of more than 60 billion dollars each year.

1.2 Problem Description

The main reason for the ineffective maintenance management is the lack of factual data that quantifies the actual need for repair or maintenance of plant machinery, equipment, and system (Mobley, 1990). In the last decades, researchers and engineers never stop striving for collecting historical information, building up database, predicated on statistical trend data or finding method to measure the numerical value of every maintenance-related term. Thanks to their effort, we have many different kinds of database available now, such as OREDA, HSE report, etc.

However, we still have not found a method to quantitatively assess the contribution of maintenance activities till now. Contribution of maintenance activities is the most intuitional indicator that can indicate value creation and risk reduction. As the world market becomes more benefit-oriented, we are more and more interested in finding out how we can quantify contribution of maintenance with respect to HSE and costs? How much risk is reduced due to effective and efficient maintenance management?

1.3 Aim of the Research

The purpose of the thesis is to study the foundation for quantitatively assessing the value of maintenance activities in order to reduce overall risk with respect to HSE and production regularity, as well as to suggest/propose ways to improve the value assessment of failure consequences.

1.4 The Scope of Work

The project shall look into the following:

- Map existing knowledge.
- Examine the risk analysis process
- Use the FMECA analysis methodology to identify failure modes, failure mechanisms, failure effects and maintenance activities to mitigate the risk.
- Quantify the change in risk if the maintenance activity is not performed.
- Suggest improvements to maintenance management based on value assessment of maintenance.

1.5 Contributions

The contributions of this thesis include the following:

1) *A methodology to quantitatively assess the contribution of maintenance activities has been discussed in the thesis*. This thesis suggests a possible foundation of how to quantify the contribution of maintenance in value creation and risk reduction.

2) *The process of how this methodology affects the maintenance management is discussed in this thesis.*

3) *A description of how to apply this methodology in practice is given in the thesis.* This thesis does not only focus on theoretical study, but also underline the importance in

practical applications. This thesis suggests some solutions in how to make the maintenance management more effective and cost efficient by using the methodology.

1.6 Limitations

The limitations of this thesis are:

1) Limited equipments and failure modes have been considered in this thesis.
2) The consequences we considered in this thesis are based on complete failure of a function. Consequences based on partial failure of equipment are not considered.
3) Consequences related to economic and HSE are considered in this thesis. The other kinds of consequence are not considered.
4) Data sample is from the Norwegian O&G industry. It does not cover all industries.

1.7 Thesis outline

The thesis is composite of 8 chapters. After the current introduction, the concept of maintenance and maintenance management is introduced in order to give the reader a comprehensive understanding of maintenance and maintenance management. After that, the methodology for quantitatively assessing the value of maintenance activities is established in Chapter 3, where the principle of the methodology, and describe the framework and process of quantitatively assessing the value of maintenance activities are described. In Chapter 4, we will do some theoretical knowledge preparation for the calculation of the value of maintenance. The following chapters are the data collection and calculation (Chapter 5) and case study (Chapter 6). Finally, the thesis ends with some discussion (Chapter 7) and suggestion for future research (Chapter 8).

On the whole, the 8 chapters can be categorized into 4 parts in logic: Introduction Part, Preparatory Part, Methodology Research Part, and Discussion and Conclusion Part. The outline of the thesis is visualized in Figure 1.1.

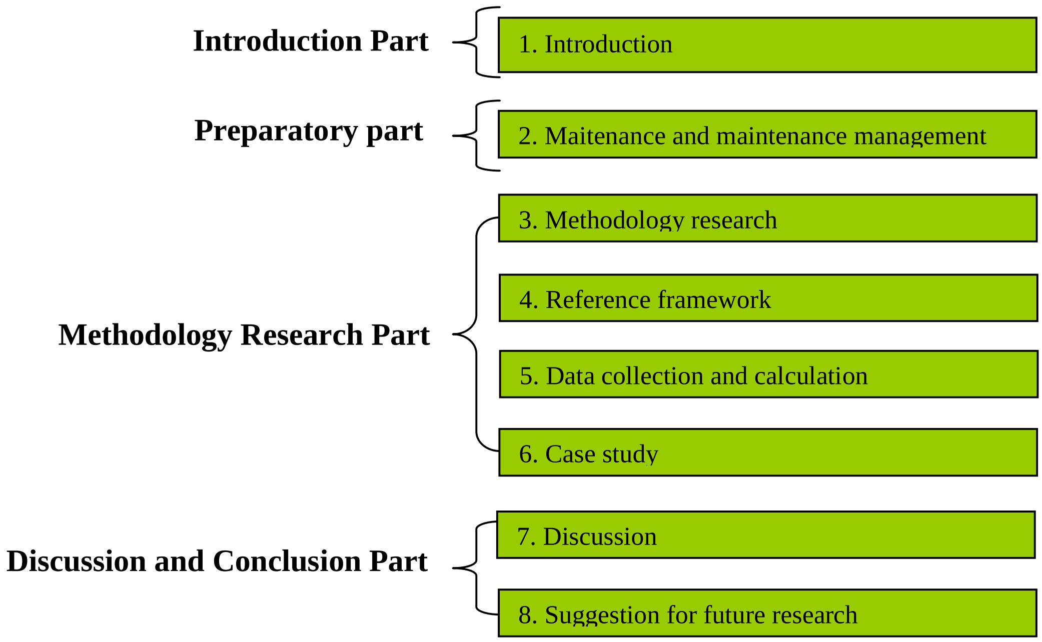

Figure 1.1 Outline of the thesis

2 MAINTENANCE AND MAINTENANCE MANAGEMENT

Before the studying of value of maintenance activities, a comprehensive understanding of maintenance and maintenance management is necessary. In this chapter, the concept of maintenance and maintenance management is introduced.

2.1 Overview of Maintenance

According to A. C. Márquez, the term of maintenance in the Oil and Gas industry can be defined as the following (EN 13306:2001, 2001):

"Maintenance is the combination of all technical, administrative and managerial decisions and actions during the life cycle of an item intended to retain an item in, or restore it to a state of specified capability. Capability is the ability to perform a specific action within a range of performance levels."

No matter how the definition various, the aim of the maintenance is widely agreed by most of companies as to support the market and operational goals according to Wilson (1999), that is subsidies the previously described company goals and operational aspects. Lofsten (1999) states that it is of importance to realize that the maintenance function add value, although not as obviously as other departments and that it is an equally important link and other departments.

Maintenance covers any activity carried out on an asset to repair equipment, or to ensure the asset continues to perform its intended functions. Maintenance includes all actions taken to prevent or reduce the consequences of failure.

Another aim for the maintenance function is to secure the safety of the installation for the personnel. Nowadays there are also extensive regulations concerning safety and safety levels must often be approved by some licensed organization. Maintenance should also guard sustainable environmental status of the installation. It should keep emissions to designated (legal or policy based) levels. Assets should be maintained in order to extend their lifetime and maintenance experiences can be communicated to designers in order to improve forthcoming design solutions, in an environmental context. These considerations are separated from the operation of the installation, but equally important, and may have implications for the scope for process optimization.

2.2 Types of maintenance

Generally, maintenance activities can be classified into the following types:

- **Run-to-Failure Maintenance** The basic logic of Run-to-Failure maintenance is to allow the equipment to run to failure and only do repair or replace activities when obvious problems occur. This maintenance management method has been a major part of plant maintenance operations since the first manufacturing plant was built, and on the surface sounds reasonable (Mobley & Knoxville, 2001). Run-to-failure is a reactive maintenance technique, no maintenance activity is taken before the equipment fails. This kind of maintenance works well if the equipment is very cheap and its shutdowns don't affect production. The advantage is that no money is invested in the maintenance activities before failure occurs.

- **Preventive Maintenance** Preventive maintenance is a schedule of planned maintenance actions aimed at the prevention of breakdowns and failures. Its main goal is to prevent the failure before it actually occurs. Preventive maintenance activities include partial or complete overhauls at specified periods, oil changes, lubrication and so on. The ideal preventive maintenance program would prevent all equipment failure before it occurs. Preventive maintenance is considered to be a kind of time-driven maintenance management; the maintenance scheduling has been and, in many instances, is predicated on statistical trend data or on the actual failure of plant equipment (Mobley & Knoxville, 2001). The premise of the PM is that all the machines will degrade with the time elapse, the probability of failures follows the Bathtub curve shown in the following figure: in the initial stage of the equipment life cycle, the probability of failure is relatively low for an extended period of time; in the normal stage, the probability of failure increases sharply with elapsed time. This PM method can greatly expand the life of equipment, but the disadvantage of the time-based maintenance is labor intensive, ineffective in identifying problems that develop between scheduled inspections, and is not cost-effective.

- **Predictive Maintenance** Predictive maintenance techniques help determine the condition of in-service equipment in order to predict when maintenance should be performed. This approach offers cost savings over routine or time-based preventive maintenance, because tasks are performed only when warranted. PdM is an condition-based maintenance management program, The using of condition monitoring techniques is the main character of PdM. Condition monitoring techniques include Vibration Measurement and Analysis, Infrared Thermography, Oil Analysis and Tribology, Ultrasonic, Motor Current Analysis, and etc.. When the failure event is diagnosed, corrective maintenance should be performed to prevent the failure deterioration. The ultimate goal of PdM is to perform maintenance at a scheduled point in time when the maintenance activity is most cost-effective and before the equipment loses optimum performance. This is in contrast to time- and/or operation count-based maintenance, where a piece of equipment gets maintained whether it needs it or not.

Normally, the type of maintenance philosophy can be assigned by the criticality of equipments. The critical machines are usually maintained with the predictive and proactive techniques; the essential machines are usually assigned with preventive maintenance. In actual operations, a mix and match of techniques is applied with a prime intention of maximizing runtime lengths and reducing downtime and costs. The present day focus on continuous process plant pumps is to adopt a mix of predictive and Preventive Maintenance.

2.3 Maintenance Management

Management process is a process of planning, leading and controlling the performance or execution of any type of activity through the deployment and manipulation of resources (human, financial, material, intellectual or intangible). One can also think of management functionally as the action of measuring a quantity on a regular basis and adjusting an initial plan and the actions taken to reach one's intended goal (Márquez, 2007). Maintenance management can be therefore considered as the process of leading and directing the maintenance organization.

The maintenance management can be defined as follows (EN 13306:2001, 2001):

> *"All the activities of the management that determine the maintenance objectives or priorities (defined as targets assigned and accepted by the management and department), strategies (defined as a management method in order to achieve maintenance objectives), and responsibilities and implement them by means such as maintenance planning, maintenance control and supervision, and several improving methods including economical aspects in the organization.*

The Maintenance Management Cycle presented in figure 2.1 illustrates the management process resulting in (ideally) low expenses and high regularity (availability) and Safety, Health and Environmental (SHE) level by effective use of input resources. Every activity in the circle consists of a vast number of steps. The controlling and connecting force for these activities is the managerial activity.

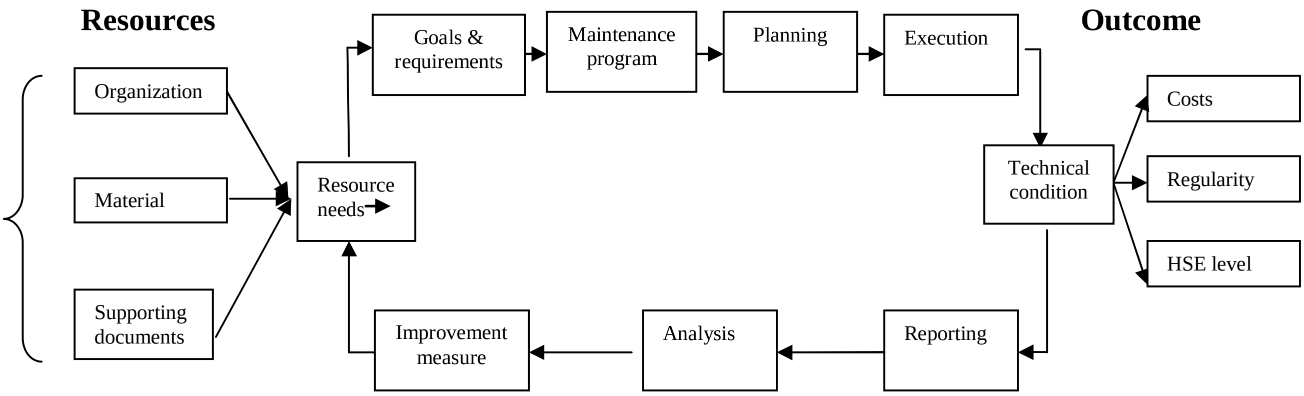

Figure 2.1 Maintenance Management cycle (NPD, 1998)

- *Goals and requirements.* Goals and requirements include the translation of previously described market and production objectives into maintenance goals and specification of requirements necessary to achieve them. It is also important to establish indicators to monitor these goals.
- *Maintenance program.* The next phase is to develop maintenance programs and methods for the maintenance work such as RCM, RBI etc.
- *Planning.* Maintenance program needs to be well planned in order to be able to execute the maintenance work efficiently.

- *Execution.* The execution involves implementing planned maintenance programs, training activities and naturally the operative maintenance. Operational maintenance does not only include the actual work and information concerning it, but also the handling of different permissions, reporting guidelines and finally control of the jobs.
- *Reporting.* In the reporting stage the mentioned guidelines come to use and different reports and trend developments are created, monitoring the maintenance work.
- *Analysis.* These reports are the foundation for the analysis of the work done in order to answer what, why and which equipment questions used in evaluations.
- *Measuring improvement.* Measuring improvement and comparing the measures to best case values is a way for continuous improvement. (NPD, 1998)

The input into this process is the organization and the design, competence and leadership in it. It also consists of the material (tools and spare parts) used and supplementary documentation such as technical documents and guidelines for work processes. Crucial for the support of these input factors is a functional CMMS. (NPD, 1998)

It is also of great importance to establish a maintenance-management policy for the entire installation in order to visualize and communicate the maintenance strategy (Wilson, 1999). This policy should be broken down into specified policies for every production line or section of the installation, with aid from the maintenance programs, in order to manage the maintenance work both in accordance with corporate goals and demands of different sections. Otherwise money and time may be wasted on unnecessary maintenance.

