FACULTY OF SCIENCE AND TECHNOLOGY

MASTER'S THESIS

Study program/specialization: Offshore Technology	Spring semester, 2013
Author: Liu Deke	
Instructor: Professor Tore Markeset	
Title of Master's Thesis: Application of risk based inspection (RBI), reliability centered maintenance (RCM) and risk based maintenance (RBM)	
ECTS: 30	
Subject heading: Industrial Asset Management	Pages: 71

Application of risk based inspection (RBI), reliability centered maintenance (RCM) and risk based maintenance (RBM)

Master thesis by

Liu Deke

214760

Industrial Asset Management

Faculty of Science and Technology

University of Stavanger

2013

Acknowledgements

This thesis is submitted as the final part of the requirements for the master degree program in Industrial Asset Management, at the University of Stavanger (UiS). The study work was carried out at the UiS and production optimization division, COSL.

Here, I would like to express my sincere thanks to my university supervisors— professor Tore Markeset, for his professional instruction, consistent help and support throughout the thesis writing.

Also I would like to thank the managers of HR department and production optimization division in COSL, as well as my colleagues, for their kind help and support during my thesis study, to provide data and information I used in the thesis and suggestions.

I am especially thanks my wife and family members for their understanding and supporting.

Abstract

Accompanying with the development of offshore oil and gas industry, the companies' demands on excellent QHSE achievement, high efficiency and benefit operation become increasingly high. A Well-developed maintenance strategy is critical to have scientific decision making of maintenance activities for complex, advanced and aging facilities utilized in the offshore oil and gas industry to achieve safe, effective and efficient operation and help companies become more competitive in the marketing.

The maintenance programs are designed, scheduled and executed based on the technical condition of facilities to achieve the companies' goals and requirement. The new trend of maintenance management has shifted from time interval based maintenance to risk approach based maintenance. By applying risk based approach in maintenance management, the hazards could be well identified, risks could be well prioritized, and then resources could be well allocated to the most critical area. Maintenance activities could be scientifically planned and scheduled to reduce risk without cause much cost.

This thesis studies to develop a unified process for the application of the risk approach based maintenance management in the China Oilfield Service Limited (COSL), to study how to applying risk approach in maintenance management during the life cycle of facilities to reduce risk, improve reliability and save cost.

Key words:

QHSE, maintenance management, risk analysis, reliability analysis, decision making, risk based inspection, reliability centered maintenance, risk based maintenance， life cycle management

摘要

随着海洋石油工业的发展，企业们不断增加努力想要获取卓越的质量健康安全环保的成就、高效率和效益作业方面，需求和要求逐渐增加。在海洋石油工业中，一个发展完善的维护保养保策略是科学维护保养决策的关键，它可以确保那些复杂、先进的及老化的设备设施安全而有效地运转，可以帮助企业们在这个市场中保持竞争优势。

维护保养计划是在设备的技术条件的基础上进行设计、计划和执行的，以此实现公司的目标和要求。维护保养管理的新趋势已经从以时间周期为基础的维护保养过渡到以风险方法为基础的维护保养。通过将风险为基础的方法运用于维保管理中，使潜在危险可以很好的辨识，风险可以很好的优先排序，然后资源能够有效的分配给最为关键的地方。通过这样的方式，维护保养活动可以科学地计划与安排，减少风险的同时又不会造成太多成本。

本论文研究如何在中海油田服务股份有限公司中建立统一化的以风险为基础的维保管理的运用程序，学习如何在设备的生命周期中将风险管理方法运用于维保管理中，以降低风险，提高稳定性和节约成本。

关键词：

质量健康安全环保、维护保养管理、风险分析、稳定性分析、决策、基于风险的检测，以可靠性为中心的维保，基于风险的维保，生命周期管理

Contents

Application of risk based inspection (RBI), reliability centered maintenance (RCM) and risk based maintenance (RBM)

1 Introduction

This chapter is aimed to introduce the background and objective of this thesis. The project activities, limitations and outlines are also mentioned.