The Benefits of Maintenance Management are as the following:

- *Low production unit cost* Proper maintenance management can improve asset reliability; ensure the resources such as labor, materials, energy, and fixed costs are used efficiently minimize expenses. While a major component of these costs is fixed, increasing throughput will decrease the unit cost of production. Base labor cost will remain constant even when production throughput is increased; incremental cost for materials and energy is also reduced as volume increases.

- *Reduce maintenance costs Improved* reliability results in lower maintenance costs. If the assets are not breaking down, a greater percentage of maintenance work can be performed in a planned and scheduled manner, which enables the workforce to be at least twice as efficient. Reducing these losses will also result in requirement of fewer spare parts, less overtime, and fewer contractors. All of these result in significant reductions in maintenance spending. It is not unusual for organizations to experience as much as a 50 percent reduction in maintenance cost as a result of moving from a reactive style of management to a proactive approach.

- *Better process stability.* Equipment breakdowns inevitably result in process unsets. It is difficult to have a stable, optimized process when the production equipment is constantly failing. This inevitably results in problems with final product quality. When reliability is improved, process variability is reduced, and statistical process capability is increased. This results in the capability to have a more stable, predictable manufacturing process.

- *Expending Equipment life.* Many organizations spend an excessive amount of capital funds to replace equipment that failed far earlier than it should have. If routine maintenance is continually deferred due to production demands or resource limitations, the organizations, the organization is in fact mortgaging the future value of the asset-taking the capital value from the future and spending it today. The end result is a wasted asset that must be replaced. The financial result is excessive write-off expenses and a requirement for a constant infusion of new capital.

- *Reduce spare parts inventory.* All organizations require some level of spare parts inventory to ensure the right parts will be available when needed. Reactive organizations typically find themselves carrying a large quantity of inventory because they cannot predict when the parts will be needed. This ties up working capital and results in excessive carrying costs. Organizations that take a proactive approach to reliability place a high value in knowing the condition of their assets. The need for parts is much more predictable. There are fewer "surprises": more parts can be purchased on a just-in-time basis. Since the volume of inventory required is based to a large degree on usage, the fewer parts we use, the fewer we need to keep on hand.

- *Reduce overtime.* Reactive organizations can never predict when a critical equipment failure will occur. Murphy's Law typically applies; it will invariably happen at the most inconvenient time and will require craft resources to be called into the facility to correct the problem. To counter this reality, most reactive organizations have a large percentage of the maintenance workforce spread across all operating shifts "just in case" a failure occurs. In this situation, the equipment is in control, not management. Large amounts of overtime are experienced. In organizations that focus on reliability, breakdowns are much less common. A larger percentage of craft resources are on day shift where adequate staff supports is available to increase their productivity. Fewer resources are waiting for breakdowns to occur because equipment condition is known and early warning signs of distress are heeded.

2.4 Maintenance-related Failures

Maintenance-related failure means the failure which is caused by improper maintenance management. Maintenance-related failures could lead reliability problems, and will generate potential risks to systems. The maintenance-related failures owe to the following issues:

- *Improper maintenance*. Most maintenance functions permit the crafts to determine how maintenance activities will be executed. As a result, many of these tasks are performed incorrectly and incompletely. The result is chronic reliability problem.
- *Poor planning*. Too many maintenance functions have eliminated the planning and scheduling function. Instead, work requests are compiled, routed to the supervisors

and issued for execution without proper planning. As a result, critical activities are not executed in a timely manner or the procedures used are inadequate.

- *Failure to perform effective preventive maintenance tasks*. Preventive maintenance, that is inspections, lubrication, calibrations, and adjustments must be performed in a timely manner to sustain reliable asset operation. Failure to adhere to these schedules and effective execution of these tasks result in reduced asset reliability.

3 RESEARCH METHODOLOGY

The main purpose of this chapter is to establish the methodology for quantitatively assessing the value of maintenance activities. In this chapter, we will introduce the principle of the methodology, and describe the framework and process of quantitatively assessing the value of maintenance activities.

For the purpose of methodology research, we define the value of maintenance activities as the following: *The value of maintenance activity could be defined as its positive contribution to the system. It expresses the net benefit we can obtain from a maintenance activity.*

3.1 Overview of the methodology

The purpose we use maintenance activities is to prevent the equipment failures. Once the maintenance activities are not performed, the failures will occur, and correspondingly is the risk to both the production and the safety. Furthermore, the value of risk is a term that we are able to quantitatively assess. Therefore, using the increasing value in risk if the maintenance activity is not done to assess the value of maintenance could be a good option.

Based on this consideration, we can calculate the value of maintenance activity by the following equation:

Value of maintenance activity= total saved risk value – total costs of maintenance

In order to facilitate the calculation, in the equation we use the term of *the total saved risk value* instead of the increasing value of risk if a maintenance activity is not performed as the latter one is a negative number. The total saved risk value is positive, and it is equal to the increasing risk value if a maintenance activity is not performed in magnitude. It means all the risk values, no matter economical or HSE related, that can be saved by the maintenance activity. It is the positive contribution of a maintenance activity. On the other hand, the term *total costs of maintenance* represent the negative contribution of the maintenance activity. Therefore, when we use the first term minus the second one, it expresses the benefit we can get from the maintenance activity. That is the value of the maintenance activity.

3.2 Philosophy of the methodology

In order to comprehensively understand the philosophy of the methodology, we must firstly study what the failure is and how the maintenance activities work on failures.

3.2.1 Failure and failure-related terms

“Failure” is the evil to industries. All the efforts the maintenance engineers done or going to do are aimed to prevent failures or mitigate the effects of failures. According to IEC50 (191), the definition of failure is: “the termination of the ability of an item to perform a required function” (IEC50 (191)). Many people may have the confusions between failure and fault. From the difference between failure and fault, we can more clearly understand the definition of failure: failure is the performance deterioration process, it is an event that results the performance of equipment out of acceptable limits; fault is hence a state resulting from a failure. The figure 3.1 illustrates the relationship between failure, fault and equipment performance.

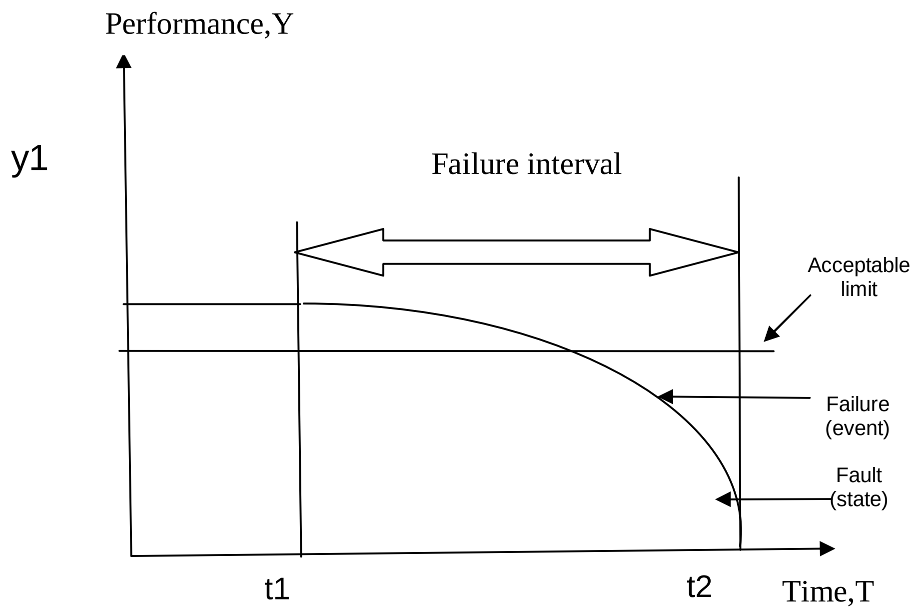

Figure 3.1 Failure development process diagram

In order to have a better understanding of failure, some failure-related terms are defined here:

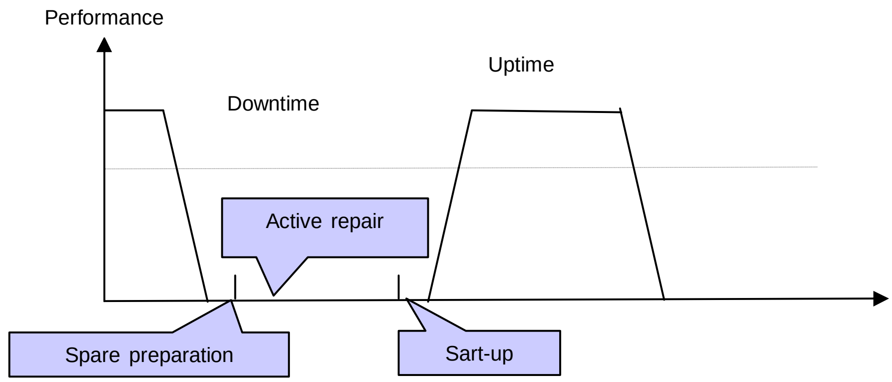

Figure 3.2 Illustration of failure-related terms

- **Mean Down Time (MDT),** is the period during which equipment is in the failed state (David J. Smith, 2001).
- **Mean Time To Fail (MTTF)** is defined as: for a stated period in the life of an item the ratio of cumulative time to the total number of failures.
- **Mean Time between Failures (MTBF)** is defined: for a stated period in the life of an item the mean value of the length of time between consecutive failures, computed as the ratio of the total cumulative observed time to the total number of failures (David J. Smith, 2001). The difference between MTTF and MTBF is that MTTF is applied to items that are not repaired, such as bearings and transistors, and MTBF to items which are repaired. The MTBF excludes the down time.
- **Failure rate** is defined as: for a stated period in the life of an item, the ratio of the total number of failures to the total cumulative observed time. Usually, λ is used to express failure rate, and $\lambda = n/T$, where n is the number of failures in the time period of T. If the failure rate is constant, we can get the equation that $\lambda = 1/MTBF$.

3.2.2 Maintenance versus failure

Failure is nature. Many factors such as wearing, improper operation and other known or unknown factors can result in failures. With the time elapsing, failures will occur on equipments, and make the equipment's performance decline. On the contrary, maintenance activities can prevent the equipment from failures. The function of maintenance is to repair equipment, or to ensure the asset continues to perform its intended functions, as well as to prevent or reduce the consequences of failure. Without maintenance, failures will go on determinating, and finally make the equipment totally fail.

Different types of maintenance actions have different effectiveness on preventing failures. In run-to-Failure maintenance, the equipment is allowed to run to failure, and repair or replace activities are only done when obvious problems occur.

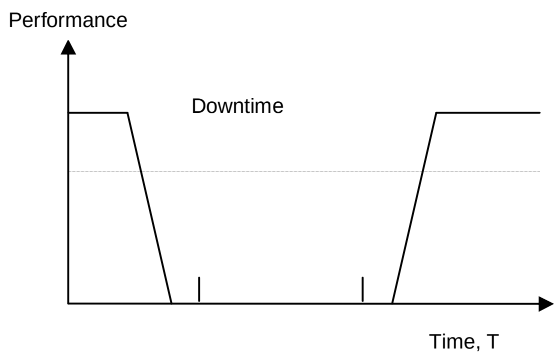

Figure 3.3 Illustration of run-to-failure maintenance

Run-to-failure maintenance is a passive maintenance management. Studies show that, it is the most expensive method of maintenance management, the major expenses associated with this type of maintenance management are (R. Keith Mobley, Knoxville, 2001):

- high spare parts inventory cost
- high overtime labor costs
- high machine downtime and low production availability

Preventive maintenance is a time-driven maintenance management. In PM, the maintenance actions are done periodically to prevent the failure occurrence. The maintenance schedule is set based on the prediction of the failure rate. Therefore, sometimes failures may occur before the maintenance actions. Then, corrective maintenance is also needed. From figure 3.4 we can see, maintenance actions should be done at time t_1, t_2, and t_3. This figure also illustrates that the disadvantage of PM is ineffectiveness and not cost-efficient.

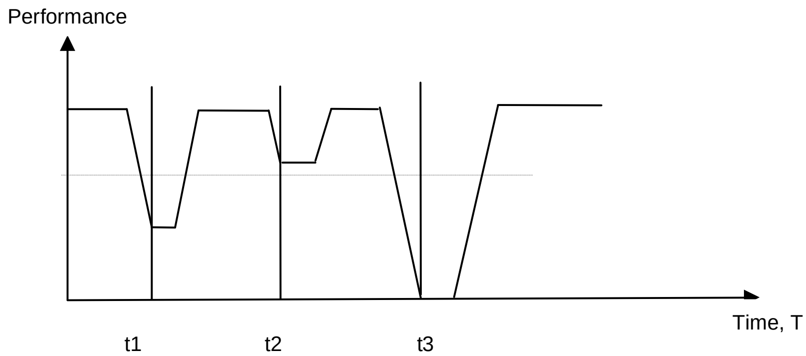

Figure 3.4 Illustration of preventive maintenance

Predictive maintenance is a condition based management. It relies on the help of condition monitoring techniques to when maintenance should be performed. It is more accurate and effective. In ideal situation, all failures that is out of the acceptable limit can be detected, and hence be corrected.

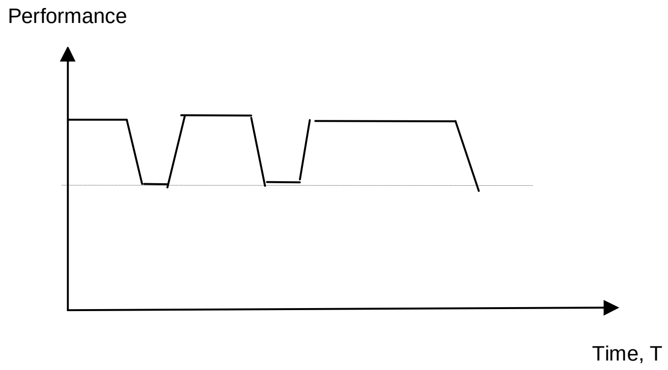

Figure 3.5 Illustration of preventive maintenance

3.2.3 Process of the quantitative assessment

The process of quantitatively assessing the value of maintenance activity includes 6 steps, the framework of the methodology is shown in figure 3.6.

Step 1- Description of selected equipment:

The assessment process should commence with the description of the selected equipment. As the foundational function of maintenance is to remain and restore the function of equipment, before we assess the value of maintenance, we should understand what the property of the equipment is and whatfunction the equipment has. This step contains a description of each equipment unit for which data have been collected, e.g., pump, turbine, and etc.. This step includes the description of equipment's function, the situation of the equipment's assignment, as well as some technical data (e.g., capacity, size).

Step 2- Identify the possible maintenance activities:

In this step, we should identify the possible maintenance activities that normally be implemented in the equipment, and describe the function, mechanism, and costs of each maintenance activity. Since the function of these maintenance activities is to prevent the failure modes, the value of a maintenance activity is just the risk values saved from the failure modes it against to. Normally, one maintenance activity may have the ability to prevent several failure modes, therefore, the value should be the sum of all the failure modes.

Step 3- Identify the failure modes if one of the maintenance acivities is not performed:

First, we assume one of these maintenance activities is not performed, and identify what failure modes will occur in the equipment. The analysis of failure causes and failure effects is also necessary. Failure causes is critical to the identification of failure modes as the mechanism of failures is very complex. Generally, a certain failure mode can be initiated by different causes, for example, an external leakage may be caused by damage to shaft seals, or material failures, or failures on seals, and etc.. And also, failures of different items can be resulted from a same cause. However the failure modes are the same, if the failure causes are different, the consequences will various. For example, the external leakage of a pump that caused by a failure on shaft seals can be repaired on line, but, the external leakage caused by an internal material failure may lead to a shutdown. And the repair costs various greatly. The identification of failure mode effects is used to deduce the consequences of the failure mode.

Step 4- Identify the frequency of each failure mode:

The frequency of the failure modes can be identified from many ways, such as historical report from operators, reliability report from authorities (for example OREDA), experts' judgment, OEM's documents, and etc.

Step 5- Deduce the consequences of each failure mode:

In this step, we need to identify the consequences of each failure mode. All the risks to personnel, to environment, and to asset should be considered.

Step 6- Express the values of the maintenance activities.

The whole assessment process is completed in this step. Til this step, we have got both the *total saved risk value* and the *total costs of maintenance*, therefore we can figure out the value of the maintenance activity by the equation:

Value of maintenance activity= total saved risk value – total costs of maintenance

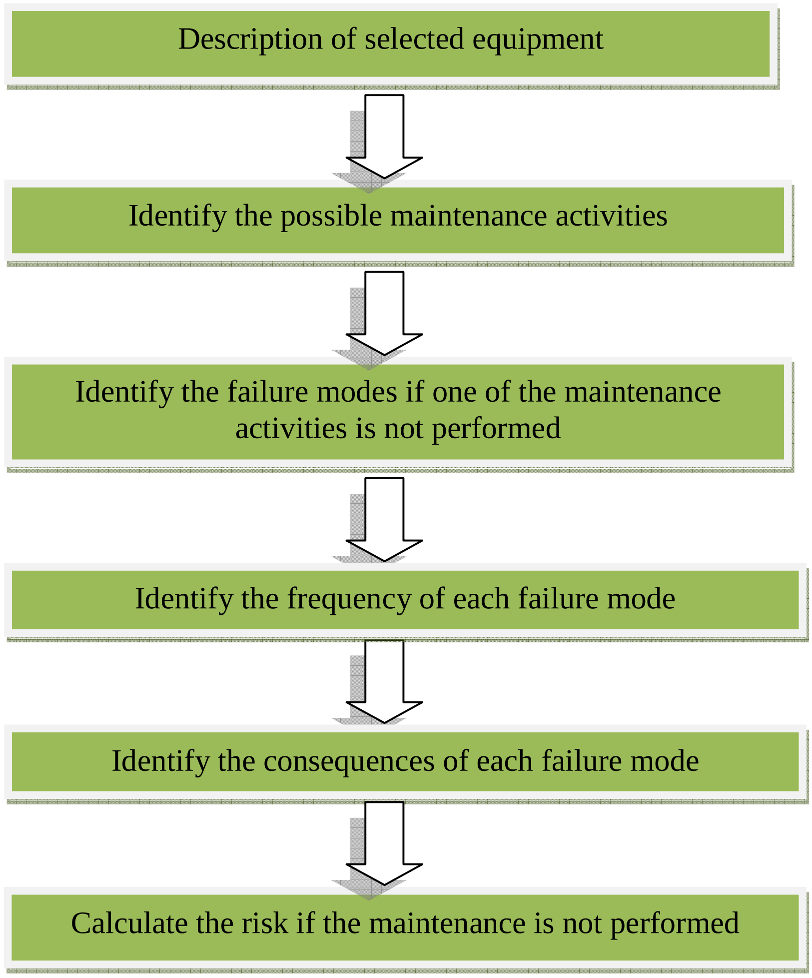

Figure 3.6 Framework of quantify the value of maintenance activity

4 REFERENCE FRAMEWORK

This chapter consists of a theoretical reference framework. The main purpose of this chapter is to prepare basic theoretical knowledge to the data collection and calculation.

From the discussion in last chapter we can see, the process of quantitatively assessment for value of maintenance activities actually contains two fundamental elements: the one is failure mode identification and analysis, and the other is risk assessment. Recall the equation of value of maintenance activities: *Value of maintenance activity= total saved risk value – total costs of maintenance*, in order to get the *value of maintenance activities*, we must calculate the *total saved risk value*. And the result of the *total saved risk value* is coming from these two elements determine. Therefore, the theoretical knowledge preparation of these two elements is quite necessary.

4.1 Failure mode and failure mode identification

Failure mode is "The manner by which a failure is observed; it generally describes the way the failure occurs" (Dodson B. & Nolan D., 1999). From the definition we can see, failure mode describes the state of the failure that we can observe from the outside. For example, “Internal leakage” is thus a failure mode of a vessel, since the vessel looses its required function to “contain liquid.” Wear of the vessel surface, however, represents a cause of failure and is hence not a failure mode of the vessel.
Failure modes have various kinds of classification according to different manners. As Blanche and Shrivastava suggested (Blanche K.M, Shrivastava A.B, 1994), failure modes can be classified into:

1) Intermittent failures: Failures that result in a lack of some function only for a very short period of time. The functional block will revert to its full operational standard immediately after the failure.
2) Extended failures: Failures that result in a lack of some function that will continue until some part of the functional block is replaced or repaired. Extended failures may be further divided into:
(a) Complete failures: failures that result in a lack of a required function.
(b) Partial failures: Failures that lead to a lack of some function but do not cause a complete lack of a required function.

Both the complete failures and the partial failures may be further classified:
(a) Sudden failures: Failures that could not be forecast by prior testing or examination.
(b) Gradual failures: Failures that could be forecast by testing or examination. A gradual failure will represent a gradual “drifting out” of the specified range of performance values. The recognition of gradual failures requires comparison of actual device performance with a performance specification, and may in some cases be a difficult task.

This kind of classification is illustrated in figure 4.1.

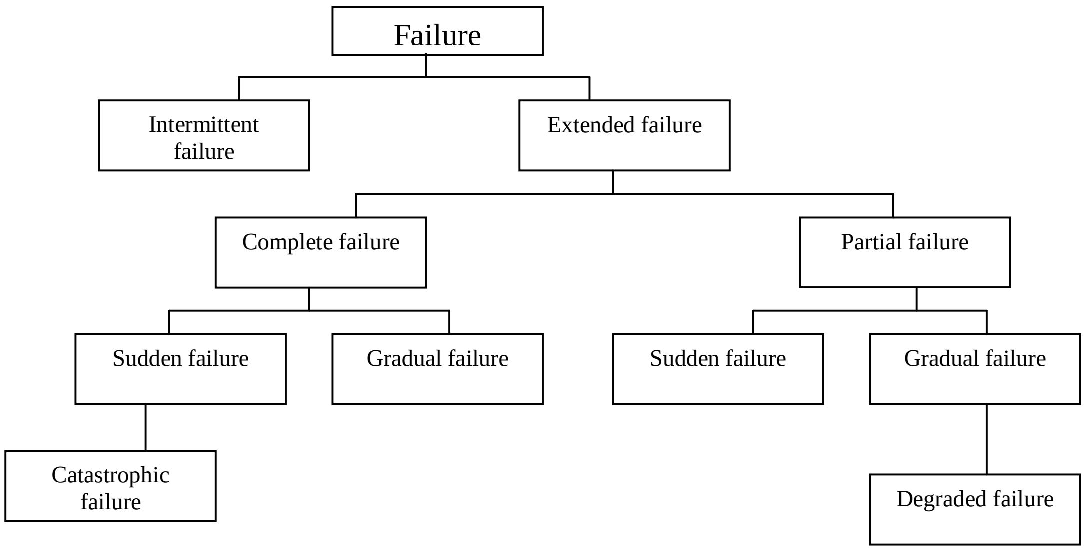

Figure 4.1 Failure classification (adapted from Blanche and Shrivastava 1994)

Some other classifications, for example, include: divide failures into primary failures, secondary failures, or command faults, and so on.

In this paper, we use the classification suggested by OREDA according to the severity of failures. This method of classification has the similar principle with the method suggested by Blanche and Shrivastava, which include:

- *Critical failure*: immediate and complete loss of a system's capability
- *Degraded failure:* not critical, but be gradual or partial, and may develop into a critical failure in time.
- *Incipient failure*: if not attended to, could result in a critical or degraded failure in the near future.
- *Unknown failure:* Failure severity was not recorded or could not be deduced (not be considered here since it is irregular).

This method illustrates that failure is a dynamic process, which develops from incipient state to critical state. And from this classification we can see that, the critical failure is the later period of a failure event, and the primary purpose of maintenance is to prevent failure developing into a critical failure.

4.1.1 Failure modes identification and analysis techniques

In order to study the failures, many failure modes identification and analysis techniques were developed, such as:

- **Failure Mode Effects (and Criticality) Analysis (FME(C)A).** FMEA is a procedure for analysis of potential failure modes within a system for classification by severity or determination of the effect of failures on the system (http://en.wikipedia.org/). If the criticalities or priorities are assigned to the failure mode effects, then, we call this method the Failure Mode Effects and Criticality Analysis (FMECA).

- **Fault Tree Analysis (FTA).** A fault tree is a logic diagram that displays the interrelationships between a potential critical event in a system and the causes for this event.
- **Cause and Effect Diagrams (CED).** This method is used to identify and describe all the potential causes that may result in a specified event.
- **Event Tree Analysis (ETA)**. Event tree analysis is used to identify the initiating event in an accident.
- **Reliability Block Diagrams (RBD).** A reliability block diagram is a success-oriented network describing the function of the system.

4.1.2 FMEA

These techniques are all most commonly used in failure identification and analysis depending on their special properties. In this paper, we use FMEA to identify the failure modes if the maintenance activities are not performed, as well as their causes and effects to the system.

Failure mode and effects analysis (FMEA) is a procedure by which each potential failure mode in a system is analyzed to determine the results or effects thereof on the system and to classify each potential failure mode according to its severity (MIL-STD-1629A). Failure modes and effects analysis (FMEA) is widely used in manufacturing industries in various phases of the product life cycle and is now increasingly finding use in the service industry.

Failure cause is the physical or chemical processes, .design defects, quality defects, part misapplication, or other processes which are the basic reason for failure or which initiate the physical process by which deterioration proceeds to failure (MIL-STD-1629A).

Failure effect is the consequence(s) a failure mode has on the operation, function, or status of an item. Failure effects are classified as local effect, next higher level, and end effect (MIL-STD-1629A).

FMEA is used to identify potential failure modes, determine their effect on the operation of the product, and identify actions to mitigate the failures. A crucial step is anticipating what might go wrong with a product. While anticipating every failure mode is not possible, the development team should formulate as extensive a list of potential failure modes as possible.

FMEA's provide the engineer with a tool that can assist in providing reliable, safe, and customer pleasing products and processes. Since FMEA help the engineer identify potential product or process failures, they can use it to:

- Develop product or process requirements that minimize the likelihood of those failures.
- Evaluate the requirements obtained from the customer or other participants in the design process to ensure that those requirements do not introduce potential failures.
- Identify design characteristics that contribute to failures and design them out of the system or at least minimize the resulting effects.
- Develop methods and procedures to develop and test the product/process to ensure that the failures have been successfully eliminated.
- Track and manage potential risks in the design. Tracking the risks contributes to the development of corporate memory and the success of future products as well.

FMEA is designed to assist the engineer improve the quality and reliability of design. Properly used the FMEA provides the engineer several benefits. Among others, these benefits include:

- Improve product/process reliability and quality
- Increase customer satisfaction
- Early identification and elimination of potential product/process failure modes
- Prioritize product/process deficiencies
- Capture engineering/organization knowledge
- Emphasizes problem prevention
- Documents risk and actions taken to reduce risk
- Provide focus for improved testing and development
- Minimizes late changes and associated cost
- Catalyst for teamwork and idea exchange between functions

The FMEA shall be initiated as an integral part of early design process of system functional assemblies and shall be updated to reflect design changes. Current FMEA analysis shall be a major consideration at each design review from preliminary through the final design. The analysis shall be used to assess high risk items and the activities underway to provide corrective actions. The FMEA shall also be used to define special test considerations, quality inspection points, preventive maintenance actions, operational constraints, useful life, and other pertinent information and activities necessary to minimize failure risk. All recommended actions which result from the FMEA shall be evaluated and formally dispositioned by appropriate implementation or documented rationale for no action. Unless otherwise specified, the following discrete steps shall be used in performing an FMEA:

1) Define the system to be analyzed. Complete system definition includes identification of internal and interface functions, expected performance at all indenture levels, system restraints, and failure definitions. Functional narratives of the system should include descriptions of each mission in terms of functions which identify tasks to be performed for each mission, mission phase, and operational mode. Narratives should describe the environmental profiles, expected mission times and equipment utilization, and the functions and outputs of each item.