1.1 Background

The offshore oil and gas exploration and production are high risk operations, which are mainly depended on the capability of offshore facilities. In this industry, even a small failure of facilities could cause serious consequences, such as environmental pollution, immediate personnel injuries and long-term health problem, loss of income and reputation, etc. For example, in 2010, an oil spill in the Gulf of Mexico caused by the "Deepwater Horizon" killed 11 workers and injured 17 others, released 5 million barrels of oil. That has been considered as the largest oil spill in the offshore oil and gas industry. So excellent QHSE，high benefit and efficient operation are more attractive to the companies in the oil and gas industry. Almost every offshore oil and gas filed operator wants to develop maintenance strategy to control the risk.

The objective of maintenance is to reduce the business risk, which could prevent the failures from occurring, using a set of technical, administrative and managerial activities required to keep these means of production in the desired operating condition, or to restore them to this condition(Pintelon et al., 2000). It also could reduce the downtime and extend the life of the equipment. However, in oil and gas industry, the maintenance costs are 40% of the total costs and most of it is resulted of improperly or unscientific planned maintenance activities(Mobley, 2002). The high demands of conduct maintenance activities in cost-effective and cost-efficient ways make the senior managers of assets management continuously search the ways to optimize and improve the maintenance and inspection management. That led the development of maintenance management, which has shifted from time-based preventive maintenance to the risk-based maintenance, to improve the inspection and maintenance activities planning(CEN, 2008). The risk approach based maintenance could have a better decision making to allocate scare resources to the most important maintenance and inspection activities, based on the priorities of risk and resources limitation. That could control the cost of maintenance management while not compromising with risk.

1.2 Problem description

With the booming development of China's economy, the demands of oil and gas resource have been extremely increased. It has boosted the development of china's offshore facilities, which the offshore oil and gas industry mainly based on. As the leading integrated oilfield service provider of the offshore oil and gas market in China, China oilfield service limited (COSL) has a large fleet of offshore oilfield service facilities(COSL, 2010). In recent years, more and more advanced and automatic facilities came into service, such as the HYSY 981 in South China Sea, COSL innovator and COSL pioneer in Norwegian continent. And some other complex facilities have been planned to construct in recent years. Besides the newly utilized equipment, COSL still has a lot of aging facilities. For example: in the main facilities, there are 8 of drilling platforms, 5 exploration ships have been in service for more than 30 years.

According to the bathtub model, during life cycle of facilities, the infant mortality and end of life have more risk of potential failures. And the more advanced the equipment are, the more complex they will be and the more components will be related, the more uncertainties will be inherited, also the aging equipment has more uncertainties. These uncertainties will increase the possibility of potential failures, and cause more pressure on the maintenance management in COSL. So for COSL, one critical part of in life cycle management is to reduce the risk for the whole life cycle of facilities.

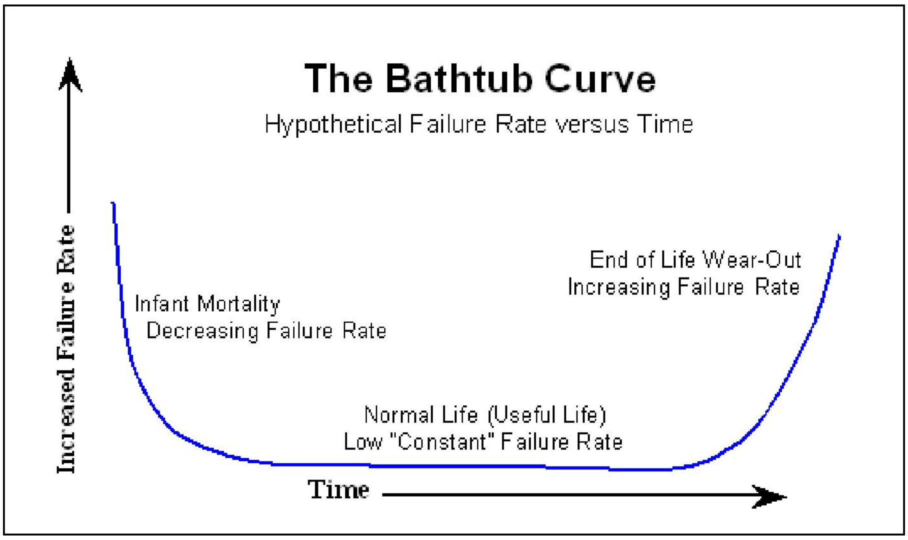

Figure 1 The Bathtub Curve: source from(Wilkins, 2002)