2) Construct block diagrams. Functional and reliability block diagrams which illustrate the operation, interrelationships, and interdependencies of functional entities should be obtained or constructed for each item configuration involved in the system's use. All system interfaces shall be indicated.

3) Identify all potential item and interface failure modes and define their effect on the immediate function or item, on the system, and on the mission to be performed.

4) Evaluate each failure mode in terms of the worst potential consequences which may result and assign a severity classification category.

5) Identify failure detection methods and compensating provisions for each failure mode.

6) Identify corrective design or other actions required to eliminate the failure or control the risk.

7) Identify effects of corrective actions or other system attributes, such as requirements for logistics support.

8) Document the analysis and summarize the problems which could not be corrected by design and identify the special controls which are necessary to reduce failure risk.

4.2 Risk and risk assessment

Offshore installations are characterized by high risks. Since the exploration actions commenced in NCS, more than 20 major accidents have occurred. It will be a great interest if we can comprehensively understand the risks and find out methods to prevent or mitigate the risks.

4.2.1 Overview of risk

As Terje Aven pointed, "*risk is used to express the danger that undesirable events represents to human beings, the environment and economic value*" (Terje Aven, 2002). The risk associated with failure is difined as the product of probability of failure and consequence of failure (DNV RP-G 101, 2002), where the consequence of failure means the different effects of failure.No mater how the expression of risk various, by distributions, expected values, etc. a most commonly used expression of risk is that risk is the combination of probability and consequences.

The expression of risk is shown in the following equation, which is calculated by multiplying probability and numerical value of the consequence for each accident sequence i, and summed over all potential accident sequences:

$$R = \sum_i (P_i * C_i)$$

Where:

P = probability of accidents

C = consequence of accidents

It should be noted that the expression of risk as expected consequence is a statistical expression, which often implies that the value will have to be established over a long period, with low annual values (J. E. Vinnem, 2007). Risk is usually regarded to be a statistical or prababitic term, which links with future uncertainty. The risk consequence may never be observed.

4.2.2 Risk elements

When accident consequences are considered, these may be related to personnel, to the environment, and to assets and production capacity (J. E. Vinnem, 2007). The consequence of failures can therefore be categorized into the following dimensions:

1) Personnel risk which includes:

- Fatality risk
- Impairment risk

2) Environmental risk

3) Asset risk which include:

- Material damage risk
- Production delay risk

Personnel risk

It should be noted that risk to personnel is mainly focused on fatality risk, or aspects that are vital for minimization of fatality risk (J. E. Vinnem, 2007). In the Oil & Gas industry in Norwegian, people use the term “major accident” as the criteria. The interpretation of “major accident” is the accident which has the potential to cause five fatalities or more. In reflecting these criteria, people take more attention on preventing fatality risks. The frequency of impairment is the term used to express the risk aspects to the safety of personnel.

Fatality risk

Fatality risk is the most serious consequence among all of the consequences in the case of offshore installation. There are a number of ways to express the fatality risk, such as platform fatality risk, individual risk, and group risk and f-N curve. The following are the main characteristics that are used in order to form the example shown in table:

- The average number of persons on the platform is 220.
- Each person has an annual number of 3000 exposure hours offshore.
- Elements of risk are shown in table:

Table 4.1 Fatality risk form (adopt from J. E. Vinnem, 2007)

Risk values	Average manning	Fatalities per accident				
		1	2-5	6-20	21-100	101-220
Sum frequencies	220	0.033	0	0.01	0.003	0.0008
Geometrical mean		1	3.2	10	44.7	148
Consequence						
PLL contribution		0.033	0	0.1	0-134	0-118
Total PLL	0.386					
FAR value	20.0					
AIR value	0.00058					

The following figures which are published by HSE could give us a general impress of fatality risk in offshore installations (Offshore safety statistics bulletin 2006/2007):

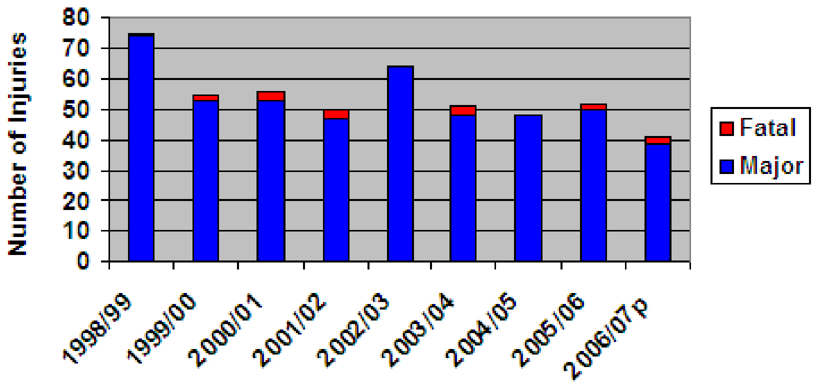

Figure 4.2 Fatal and Major Injuries 1997/1998 – 2006/2007p

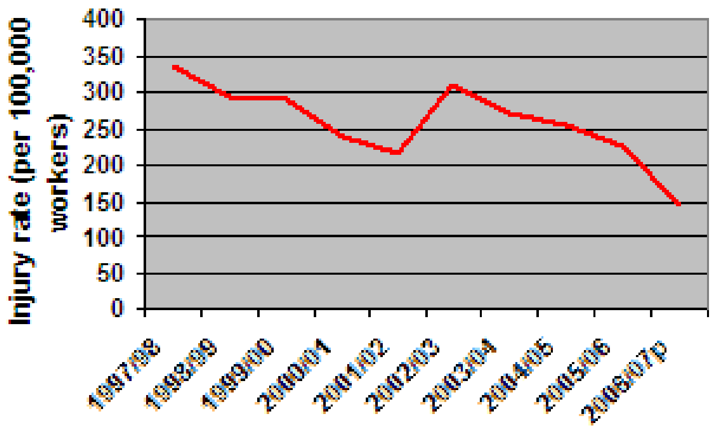

Figure 4.3 Combined Fatal and Major Injury Rate 1997/1998 – 2006/07p

Environment risk

The environment risk from offshore installations is dominated by the largest spills from blowouts, pipeline leaks or storage leaks; process leaks, although more frequent, are not normally capable of causing extensive damage to the environment (J. E. Vinnem, 2007). The exclusion of non-process leaks is due to the fact that the circumstances surrounding of hydrocarbon leaks are different with the circumstances associated with leaks from auxiliary system, drilling system, etc (Vinnem, J.E etal, 2007).

Figure 4.4 shows the number of hydrocarbon leaks for all installations during 10 years period, from 1996 to 2006. It is rather difficult to make a clear conclusion due to the variation in the data, but from 2002 to 2006, there is an obvious declining trend for categories leak rate 0.1 - 1 kg/s and 1 - 10 kg/s. The declining trend is not likely happened to category leak over 10kg/s since there was an incident on Visund platform in 19 January 2006, where one huge gas cloud was formed at the free surface of all installation. That incident was initiated by leaks that estimated to be 900kg/s.

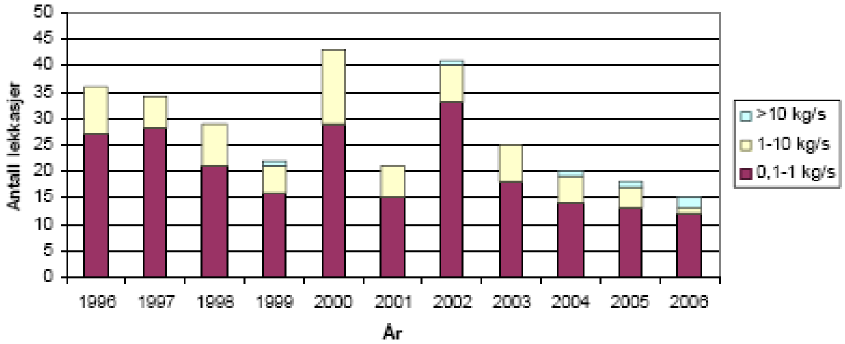

Figure 4.4 Number of Leaks for all installations in Norwegian Sector (source: PSA, 2007)

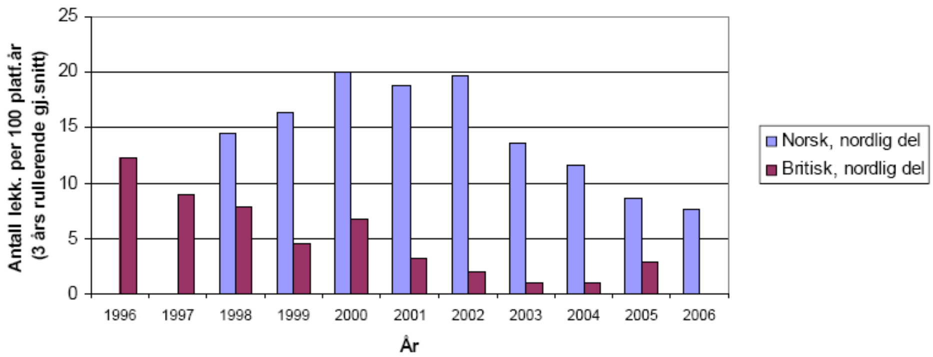

Figure 4.5 Number of Hydrocarbon Leaks in Norwegian and British continental shelf, normalized against installation, rolling 3-years average (source: PSA, 2007)

Asset risk

The asset risk is comprised of possible damage to equipment and structures, as will as the resulting disruption of production (J. E. Vinnem, 2007). According to the definition, when we calculate the asset risk, the following aspects should be considered:

- *Cost of spare parts.* The spare parts are the materials that used to replace the damaged parts of equipment or structures, as well as the consumed materials that are used in the repair actions.
- *Cost of repair action.* The cost of repair action is the cost of implementing the repair action, which mainly means the maintenance man-hour cost required to maintain the system and equipment within the vendors' scope of supply.
- *Downtime loss.* The production lost in downtime.
- *Production degraded loss.* The loss due to the degradation of production.

4.2.3 Probability and frequency

Probabilities are used when considering future events with more than one possible outcome. In a given situation only one of these outcomes will occur; in advance we cannot say which. Such situations are called stochastic, as opposed to deterministic situations where the outcome is determined in advance. The probability of an event is a measure of the chance that an event will occur. It is measured as a value in the interval (0,1). Probabilities are usually assessed (estimated) by experience data, such as accident statistics and the operating statistics of components and systems.

A frequency expresses an average number of events per unit of time or per operation. The connection between frequency and probability is illustrated in the following example. Assume that we for a specific company have calculated a frequency of accidents leading to personnel injuries, are 7 per year, i.e. 7/8760 = 0.0008 per hour. The probability that such an accident will occur during one hour can therefore be assessed at 0.0008= 0.08%. such a probability interpretation of the frequency value can be justified when this value is small; how small depends on the desired accuracy. As a rule of thumb one often use "less than 0.01" (T. Aven, 2002)

According to Aven & Vinnem, there are two main interpretations of probability (T. Aven & J.E Vinnem, 2007):

a) *The classical interpretation.* A probability is interpreted in the classical statistical sense as the relative fraction of times the events occur if the situation analysed were hypothetically "repeated" an infinite number of times. According to this interpretation, the probability of an event A, is also called relative frequency, which is defined in the following way: if an experiment is performed n times and the event A occurs n_A times, then $P(A) = lim_{n\rightarrow\infty} n_A / n$. the probability P(A) is a theoretical quantity that usually is unknown and has to be estimated from experience data.

b) *Subjective probability*. Probability is a measure of expressing uncertainty as to the possible outcomes, seen through the eyes of the assessor and based on some background information and knowledge. This interpretation expresses a person's or groups' uncertainty/belief about what will happen. For example" the probability that Viking will win a medal in this year's soccer league is 25%".

Following definition a) we produce estimates of the underlying true risk. This estimate is uncertain, as there could be large differences between the estimate and the correct risk value. As these correct values are unknown it is difficult to know how accurate the estimates are.

Following definition b), we assign a probability by performing uncertainty assessments, and there is no reference to a correct probability. There are no uncertainties related to the assigned probabilities, as they are expressions of uncertainties.

If there is a real risk level, it is relevant to consider and discuss the uncertainties of the risk estimates compared to the real risk. If probability is a measure of the analyst's uncertainty, a risk assignment is a judgment and there is no reference to a correct and objective risk level.

In some cases we have references levels through historical records. These numbers do not however express risk, but they provide a basis for expressing risk. In principle, there is a huge step from historical data to risk, which is a statement concerning the future. In practice, many analysts do not distinguish between the data and the risk derived from the data. This is unfortunate, as the historical data may, to varying degree, be representative for the future, and the amount of data may often be very limited. A mechanical transformation from historical data to risk numbers should be avoided.

The risk analyses establish a basis for making decisions relating to choice of arrangements and measures, including maintenance actions and strategies. They are especially suitable for identifying equipment and activities that significantly affect risk, and or analyzing the effect of risk reducing activities. (S. Apeland & T. Aven, 2000)

4.2.4 Risk assessment

Risk may be expressed by the consequence spectrum (K_1, F_1), (K_2, F_2),…, where F_i designates the frequency of undesirable events leading to the consequence K_i, or possibly the probability that an undesirable event shall occur which gives the consequence K_i (J.E Vinnem, 2007).

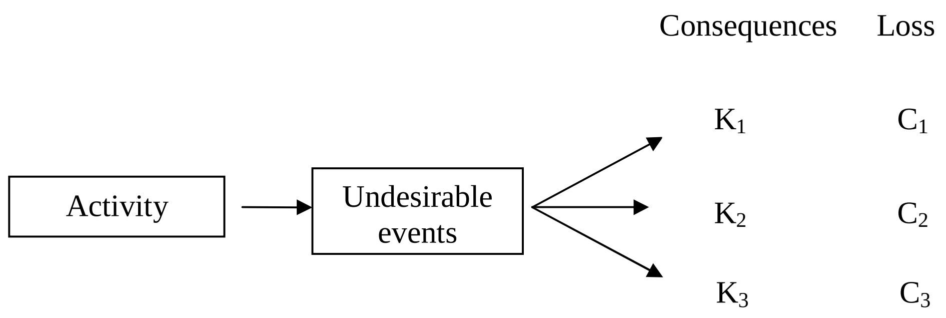

Figure 4.6: General risk model

Normally, we use *statistically expected (mean)* loss as a measure to express the consequences of risk. Once the losses C_1, C_2, ….., are determined The value is calculated by multiplying the losses by the corresponding frequencies (probabilities) and summing over all the relevant consequences, i.e.

$$\textit{Statistically expected loss} = C_1 \times F_1 + C_2 \times F_2 + \ldots$$

The rigor of assessment should be proportionate to the complexity of the problem and the magnitude of risk (HSE, 3/2006). Based on this consideration, there are three types of approach to assess risk, they are:

- *Qualitative* (Q), in which frequency and severity are determined purely qualitatively.
- *Semi-quantitative* (SQ), in which frequency and severity are approximately quantified within ranges.
- *Quantified risk assessment* (QRA), in which full quantification occurs.

This division of risk assessment reflects the different requirements of the risk assessment level of detail from low to high, see figure 4.7. The amount of detail and effort required increases from qualitative (Q) to semi-quantitative (SQ) to quantified risk assessment (QRA).

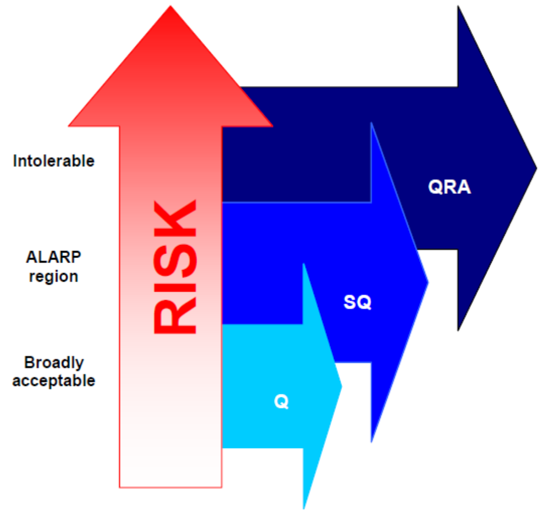

Figure 4.7 Level of risk assessment (source: *Guidance on Risk Assessment for Offshore Installations,HSE*)

When we make the decision of which approach should be use, the following dimensions must be taken into account:

- The level of estimated risk (and its proximity to the limits of tolerability).
- The complexity of the problem and/or difficulty in answering the question of whether more needs to be done to reduce the risk.

When we consider the Q or SQ approaches, a risk matrix is usually used as a method to rank and present the risks. It is important that the risk matrix used should be capable of discriminating between the risks of the different hazardous events for the installation (HSE, 3/2006). Normally, the more complex the matrix is, the better it is in discrimination. A 5 x 5 matrix will give greater opportunity for such discrimination than a 3 x 3.

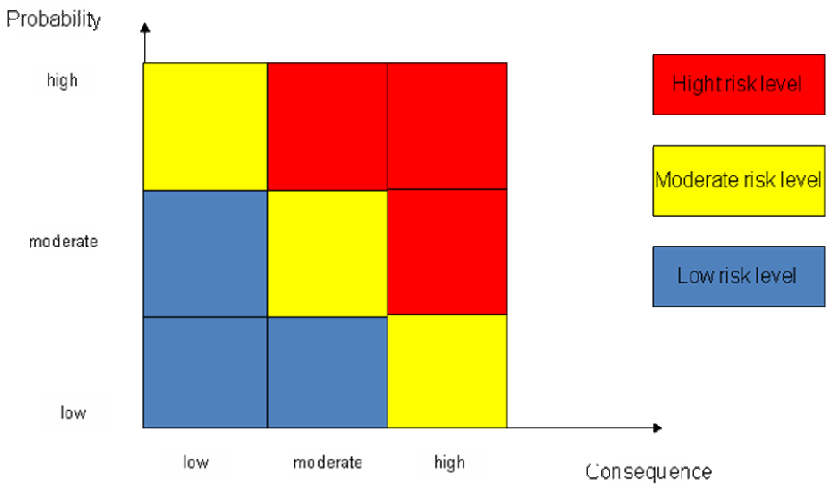

Figure 4.8: Risk matrix

Quantitative risk assessment is very useful because quantification of risk results in the numerical value of risk, it provides important decision-making tools to the maintenance managers. By using the results of a QRA, the manager is able to answer questions such as

- Which events are most likely to happen?
- Which event is the most critical?
- Is it necessary to reduce the risk?
- What mitigation measures are most effective?

5 DATA COLLECTION

A data collection sheet is drawing out in this chapter to explain what data should collect and how to do calculation.

In order to collect and analyze the data, a sheet for assessment is designed, see the sample in figure 4.1, and the original sheet is in Appendix A:

Taxonomy code	Equipment Description			Maintenance concepts			FMEA If Maintenance activity is not performed			Risk Assessment												The Value of Maintenance
	Equipment function	Equipment assignment	Equipment capability	Maint. activity	Maint. Function	Maint. Cost	Failure Mode	Failure Mech.	Failure effects	Severity Class	Frequency (per million hours)	Active Repair Hours	Manhours	Consequence loss							Total risk value (NOK/year)	
														Economic Loss(production rate 8,300 bar/hour, oil price 330NOK/bar, manpower price 200NOK/manhour)				HSE Loss				
														Downtime loss(MNOK)	Repair cost (MNOK)	Clean-up and fine cost of oil leakage(1,4M NOK/ton)	oil lost cost	Pesonnel Injury	Environment	Fatality		

Figure 5.1 Sheet for assessment of value of maintenance

The data collection sheet contains five parts: Taxonomy number, Equipment description part, Maintenance concepts part, Failure mode effects analysis part, and Risk assessment part. In the end of the sheet is the value of each maintenance activity. The sheet is designed following the logic of the quantitative assessment process of the maintenance value.

5.1 Taxonomy code

Taxonomy code is the ID of equipment. For each of the equipments, a group of letters is given. These letters describe the equipment's type, design property, and the functional system where the equipment belongs to. Using the taxonomy code, we can fast identify the target equipment we want to study. For example, the taxonomy code PU-CE-FF, which is illustrated in figure 4.2, means a centrifugal pump used in fire-fighting system.

EQUIPMENT CLASS		DESIGN CLASS		SYSTEM	
Description	Code	Description	Code	Description	Code
Pumps	PU	Centrifugal Reciprocating Rotary	CE RE RO	Water fire fighting Sea water injection Oil handling Gas utilities Gas processing	FF WI OH GU GP ....
Fire & Gas detectors	FG	Smoke/combustion Heat Flame	BS BH BF	Fire detection	FD
		Hydrocarbon gas H2S gas	AB AS	Gas detection	GD

Figure 5.2 Taxonomy code (source: OREDA 2002)

5.2 Equipment description part

The equipment description part contains a description of each equipment unit for which data have been collected, e.g., pump, turbine, and etc.. This part includes the description of equipment's function, the situation of the equipment's assignment, as well as some technical data (e.g., capacity, size).

The data and information we need to collect in this part include:

- *The equipment's function in the system.* Failure means loss of function. Therefore, the equipment's function is directly linked with the failure effects. This information can help to determine the failure effects to the system, e.g., will it affects the production regularity or the Health, Safety and Environment, or both of them if the equipment fails.

- *The equipment's performance*. Regularity performance measures are used both in analyses for prediction and for reporting of historical performance in the operational phase. This information can be used to determine how much the effect is if a failure mode occurs. For different equipment or facility, we use different measures to record its performance:

a) for oil production equipments, we use production rate (volume oil per time)
b) for injection equipments, we use injection rate (volume per time)
c) for transport equipments, we use flow rate (volume per time)
d) for storage equipments, we use storage capacity (volume)
e) for other equipments, we decide the measures according to their individual function.

- *The assignment of the equipments*. This term describes the assignment of the equipments with the same function in the system, which includes how many homogeneous equipment in the system, the layout (parallel or serial), and etc.. This information can also help us to determine the equipment's criticality and the effects if the equipment fails. For example, the equipment which has no standby or installed spares or the equipment which is in a serial connection is much more critical than the equipment which is parallel connected by another equipment with the same function, because once the equipment fails, the whole process may be shutdown. And as the number of equipments that are parallel connected increases, the criticality of the equipment decreases.

5.3 Maintenance concept part

The Maintenance part contains information about the maintenance activities that are implemented on the equipment, which includes the name of the maintenance activity, its function, the cost of the maintenance activity, and its value.

5.4 Failure mode effects analysis part

This part contains the identification of the failure modes, failure mechanism, and the failure mode effects.

5.5 Risk assessment part

The risk assessment part is the core of the sheet. In this part, the following terms should be identified:

- Severity class
- Failure frequency
- Active repair hours
- Consequence loss
- Risk value
- HSE risk assessment

5.5.1 Severity class

As we mentioned before, based on the severity, the failures can be classified into:

- *Critical failure*: immediate and complete loss of a system's capability
- *Degraded failure:* not critical, but be gradual or partial, and may develop into a critical failure in time.
- *Incipient failure*: if not attended to, could result in a critical or degraded failure in the near future.
- *Unknown failure:* Failure severity was not recorded or could not be deduced (not be considered here).

This classification is adopted by OREDA. Since the reliability data we used in this papare is based on OREDA, we also follow the way of classifying the failures.

Among these four failures, only the critical and degraded failures are interesting to the research. That is because the purpose we apply preventive maintenance or predictive maintenance is to detect and eliminate failure at the incipient state, so that it cannot bring damage to the system. Therefore, we will only collect critical and degraded failure data in the sheet.

5.5.2 Failure frequency

According to the Norsok Standard Z-008, the assessment of failure probabilities is implicitly expressed by the maintenance intervals documented for the different generic maintenance concepts, which again should be based on well documented operational experience and failure characteristics (Norsok Standard Z-008). The OREDA is estimated from both the historical records and the experts' judgment, it is the most trustable database available now. In this sheet, we will adopt the failure frequency data from OREDA.

5.5.3 Active repair hours and man-hour

The active repair hours can be used to calculate the downtime loss. We can also adopt the data from OREDA.

5.5.4 Consequence loss

The consequence of risk has two perspectives, the economic perspective and the HSE perspective. The economic perspective can be expressed quantitatively, but the HSE perspective can not. According to the Norsok Standard Z-008, the consequences of MF failures are assessed according to the effect on the plant and system level with respect to production loss and direct cost measured in downtime and monetary terms, while consequences of personal injury and environmental damage are classified according to pre-defined consequence classes and acceptance criteria (Norsok Standard Z-008). In this column, we only collect the data of economic perspective.

The economic consequence should be presented in financial terms using appropriate currency units (DNV RP-G 101, 2002), it includes the loss due to the damage on the production regularity and the HSE loss which can be presented in financial terms. The terms we need to collect include:

- Production degradation loss
- Downtime loss
- Repair cost
- lost Oil cost
- Clean-up and fine cost of oil leakage

Production degradation loss (PDL):

PDL=y1-∫Y(t) dt, but since only degraded failure is considered here, the failure interval t1-t2 is small, we approximately calculate PDL by PDL=1/2*y1*(t2-t1), and the result is so small compare with the downtime loss, that it can be ignored.

Downtime loss (DL):

*DL= down time * Production rate*

Repair cost (RC):

Repair cost includes two terms: *Corrective maintenance man-hours (CMM),* and *Corrective maintenance spare parts (CMSP)* (Norsok Standard O-CR-001). The equation is: *RC= CMM+ CMSP*

Lost oil cost (LO):

Oil lost cost is the monetary value of the lost oil due to leakage or other reasons. The equation is: *LO = the volume of lost oil * oil price*

Clean-up and fine cost of oil leakage (CFC):

This term expresses the economic perspective of the environmental risk. According to the research by Exxon Valdez in the Prince William Sound in Alaska in 1989, the criteria are:

- Approximately 440 000 NOK (1997 value) per ton oil spilled in clean-up cost.
- Approximately 1 million NOK (actual values paid) per ton oil spilled in compensation, fines, etc.

If one turns to more moderate spills (500 tons to 5 000 tons), a typical clean-up cost may be in the order of 150 000 NOK per ton oil that has stranded. (Norsok Standard Z-013).

HSE risk assessment

The HSE risk has 2 perspectives:

- Environment perspectives. According to Norsok Standard Z-013, valuation of risk to environment may include many different aspects:

a) Clean up cost.
b) Cost of lost oil.
c) Compensation to the fishing and fish farming industries, local communities, etc. for loss of income due to environmental damage.
d) Intangible aspects, e.g. loss of reputation, social effects.

- Personnel perspectives, which include personnel injury and fatality. in production system, the causes include:

a) Fire & Explosion (major accident)
b) Falling load
c) Poisoning, asphyxiation, radiation.
d) Electric shock.
e) Damage caused by tools, machinery

It should be noted that, the HSE consequence is much more difficult to be quantitatively expressed, because:

1) It is more complex, contains tangible and intangible perspectives, some intangible perspectives such as the damage to the ecology, the social effects, is difficult to quantify.
2) Normally, the HSE risk is dominated by large system or plant level accident, or major accident, e.g. Fire & Explosion. These system or plant level accidents are mostly caused by the synergic effect of many small, equipment level failures. A single equipment level failure can rarely cause such kind of accident. For example, a fire & explosion accident must have two necessary conditions, they are flammable materials and ignition sources, sometimes, the failure of fire detect and fire-fight system may be also an option. Therefore, the leakage failure may have the risk of fire, but only a leakage cannot initiate a fire accident.