Currently the maintenance strategies in COSL are not well enough defined resulting in costly maintenance without reducing risk enough. Although COSL has been aware of the well-developed maintenance strategy is effective to control the business risk and realized that risk, cost and benefit have a triangle relationships, are closely related and cannot be evaluated separately(Kumar). COSL's the maintenance strategy is still mainly based on the preventive or time-based maintenance. The philosophy of time-based maintenance strategy is to "schedule and plan maintenance activities predetermined time intervals, based on calendar days or runtime hours of machines" without considering the cost (Scheffer and Girdhar, 2004). So the current maintenance strategy is not completely met with the requirement of COSL to balance controlling risk, reducing cost and gaining benefit.(Markeset and Kumar, 2001)

And in the development of COSL, what challenges facing are how to meet stricter QHSE standard and the higher demands of high profitability and efficiency. That needs COSL to have well-developed maintenance strategy, reducing the potential risks and operation cost. How can COSL optimize the limited resources and costs focusing on the most critical area, reduce the efforts on the non-critical area(Santos and Hajri, 2000)? How can COSL reduce the maintenance cost without compromising the risk? How to find a scientific way to schedule the maintenance activities in cost-effective and cost-efficient ways?

1.3 Objectives of thesis

Maintenance procedures and processes need to be better defined using modern maintenance theory and practice. By applying RBI and RCM in a RBM approach, the practices could be improved. On this background this thesis will focus on suggesting improvements in COSL maintenance strategies by using a risk based approach. The objective of this thesis is to study how to develop a simple unified process for the application of RBM, RBI and RCM to reduce the risks in maintenance and inspection management at one technical system of one COSL rig.

1.4 Project activities

This thesis will study the application of RBM, RBI and RCM in one unified process according the following activities:

1) study the literature of maintenance management and risk management
2) study the methodology and application of RBM, RBI and RCM
3) illustrate the practical procedures of risk-based approach in maintenance management
4) study how to apply the risk-based approach with respects to COSL
5) case study of risk-based approach on one typical technical system
6) Make suggestion and recommendation on the future application of risk-based approach in COSL's maintenance and inspection management

1.5 Limitations

The limitations of this thesis are:

1) The study for the unified process of application of RBI, RBM and RCM is based on one COSL rig.
2) The literatures are mainly based on the NORSOK standard, DNV, API standard, and CEN regulation.
3) Limited failure modes and analysis tools have been considered.
4) Both qualitative and quantitative analyses have been used during the risk assessment and evaluation process.
5) Data sample and case study are based on Norwegian O&G industry and COSL.
6) During the risk analysis and reliability calculations process, some assumptions and experiences have been used.

2 Maintenance and Inspection Management and Risk Management

This chapter introduces the basic concepts and development of inspection, maintenance and risk management, to make sure a comprehensive understanding before the complex analysis and calculation process.

2.1 Maintenance management

This part introduces the definition and development of maintenance and inspection, as well as the typical progress procedures of maintenance activities.

2.1.1 The definition of maintenance and inspection

There is no equipment can be always functional without failures, which are mainly from the design, the manufacturing, and the operation of the equipment. These failures will increase the risks related to safety, environment, quality, and cost aspects in the business. In order to reduce the risk of business, it is important to prevent these failures from occurring by maintain or restore the equipment in the specified or desired state. The maintenance and inspection are the activities used to reduce the risk of assets. Maintenance definition can be defined as: the set of activities required to keep these means of production in the desired operating condition, or to restore them to this condition(Pintelon et al., 2000). The objective of maintenance includes all technical, administrative and managerial actions during the life cycle of an item and, intends to restore it to a state in which it can perform the required function(Malmholt). The role of inspection is to check/confirm whether degradation is occurring and provide necessary information for the maintenance management on the condition of assets(DNV-PR-G101). Inspection is one of activities used to control and minimize the risk of equipment. Generally, the inspection activity has the same objective with the maintenance activity to reduce the risk. So the general maintenance encompasses maintenance activities and inspection activities.