However, the HSE risk of a failure is much more critical than the economic risk, as once it happened, it will be damaged. Therefore, although we are not able to use numerical value to express the HSE risk, we need to use some other ways, such as qualitative assessment to record the potential HSE risk of a failure. And when we make maintenance plan, the maintenance activities that have the contribution to HSE risk have the priority to be implemented.

The standards to classify the HSE consequences are given by many documents, such as the HSE's report " Offshore Hydrocarbon Releases", Norsok Standards S-002, Z-013, Z-016, and etc. Based on these standards, we can qualitatively assess the HSE risk of failures.

1) General consequence classification

To classify the most serious effect of loss of functionality (both loss of MF and sub functions) the consequence classes defined in Table 5.1 should be applied, unless otherwise specified. (Norsok Standards Z-013).

Table 5.1 General consequence classification

Class	Health, safety and environment (HSE)	Production	Cost (exclusive production loss)
High	Potential for serious personnel injuries. Render safety critical systems inoperable. Potential for fire in classified areas. Potential for large pollution.	Stop in production/significant reduced rate of production exceeding X hours (specify duration) within a defined period of time.	Substantial cost - exceeding Y NOK (specify cost limit)
Med.	Potential for injuries requiring medical treatment. Limited effect on safety systems. No potential for fire in classified areas. Potential for moderate pollution.	Brief stop in production/reduced rate of production lasting less than X hours (specify duration) within a defined period of time.	Moderate cost between Z – Y NOK (specify cost limits)
Low	No potential for injuries. No potential for fire or effect on safety systems. No potential for pollution (specify limit)	No effect on production within a defined period of time.	Insignificant cost less than Z NOK (specify cost limit)

2) Consequence classification for containment (External leakage)

Table 5.2 Consequence classification for containment (External leakage)

Class	Health, safety and environment (HSE)	Production	Cost (exclusive production loss)
High	When substance is: • Hydrocarbons (highly ignitable gases and unstabilized oil) and other flammable media. • Liquid/steam, exceeding 50 ºC or 10 bar. • Toxic gas and fluids. • Chemicals (see B.1)	As for production, class 'High' in Table 1.	As for cost, class 'High' in Table 1.
Med.	When substance is: • Stabilised oil, diesel and other less ignitable gases and fluids. • Liquid/steam, less than 50 ºC and 10 bar • Toxic substance, small volume. • Diesel	As for production, class 'Medium' in Table 1.	As for cost, class 'Medium' in Table 1.
Low	When substance is: • Non-ignitable media. • Atmospheric gasses and fluids harmless to humans and environment. • Negligible toxic effects. • Harmless chemicals (see B.1).	As for production, class 'Low' in Table 1.	As for cost, class 'Low' in Table 1.

3) Effect of pollution

The Norsok Standards Z-013 suggests the consequence classification caused by pollution as following:

Potential for large pollution:
- Hydrocarbons : > 100 m^3
- Chemical group 1 : > 200 liters
- Chemical group 2 : > 1 m^3
- Chemical group 3 : > 10 m^3

Potential for moderate pollution:
- Hydrocarbons : 1 – 100 m^3
- Chemical group 1 : 25 – 200 liters
- Chemical group 2 : 0.25 – 1 m^3
- Chemical group 3 : 1 – 10 m^3

No potential for pollution exceeding:
- Hydrocarbons : < 1 m^3
- Chemical group 1 : < 25 liters
- Chemical group 2 : < 200 liters
- Chemical group 3 : < 1 m^3

4) *Cost of human life*

As the Norsok Standard Z-013 pointed, various studies have on the other hand, shown that our society implicitly uses such values, as decision support related to investment in accident prevention measures in transportation, medical treatment, life insurance, etc.

- £ 0,6 M (6-7 MNOK) in nuclear industry, published by HSE
- 10-20 MNOK, published by Norsok Standard Z-013

100 MNOK or more if consider the willingness to pay for averting a statistical fatality, Norsok Standard Z-013

Total risk value

Since only the economic risk is able to be quantified, the total risk value should be expressed by the monetary risk value of each failure modes. The total risk value is calculated by the product of frequency of failure mode and the sum of its consequence losses.

$$\textit{Total risk value} = \textit{Frequency} * \sum (PDL+DL+RC+LO+CFC)$$

finally, we can get the value of maintenance activity by using the *Risk value* minus the *Cost of maintenance activity*. Although the HSE risk cannot be expressed by numerical value, it is also the contribution of maintenance activity, and need to be well considered.

6 CASE STUDY

In this chapter, pumps used in offshore Oil & Gas production system will be taken as an example to illustrate how to quantify the values of maintenance activities, as well as the illustration of how much are the values.

6.1 Background

Offshore installation is a huge and complicated system. Normally, an offshore Oil & Gas production system can be categorized into four sub-systems according to their function, include production system, process system, drilling system, and utility system. Under these four sub-systems, there are amount of units and equipments. The following figure gives a simplified overview of the typical oil and gas production system (Devold, 2008).

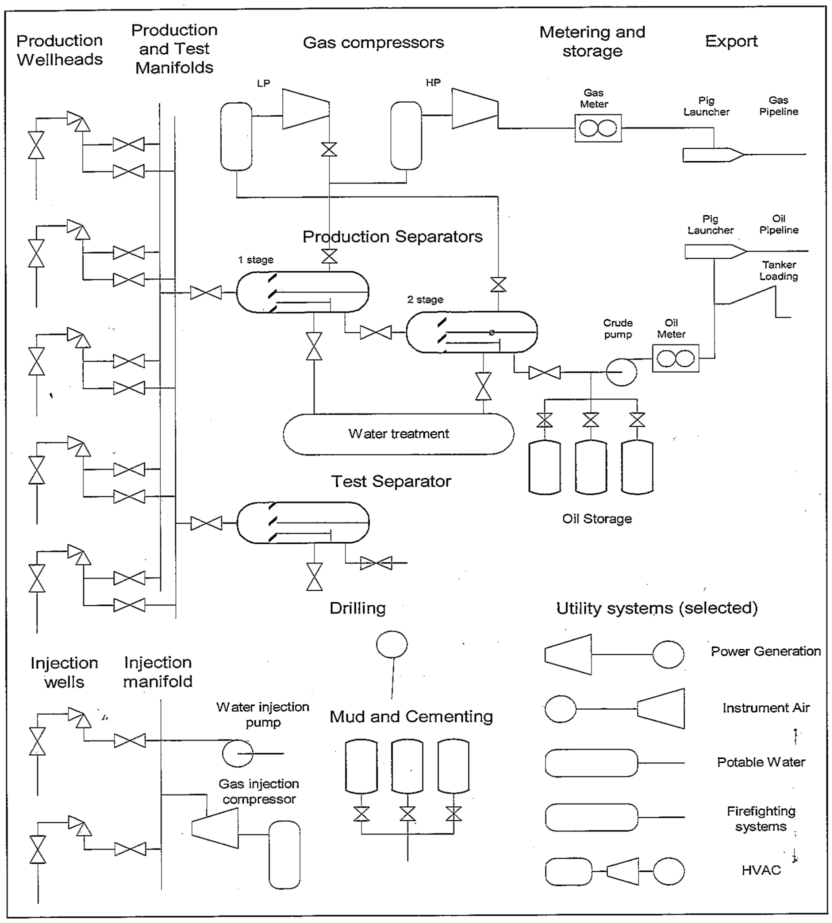

Figure 6.1 Overview of Oil and Gas production system (source: Håvard Devold, 2008)

In this chapter, we will select three pumps from three different function sub-systems as a case study, to evaluate the maintenance actions on them by this quantitative assessment method.

6.2 Introduction

Pump as an energy transfer device is widely used in offshore installations. As pump has the function of raising, transporting, and compressing liquid, it can be found in almost every section of petroleum industry, such as in fire-fighting system, piping system, production system, and processing system.

6.2.1 Overview of a typical pump

A typical pump system is usually divided into six sub-units (OREDA, 2002):

- Driver unit
- Power transmission unit
- Pump unit
- Control and monitoring unit
- Lubrication unit
- Miscellaneous (include all sub-units that are unknown)

The construction of a typical pump system and the maintainable items are shown individually in the figure 6.2 and table 6.1. Generally, all pumps are similar in their construction and components. However, for their different application, they may be design and built differently.

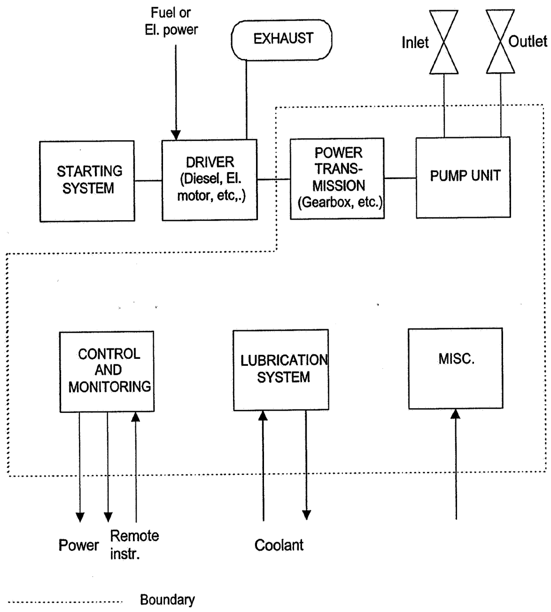

Figure 6.2 Construction of a typical pump system (adapt from OREDA)

PUMP				
Power transmission	Pump	Control and Monitoring	Lubrication system	Miscellaneous
• Gearbox/var. drive • Bearing • Seals • Lubrication • Coupling to driver • Coupling to driven unit • Instruments	• Support • Casing • Impeller • Shaft • Radial bearing • Thrust bearing • Seals • Valves & piping • Cylinder liner[5] • Piston • Diaphragm[6] • Instruments	• Instruments • Cabling & junction boxes • Control unit • Actuating device • Monitoring • Internal power supply • Valves	• Instruments • Reservoir w/heating system • Pump w/motor • Filter • Cooler • Valves & piping • Oil • Seals	• Purge air • Cooling/heating system • Filter, cyclone • Pulsation damper

Table 6.1 Maintenance items of a typical pump

6.2.2 Types of pumps commonly used in offshore installation

Generally, two types of pump are usually used in offshore installations. They are:

- *Centrifugal pump*. Centrifugal pumps are the most commonly used pumps in petroleum industry. Among all the installed pumps in a typical petroleum plant, almost 80-90% are centrifugal pumps (Girdhar & Moniz, 2005). Centrifugal pumps have the advantage of design simplicity, high efficiency, wide range of capacity, head, smooth flow rate, and ease of operation and maintenance (Girdhar & Moniz, 2005). They are widely used for fire fighting, injection, oil handling, O&G processing, etc,.
- *Positive displacement pumps*. Positive displacement pumps, which life a given volume for each cycle of operation, can be divided into two main classes, reciprocating and rotary (Girdhar & Moniz, 2005.). Reciprocating pumps are usually used for chemical injection, gas processing, and gas treatment, while rotary pumps are mainly used for oily water treatment in offshore installation.

6.2.3 Application of pumps in offshore installation

Pumps are used in every phase of petroleum production, transportation, and refinery (Girdhar & Moniz, 2005). The primary areas that pumps applied in offshore O&G production system include (Karassik & Igor, 2000):

- *Fire pumps*. Normally, the active fire-fighting system centers around a ring main which pressurized by at least two fire pumps as shown on the sketch. (Angus Mather). The fire pumps may be manually activated from strategic locations such as the main control room, helideck and process areas, or automatically by a significant drop in ring. The number of fire pumps required will be determined from the fire and explosion analysis but normally, at least two independently powered fire pumps will be found on an offshore installation. The number of pumps installed should reflect the possibility of the unavailability of equipment due to breakdown or maintenance requirements. Each pump should be capable of supplying adequate water to operate the largest section of deluge equipment in addition to maintaining the pressure.

- *Production pumps.* Production pumps include reciprocating units for mud circulation during drilling and sucker-rod, hydraulic rod less, and motor driven submersible centrifugal units for lifting crude to the surface. The most common use of centrifugal pumps in production is for water flooding (secondary recovery, subsidence prevention, or pressure maintenance).

- *Transportation pumps.* Transportation pumps include units for gathering, for on and offshore production, for pipelining crude and refined products, for loading and unloading tankers, tank cars, barges, or tank trucks, and for servicing airport fueling terminals. The majority of the units are centrifugal. Refining units vary from single stage centrifugal units to horizontal and vertical multistage barrel type pumps handling a variety of products over a full range of temperatures and pressures. Centrifugal pumps are also used for auxiliary services, such as cooling towers and cooling water. Except for some comments about the use of displacement pumps for handling viscous liquids, this section is restricted to centrifugal pumps, the type most frequently used in the petroleum industry. It also includes an overview of the requirements for some of the principal types of centrifugal pumps.

Identification the application area of a pump is a fundamental and critical work in this quantitative method. That is because for different use, the types, size, functions of pumps various. And as the operational environment, the performance requirement, and the medium that the pumps transport are different, the failure modes of pumps will be different. These factors determined the pumps diversities in major failure modes, failure frequency, as well as the effects to the whole system if a pump failed. For example, as the OREDA pointed, the centrifugal pump can be used in 20 application areas, include: chemical injection, combined function, cooling systems, crude oil handling, emergency power, gas processing, gas treatment, sea water lift, water fire fighting, and so on. Among these tasks, the pumps used for chemical transportation e.g. chemical injection, crude oil handling are easier to have corrosions than the pump used for transporting water such as water injection and fire fighting; the failure of a pump for injection will affect the production regularity, while the failure of a pump for fire fighting could lead to an fire accident.

6.2.4 Operational characters of pumps

It is a complicate task to evaluate the performance of a pump as there are many factors that can influence the performance. For the purpose of assessing the value of maintenance activity in this paper, we only need to understand three primary characters of pumps, they are introduced as following:

1) *Flow rate*. Low rate is the first and most important character we need to collect as the pump is a liquid transportation machinery. The units of flow rate that are mostly used are m^3/h or gpm (gallon per minute).

2) *Head*. Significance of using the ***"head"*** term instead of the ***"pressure"*** term. The pressure at any point in a liquid can be thought of as being caused by a vertical column of the liquid due to its weight. The height of this column is called the static head and is expressed in terms of feet of liquid. The same *head* term is used to measure the kinetic energy created by the pump. In other words, head is a measurement of the height of a liquid column that the pump could create from the kinetic energy imparted to the liquid. Imagine a pipe shooting a jet of water straight up into the air, the height the water goes up would be the head. The head is not equivalent to pressure. Head is a term that has units of a length or feet and pressure has units of force per unit area or pound per square inch. The main reason for using head instead of pressure to measure a centrifugal pump's energy is that the pressure from a pump will change if the specific gravity (weight) of the liquid changes, but the head will not change. Since any given centrifugal pump can move a lot of different fluids, with different specific gravities, it is simpler to discuss the pump's head and forget about the pressure. The term of head is expressed by the equation of $H=(P_d-P_s)*10/\rho$, where: P_d is the discharge pressure, P_s is the suction pressure, and ρ is the specific gravity of the liquid.

3) *Pump efficiency*. The pump does not completely convert kinetic energy to pressure energy since some of the kinetic energy is lost in this process. Pump efficiency is a factor that accounts for these energy losses. Every pump is designed for a specific flow and a corresponding differential head, though it is possible to operate at certain percentage points away from the designed values.

Table 6.2 shows the operational characters of a typical centrifugal pump:

Table 6.2 Operational characters of a centrifugal pump

	1	2	3	4	5
Operating Time (hours)	500	1,000	1,500	2,000	1,500
Flow Rate (gpm)	400	600	800	1,000	1,200
Head (feet)	160	155	145	134	120
Pump Efficiency (%)	63	76	82	82.5	80

The relationships between flow rate and head, and flow rate and pump efficiency are shown in figure 6.3.

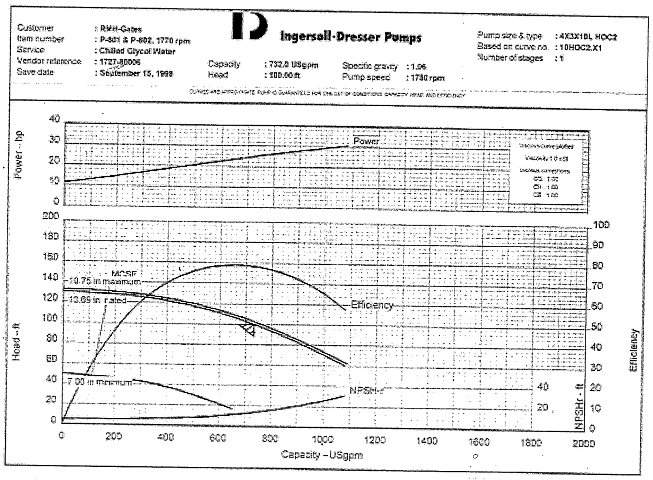

Figure 6.3 A typical pump characteristic curve

6.3 Pump system modeling

Before we go on the discussion, some assumptions should be done for theoretical study:

- No maintenance actions are performed on the equipment. Once a failure occurs, we will let the equipment run to complete failure.

- The effectiveness will not be considered in this paper. As we mentioned before, the preventive maintenance is ineffective due to the difference between the maintenance frequency and the failure frequency. To some extent, the predictive maintenance also has effective problems. These effectiveness problems will not be considered in this paper, we assume the failures can be detected immediately as they occur, and sequentially corrective maintenance will be implemented.

- In order to illustrate the exact contribution value of maintenance activity, we assume there is no acceptable limit on the equipment performance. Once the performance start declining, we believe failure occurs.

In order to illustrate how to quantitatively assessing the value of maintenance activity, we build up a model of the pump system in an offshore production system:

An offshore platform is located in an oil field in the North Sea. The total numbers of wells are 6 produce wells and 3 injection wells. Every third well will be a water injector. The production well rate is 5000 m^3/day and the processing capacity of the platform will be 25000 m^3/day. The injection wells are driven by centrifugal pumps which has the injection rate is 6000 m^3/day, each well has the estimated increased oil production of

2400 m^3/d. The transportation system in the processing section is driven by a group of centrifugal pumps, each of them has the flow rate of 1300 m^3/h. The platform also has a fire-fighting system, which is composed by 2 fire-fighting pumps. Each of the pump has the flow rate of 900 m^3/h.

The figures we used in this model are adapted from "*Pump Handbook"* (Karassik & Igor, 2000) and "*Subsea Pumps*" (Sølvik, 2007).

According to the pump system modeling, the description of pumps is shown in Table 6.3:

Table 6.3 Description of pumps

Taxonomic code	**Equipment function**	**Equipment capacity**
PU-CE-WI	Water injection	Injection rate 6000 m^3/d, estimated increased oil production of 100 m^3/h
PU-CE-OP	Transport oil in oil processing system	Flow rate 1300 m^3/h
PU-CE-FF	Fire-fighting pump	Flow rate 900 m^3/h

6.4 Assess the value of maintenance activities

6.4.1 Failure modes identification

As OREDA lists, the typical failure modes that often occur on pumps include:

- abnormal instrument reading
- breakdown
- erratic output
- external leakage-process medium
- external leakage-utility medium
- fail to start on demand
- fail to stop on demand
- high output
- internal leakage
- low output
- minor in-service problems
- noise
- overheating
- parameter deviation
- spurious stop
- structural deficiency
- unknown

- vibration

Among these failure modes, *external leakage (process and utility medium), internal leakage, and fail to start on demand* are the major failure modes which typically occur on centrifugal pumps, see table 6.4. For different pumps, the frequency of major failures various as the design features, functions, etc. are different. For example, the oil processing pumps are used to transport chemical liquid which may mixed with crude oil, produced water, sand, etc., therefore, the leakage failures occur more frequently than the other two types of pumps, as the water injection pumps and fire-fighting pumps are used to transport pure water.

Table 6.4 Major failure modes on pumps

Taxonomic code	**Failure Modes**	**Severity class**	**Failure Frequency (10^6 hours)**	**Active rep.hr**	**manhours**
PU-CE-WI	Breakdown	Critical	0.93	4.0	8.0
	External leakage-process medium	Critical	11.47	39.0	52.0
		Degrade			
	External leakage-utility medium	Critical	3.27	15.1	30.4
		Degrade	11.22	32.5	53.4
	Fail to start on demand	Critical	13.76	57.2	63.4
		Degrade	37.36	17.2	25.7
PU-CE-OP	Breakdown	Critical	4.96		
	External leakage-process medium	Critical	66.25	11.2	11.2
		Degrade			
	External leakage-utility medium	Critical			
		Degrade	93.14	6.2	55.8
	Fail to start on demand	Critical	7.18	6.0	6.0
		Degrade			
PU-CE-FF	External leakage-process medium	Critical			
		Degrade	25.8	1.0	2.0
	External leakage-utility medium	Critical			
		Degrade	372.7	7.1	14.2
	Fail to start on demand	Critical	31.38	3.6	12.8
		Degrade	49.37	3.3	6.5

6.4.2 Failure causes and failure effects

The failures of centrifugal pumps can be categorized as following types according to the failure mechanism:

- Hydraulic problems include lose of priming, cavitations, suction of foreign materials, and etc.
- Mechanical problems include the general mechanical problems, problems in sealing area, bearing, shafts, valves, and etc.
- Other problems

(The detailed information about failure causes of centrifugal pumps are illustrated in Appendix B)

Failures are defined as the complete or partial lose of function of the equipment. Different failure modes on a pump may have different failure mode effects. Some failure modes may cause completely loss of the pump's function, which means the breakdown of pump; some may only cause the partial loses of its function, for example the reduction of the pump's transportation capability, or leakage. On the other hand, as the pumps' functions are different, the same failure modes on different pumps may have different effects to the system. For example, the water injection pump's function is to improve the well's production rate by maintaining the pressure of the reservoir, therefore, the breakdown and fail to start on demand of this pump can cause the reduction of production rate. But on the contrary, the fire-fighting pump is safety-related equipment but not production-related equipment, therefore, its breakdown and fail to start on demand can not effect the production of the system. But, they can lead to the potential risk of a fire accident. Another illustration is the different effects of leakages on the water injection pump and the oil processing pump. The oil processing pump's function is to drive the liquid flow in processing system. The leakage of oil processing pump may lead to the loss of oil products. But since the process medium in water injection pump is water, it will not effect the production.

Table 6.5 failure causes and failure effects of pumps

Taxonomic code	Failure Modes	Failure causes	Effects on production	Effects on HSE
PU-CE-WI	Breakdown	Suction of foreign objects, damage to impeller, bearing breakdown, internal damage	Stop water injection, reduction of oil production	No
	External leakage-process medium	Mechanical failures (general, sealing, bearing, shafts)	Normally has no effects on production	Leakage of water, no effects on HSE
	External leakage-utility medium	Bearing breakdown, internal damage	Normally has no effects on production	Effects on environment
	Fail to start on demand	Instrument failure	Stop water injection, reduction of oil production	No
PU-CE-OP	Breakdown	Suction of foreign objects, damage to impeller, bearing breakdown, internal damage	Stop oil transportation, reduction of O & G production	No
	External leakage-process medium	Mechanical failures (general, sealing, bearing, shafts)	20 m^3 oil leakage, but only 2 m^3 spill into the sea	Pollution to environment, potential of fire
	External leakage-utility medium	Bearing breakdown, internal damage	Normally has no effects on production	Pollution to environment, potential of fire
	Fail to start on demand	Instrument failure	Stop oil transportation, reduction of O & G production	No
PU-CE-FF	External leakage-process medium	Mechanical failures (general, sealing, bearing, shafts)	No	Potential risk in fire-fighting
	External leakage-utility medium	Bearing breakdown, internal damage	No	No
	Fail to start on demand	Instrument failure	No	Potential risk in fire-fighting

6.4.3 Assess the risk values of the failure modes

In order to facilitate the calculation, we do the following assumption: *Oil price: 50 USD/bbl, that is 2062,5NOK/m^3; 1 USD = 6,5 NOK; the manhour cost of repaire is 500 NOK/h; the average cost of spare material(include the costs of purchasing spare parts,* *repair tools, and all the other material consumption) is 10,000 NOK/time; the clean-up cost and fine cost of oil leakage is totally 1,4MNOK/tone, that is 1,2MNOK/m^3.*

The equations of calculation are shown as following:

- *Downtime loss = Activity repair time * production rate*
- *Repair cost = cost of spare material + man-hour cost * man-hour*
- *Clean-up and fine cost of oil leakage = 0,12 MNOK/m^3 * volume of oil spill*
- *Oil lost cost = oil price * volume of leakage*

Thus, the total risk values of the failure modes are the following:

Table 6.6 Total risk values of failure modes

Tax. code	FM	Sever. Class	Frequency (10^6 hours)	Consequence loss				Total risk value (MNOK/ year)
				Economic Loss (MNOK)				
				Downtime loss	Repair cost	Clean-up and fine cost of oil leakage	oil lost cost	
PU-CE-WI	Breakdown	Critical	0.93	0,825	0,014			0,006844
	External leakage-P	Critical	11.47		0,036			0,003622
		Degrade						
	External leakage-U	Critical	3.27		0,0252			0,000723
		Degrade	11.22		0,0367			0,003612
	Fail to start on demand	Critical	13.76	11,7975	0,0417			1,429012
		Degrade	37.36	3,5475	0,02285			1,170073
PU-CE-OP	Breakdown	Critical	4.96					
	External leakage-P	Critical	66.25		0,0156	0,24	0,041	0,172512
		Degrade						
	External leakage-U	Critical						
		Degrade	93.14		0,0379			0,030965
	Fail to start on demand	Critical	7.18		0,013			0,000819
		Degrade						
PU-CE-FF	External leakage-P	Critical						
		Degrade	25.8		0,011			0,002489
	External leakage-U	Critical						
		Degrade	372.7		0,0171			0,055905
	Fail to start on demand	Critical	31.38		0,0164			0,004514
		Degrade	49.37		0,01325			0,005738

6.4.4 Maintenance activities against the failure modes

In the following discussion, we implement a group of maintenance activities on the three different pumps. The purpose of doing this is to illustrate the deviations of values due to implement the same maintenance activity on different pumps, see table 6.7.

Since the vibration control is an online maintenance activity, the cost includes: the cost of implementing the vibration monitoring, the cost of corrective or preventive maintenance, and the man-hour cost. On contrary, the loop test is an off-line maintenance activity; therefore, beside the same costs as the vibration control, it also includes the production loss due to the shutdown of process.

Table 6.7 Maintenance activities against failure modes

Taxonomic code	**Failure Modes**	**Maint. activity**	**Description of maint.**	**Cost of maint. (MNOK/Y)**
PU-CE-WI	Breakdown	Vibration control	Online vibration monitoring and maintenance every 3 month	0.001
	External leakage-process medium	Vibration control	Online vibration monitoring and maintenance every 3 month	0.001
	External leakage-utility medium	Vibration control	Online vibration monitoring and maintenance every 3 month	0.001
	Fail to start on demand	Loop test	PAS test every 24 month, 1 hour shutdown	0.21
PU-CE-OP	Breakdown	Vibration control	Online vibration monitoring and maintenance every 3 month	0.001
	External leakage-process medium	Vibration control	Online vibration monitoring and maintenance every 3 month	0.001
	External leakage-utility medium	Vibration control	Online vibration monitoring and maintenance every 3 month	0.001
	Fail to start on demand	Loop test	PAS test every 24 month, 1 hour shutdown	2.68
PU-CE-FF	External leakage-process medium	Vibration control	Online vibration monitoring and maintenance every 3 month	0.001
	External leakage-utility medium	Vibration control	Online vibration monitoring and maintenance every 3 month	0.001
	Fail to start on demand	Loop test	PAS test every 24 month, 1 hours shutdown	0.001

6.4.5 Identify the value of maintenance activity

According to the definition, *"The value of maintenance activity is the benefit we can obtain from a maintenance activity"*, the value of maintenance activity = the risk value saved from the failures due to a maintenance activity is not performed – the cost of the maintenance activity, where, the vibration control is used to prevent the failure modes of breakdown, external leakage (process and utility), so the risk values that the vibration control can save are the sum of the two failure modes.