The maintenance can be classified into different types: it can be simply divided into planned maintenance and unplanned maintenance; it is also popular to classify maintenance using corrective maintenance, preventive maintenance and predictive maintenance. Actually, the predictive maintenance is one type of preventive maintenance based the condition of equipment to predict maintenance needs. But traditional preventive maintenance means periodic maintenance based predefined time interval, such as every one month, every 1000 running hours…The preventive maintenance is planned, and some corrective is also planned, although most of corrective maintenance is unplanned. Figure 2 shows a kind of classification of maintenance.

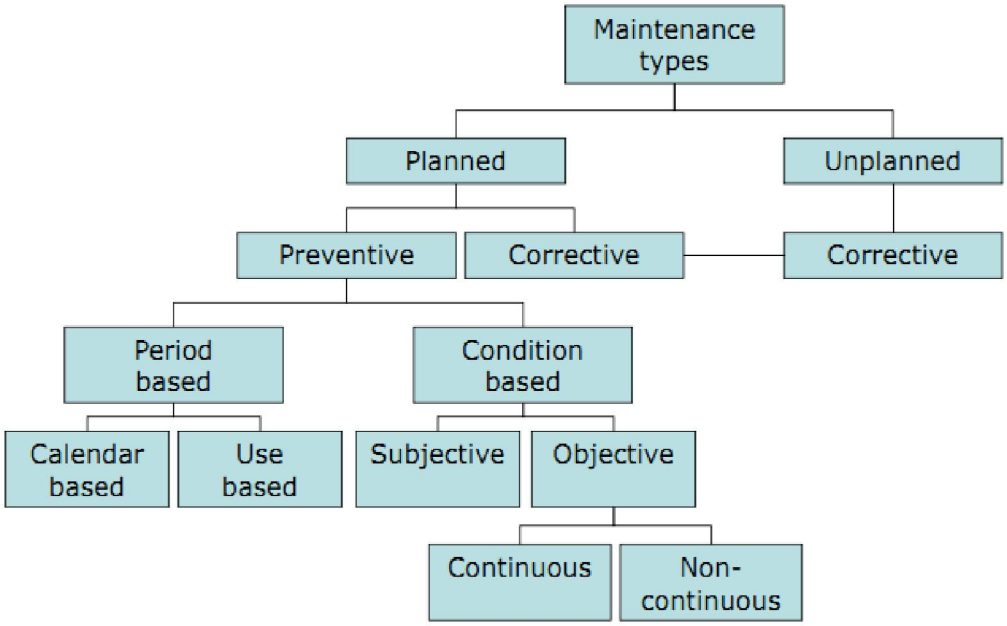

Figure 2 Maintenance classification: source from (Markeset, 2012)

2.1.2 The development of maintenance

Over the past several decades since 1940, accompanied with the development of technology and global business, the physical assets such as plant, equipment and building have had huge changes, become increasingly complex, advanced, automatic, and international. It is imperative to have a systematic strategy to guide the maintenance and inspection actions, which could ensure the profitability and efficiency of the assets. It is believed that Well-run maintenance and inspection is a prerequisite for attaining these objectives. (GROOTE, 94) Because the profitability and efficiency of the investment in production equipment can only be guaranteed if the following components are ensured: productivity, quality, safety and environment (Pintelon et al., 2000). In the European industry, the maintenance management has been considered as profit-center, and improving maintenance means improving productivity, quality, safety and the protection of the environment.

In the modern business world, the pressures of keen competition, the more customer-oriented market, and the increasing level of automation make the senior managers of assets management continuously search the ways to develop the maintenance and inspection management. The maintenance management has developed from the "necessary evil" to the "profit contributor" and a part of "integrated business", which has gone through at least four generations and still in the rapid development.

✧ **The first generation**

During the first generation, the equipment was easily designed, simple, and reliable. When the failures occurred, the failed components could easily be replaced, and would not cause much matters. So the maintenance strategy was not seriously considered, just fix the equipment when it broken.

✧ **The second generation**

In the second generation, the dramatically decreased manpower and the rapid development of technology led to the awareness of that the failures of equipment should and could be prevented, which led to the development of preventive maintenance(Moubrey, 1997). The planning and controlling of preventive maintenance is mainly based on fixed time intervals without considering the cost and the condition of equipment.

✧ **The third generation**

The third generation developed during 1970s and 2000s, when the world industry business entered into a high-speed growth period, the dependence on the assets is continuously grown and the failures become more unacceptable. At the same time, the stricter QHSE standards, the higher demands on efficiency and profitability, the keen global competition, the increasing level of automation, etc. accelerated the development of third generation of maintenance management. The third generation is predictive maintenance to foresee failures through systematic approaches based on condition monitoring and reliability centered maintenance. It could achieve higher plant availability and reliability, greater safety, better product quality, no catastrophic damage to the environment, longer equipment life and greater cost effectiveness.

✧ **The fourth generation**

The fourth generation since 2000 mainly concerned on the risk and reliability during the life cycle of assets in the business. The increased awareness of risks related to equipment, personnel, environment, operation process, as well as the cost became more and more popular. And the most important improvement of maintenance management brought by the fourth generation is that it combined the maintenance and safety together as integration. That led to the development of risk based inspection (RBI) and risk based maintenance (RBM) in addition to the reliability centered maintenance (RCM) and condition based maintenance (CBM), to increase the profitability of the operation and optimize the total life cycle cost without compromising safety or environment issues(Arunraj and Maiti, 2007), using the risk and reliability analysis approaches to plan and make decision on inspection and maintenance actions.

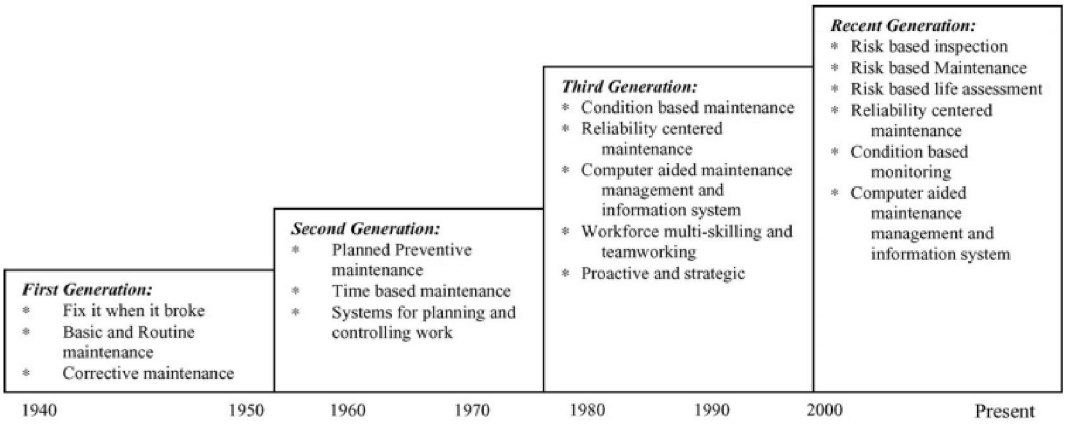

Figure 3 maintenance development: Source from(Arunraj and Maiti, 2007)

2.1.3 Maintenance management activities

The maintenance management is a systematic work process of asset management. The figure 4 presents a classic maintenance management process identifying the needed resources, the work processes loop and the ending results.