The values of maintenance activities on the three pumps are shown on the following table:

Table 6.8 Value of maintenance activity

Taxonomic code	**Maintenance activity**	**Saved risk values**	**Cost of activity**	**Contr. of maint. (MNOK/Y)**
PU-CE-WI	Vibration control	0.015	0.001	0.014
	Loop test	2.600	0.21	2.39
PU-CE-OP	Vibration control	0.203	0.001	0.202
	Loop test	0.0008	2.68	-2.68
PU-CE-FF	Vibration control	0.058	0.001	0.057
	Loop test	0.011	0.001	0.01

7 DISCUSSION

This chapter summarizes the findings of the thesis. Some aspects of the findings are discussed. Furthermore, the conclusions and the contributions of the research are discussed.

7.1 Findings from the case study

The case study finally brings out a very interesting finding to us: when we implement the same maintenance actions on the pumps with same type but different functions, the results can be very different. Recall the result shown in Table 5.8, the value of loop test is 2.39 MNOK/Y to water injection pump, but is – 2.68MNOK/Y to oil processing pump. The result reveals that the loop test, which is important to water injection pump, is not so suitable for oil processing pump.

From the new finding, we can get such conclusion that the equipment’s function, location, and working environment are very important determine matters to the value of maintenance activities. When we make maintenance strategy, these factors should be well considered.

The reason why the values of maintenance activities are so different is that the equipment’s function, location, and working environment determine what the dominate failure modes are and how serious they are. On the one hand, the equipment’s function determines the consequences of failures. Failures represent the loss of the functions. Equipments’ dominate failure modes various from each other as their main functions are different. For example, the water injection pump’s main function is to improve the well’s production rate by maintaining the pressure of the reservoir. Therefore, the failures of water injection pump can affect the oil production. The fire-fighting pump’s main function is fire-fighting. Therefore, its breakdown may lead to a fire accident. Another illustration is the different effects of leakages on the water injection pump and the oil processing pump. And, the oil processing pump’s main function is to transport hydrocarbon or chemical liquid. Its breakdown will affect the oil processing, and the leakage of oil processing pump may bring about environment and safety risks. On the other hand, the equipment’s function, location, and working environment affect the frequency of failures. The most obvious example is the comparison between oil processing pump and water injection pump. The main task of oil processing pump is to transport hydrocarbon or chemical liquid, and the work environment is strong corrosive; but the water used to extinguish the fire must be pure water. Therefore, oil processing pump is much easier to have corrosion than water injection pump, and its frequency of leakage is almost 23 times higher than the water injection pump’s. On the contrary, the water injection pump’s function is to inject water into oil reservoir, so that it needs to generate very high pressure. In this condition, the pump driver must be supplied by high electrical loads. But, the situation of oil processing pump is just opposite. Therefore, the water injection pump’s frequency of not start on demand is much higher than the oil processing pump. Different dominate failure modes and different failure severities correspondingly determine the difference of the value of maintenance activities.

7.2 Benefit of the methodology

The benefit of this quantitative assessing method may be the followings:

1) *Provide an intuitional and precise approach to for criticality analysis*. As a risk based method, it assesses the maintenance action through risk values. Therefore, whilst we get the value of maintenance actions, we get the risk value of failures, too. Since these values are numerical, we can easily and accurately know which failure modes are more critical than others, and which maintenance activity will contribute the most to the equipment.

2) *Facilitate maintenance management.* This method provides a useful decision-making tool to the maintenance management process. As we can clearly know the criticalities of maintenance activities from this method, the decision-making process in maintenance planning, or in maintenance strategy alteration will became very simply. And it is also helpful for people to make a corrective decision.

3) *Improve the effectiveness of maintenance activities.* For maintenance, effectiveness can represent the overall company satisfaction with the capacity and condition of its assets, or the reduction of the overall company cost obtain because production capacity is available when needed (Márquez, 2007). By evaluating the costs we spend on the maintenance and the benefits we could get from the maintenance, we could find out the most effective maintenance strategy which can meet the company's requirement on production optimization and cost reduction.

7.3 Practical application

As we mentioned before, in the maintenance management process, there are two very important steps. The first one is the maintenance program planning, which concerns the effectiveness of the maintenance program. The other one is the feedback step, which include feedback analysis and improvement measure. This step concerns the continuous improvement of maintenance management. Both the two steps are decision-making process which needs to do cooperation based on the value of maintenance activities. The quantitative assess method we developed in this paper provides a very useful decision-making tool to the maintenance management. It can be widely used in maintenance planning and maintenance optimization. By applying this method, we are able to evaluate if our maintenance plan is effective and cost efficient. Furthermore, it can suggest/propose ways to improve the value assessment of failure consequences.

7.3.1 Application to maintenance planning

According to EN 13306:2001, the maintenance plan consists of a "structured set of tasks that include activities, procedures, resources and the time scale required to carry out maintenance". Actually, maintenance planning is the maintenance management activity that is carried out to choose which maintenance strategy should be use. When different types of maintenance tasks are possible, the factual values of these tasks need to be evaluated.

By applying the quantitative method, we can establish a database, in which the most common and critical failure modes for equipment, the maintenance activities against the failure modes, and the values of these activities are included. When we make maintenance plan, we only need to adopt the manufacturers' recommendations, analysis the unique environmental condition and working requirement of particular equipment, and based on these considerations, choose the critical failure modes and possible maintenance activities from the database. Finally, determine the best group of maintenance activities which has the biggest value, and this may be the best maintenance strategy. Thus, the framework of maintenance planning could be:

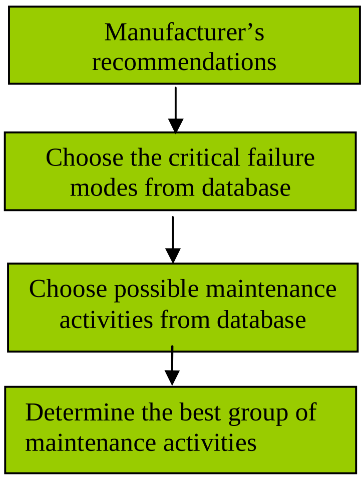

Figure 7.1 Maintenance planning model

7.3.2 Application to maintenance optimization

As the high demands on effective maintenance in industry, many researchers are now joining in the studies for maintenance optimization. As S. Apeland and T. Aven (2000) pointed, there can be various types of method to establish optimization modes, but all tools are for balancing costs and benefits. By evaluating the relationship between costs and benefits associated with each maintenance alternative, the optimal strategies can be determined (Apeland & Aven, 2000). The value of maintenance activity is just used to evaluate the relationship between costs and benefits.

In the maintenance optimization, we can use the value of maintenance activity as a measure, and try to find the best way which can maximize it. The maintenance optimization can be realized from 3 dimensions:

1) *Choose the better maintenance activity*. In most times, the reason why the effectiveness of maintenance activity is very low is that, the maintenance activity we chose is improper, or is not the most suitable. In this case, the solution is to change a better maintenance activity which has larger value.

2) Improve the inherent effectiveness of the individual maintenance activity. The inherent effectiveness is determined by the internal factors of the maintenance activity. Let's recall the equation of value of maintenance activity: *Value of maintenance activity= total saved risk value – total costs of maintenance,* where, *total costs of maintenance= the maintenance frequency * the cost of maintenance activity.* Therefore, the first method to improve inherent effectiveness is to reduce the cost of maintenance activity, and the second one is to make sue the maintenance frequency as the same with failure frequency as possible. The equation of value of maintenance activity can be used to identify the best maintenance frequency.

3) *Optimize the arrangement of maintenance activities*. Normally, we use a group of maintenance activities on equipment, but not a single maintenance activity. Therefore, the maintenance effect is a kind of synergy of all the maintenance activities. The arrangement of maintenance activities may influence the effectiveness of maintenance. For example, the effectiveness may be reduced due to the overlapping of two maintenance activities against the same failure mode. This will be discussed in future research.

8 SUGGESTION FOR FUTURE RESEARCH

The quantitative method to assess the value of maintenance activity establishes a good foundation for the research of maintenance management. As a master thesis project, the study is limited by the time. Further and more detailed researches are suggested to be done in the following areas:

1) *Effectiveness of individual maintenance activity*. In this paper, for theoretical study, we did not consider the effectiveness of maintenance activity. But, as we know, in real industry, the effectiveness of maintenance activity is a very important factor that we cannot ignore. In reality, the actual value of maintenance activity is the product of the ideal value and its effectiveness. Therefore, it is interesting to study the effectiveness of individual.

2) *The arrangement of maintenance activities*. As we discussed before, how to optimize the arrangement of maintenance activities could be an interesting area, and may need more considerations.

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Appendix A: Work sheet for assessing the contribution of maintenance activities

Taxonomy code	Equipment Description			Maintenance concepts			FMEA If Maintenance activity is not performed			Risk Assessment												The Contribution of Maintenance
														Consequence loss								
														Economic Loss(production rate 8,300 bar/hour, oil price 330NOK/bar, manpower price 200NOK/manhour)				HSE Loss			Total risk value (NOK/year)	
	Equipment function	Equipment assignment	Equipment capability	Maint. activity	Maint. Function	Maint. Cost	Failure Mode	Failure Mech.	Failure effects	Severity Class	Frequency (per million hours)	Active Repair Hours	Manhours	Downtime loss(MNOK)	Repair cost (MNOK)	Clean-up and fine cost of oil leakage(1,4M NOK/ton)	oil lost cost	Pesonnel Injury	Environment	Fatality		

Appendix B: Possible causes of centrifugal pumps problems
(Source: *Pump handbook* Karassik, Igor J. 2000)

Suction Problems

1. Pump not primed
2. Pump suction pipe not completely filled with liquid
3. Insufficient available NPSH
4. Excessive amount of air or gas in liquid
5. Air pocket in suction line
6. Air leaks into suction line
7. Air leaks into pump through stuffing boxes or through mechanical seal

7a. Air in source of sealing liquid

8. Water seal pipe plugged
9. Seal cage improperly mounted in stuffing box
10. Inlet of suction pipe insufficiently submerged
11. Vortex formation at suction
12. Pump operated with closed or partially closed suction valve
13. Clogged suction strainer
14. Obstruction in suction line
15. Excessive friction losses in suction line
16. Clogged impeller
17. Suction elbow in plane parallel to the shaft (for double-suction pumps)
18. Two elbows in suction piping at 90° to each other, creating swirl and prerotation
19. Selection of pump with too high a suction specific speed

Other Hydraulic Problems

20. Speed of pump too high
21. Speed of pump too low
22. Wrong direction of rotation
23. Reverse mounting of double-suction impeller
24. Uncalibrated instruments
25. Impeller diameter smaller than specified
26. Impeller diameter larger than specified
27. Impeller selection with abnormally high head coefficient
28. Running the pump against a closed discharge valve without opening a by-pass
29. Operating pump below recommended minimum flow
30. Static head higher than shut-off head

Other Hydraulic Problems (continued)

31. Friction losses in discharge higher than calculated
32. Total head of system higher than design of pump
33. Total head of system lower than design of pump
34. Running pump at too high a flow (for low specific speed pumps)
35. Running pump at too low a flow (for high specific speed pumps)
36. Leak of stuck check valve
37. Too close a gap between impeller vanes and volute tongue or diffuser vanes
38. Parallel operation of pumps unsuitable for the purpose
39. Specific gravity of liquid differs from design conditions
40. Viscosity of liquid differs from design conditions
41. Excessive wear at internal running clearances
42. Obstruction in balancing device leak-off line
43. Transients at suction source (imbalance between pressure at surface of liquid and vapor pressure at suction flange)

Mechanical Problems—general

44. Foreign matter in impellers
45. Misalignment
46. Foundation insufficiently rigid
47. Loose foundation bolts
48. Loose pump or motor bolts
49. Inadequate grouting of baseplate
50. Excessive piping forces and moments on pump nozzles
51. Improperly mounted expansion joints
52. Starting the pump without proper warm-up
53. Mounting surfaces of internal fits (at wearing rings, impellers, shaft sleeves, shaft nuts, bearing housings, and so on) not perpendicular to shaft axis
54. Bent shaft
55. Rotor out of balance
56. Parts loose on the shaft
57. Shaft running off-center because of worn bearings

Mechanical Problems—general (continued)

58. Pump running at or near critical speed
59. Too long a shaft span or too small a shaft diameter
60. Resonance between operating speed and natural frequency of foundation, baseplate, or piping
61. Rotating part rubbing on stationary part
62. Incursion of hard solid particles into running clearances
63. Improper casing gasket material
64. Inadequate installation of gasket
65. Inadequate tightening of casing bolts
66. Pump materials not suitable for liquid handled
67. Certain couplings lack lubrication

Mechanical Problems—sealing area

68. Shaft or shaft sleeves worn or scored at packing
69. Incorrect type of packing for operating conditions
70. Packing improperly installed
71. Gland too tight, prevents flow of liquid to lubricate packing
72. Excessive clearance at bottom of stuffing box allows packing to be forced into pump interior

Mechanical Problems—sealing area (continued)

73. Dirt or grit in sealing liquid
74. Failure to provide adequate cooling liquid to water-cooled stuffing boxes
75. Incorrect type of mechanical seal for prevailing conditions
76. Mechanical seal improperly installed

Mechanical Problems—bearings

77. Excessive radial thrust in single-volute pumps
78. Excessive axial thrust caused by excessive wear at internal clearances or, if used, failure or excessive wear of balancing drive
79. Wrong grade of grease or oil
80. Excessive grease or oil in rolling element bearing housings
81. Lack of lubrication
82. Improper installation of rolling element bearings such as damage during installation, incorrect assembly of stacked bearings, use of unmatched bearings as a pair, and so on
83. Dirt getting into bearings
84. Moisture contaminating lubricant
85. Excessive cooling of water-cooled bearings