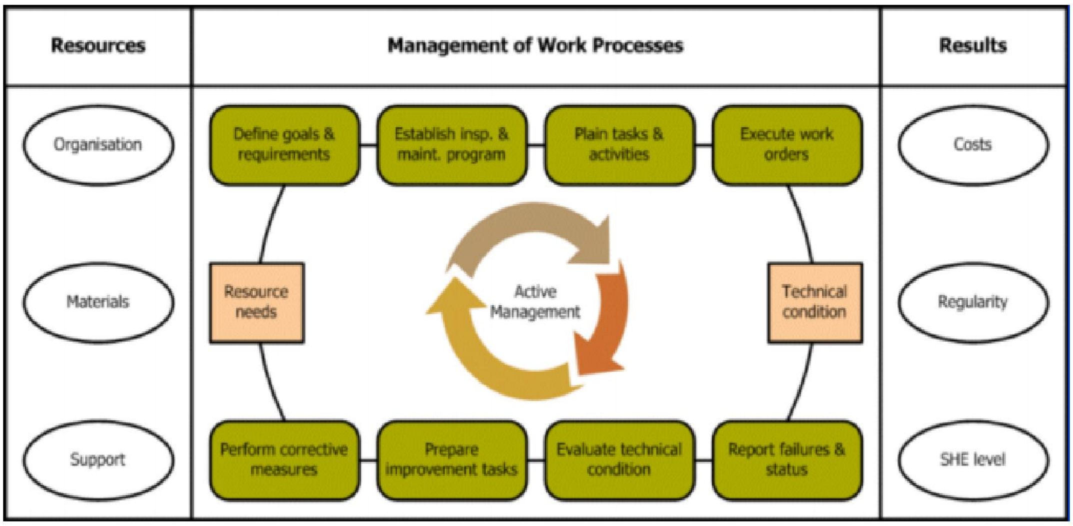

Figure 4 Maintenance management system: source from(DNV-PR-G101)

✧ **Resources needs**

The maintenance resource needs organization, materials and document support(Gusfre, 2010):

- The organization resources should include the maintenance personnel who executing the maintenance activities, the training program to qualify the maintenance personnel, the time needed to complete the tasks and the experts to provide necessary support, etc.
- The material resources should at least include the required space, spare parts and tools to conduct the maintenance activities.
- Some basic documents such as the running condition, operating and maintenance manual, data sheet, equipment drawing and history of failures are necessary to support the execution of maintenance activities.

✧ **Work process loop**

The maintenance management is an active management as the following cycle work process:

- At first, the maintenance manager integrates the resources available to set up the goals and requirement for the maintenance management;
- Then design the maintenance programs and plan the tasks and activities to guide the execution;
- When the activities are executed, the new technical condition will be updated, the maintenance personnel will report, evaluate the conducted activities;
- The effectiveness and efficiency will be measured and assessed to see if it is possible to have any improvement;
- If possible, the maintenance personnel will update the resources needed, redefine the requirement and goals, and redesign the maintenance program and activities.

✧ **Results**

The result of maintenance management is a certain level of regularity and risk level is achieved at a certain cost(Gusfre, 2010), which combining with the operational state consist the technical condition of equipment.

COSL intends to control the risk of offshore operation, and already had a series of actions to improve the reliability of equipment, reduce the storage of spare parts, and limit the downtime by applying preventive maintenance system (PMS), enterprise resource planning (ERP). Although most of activities in the maintenance management process are executed in COSL, the maintenance strategy is still based on preventive maintenance, needs a consistent and scientific maintenance management process to ensure every maintenance personnel could execute without confuse. Especially the establishing of maintenance program and planning of maintenance activities should optimized using advanced approach.

2.2 risk management

The risk management is based on applying a structured and systematic risk approach to towards assess, mitigate(to an acceptable level) and monitor risk(DNV-PR-G101).

2.2.1 Concept of Risk

There is no relatively imprecise definition of risk. Generally, risk is used to express the danger that undesirable events represents to human beings, the environment and economic values(Aven, 1992). Some other common definitions of risk are: Risk is "the considered expected loss or damage associated with the occurrence of a possible undesired event"(Arunraj and Maiti, 2007) ; risk is defined as the combination of the probability of some event occurring during a time period of interest and the consequences, associated with the event(API, 2002); Aven (2008) describes the risk through the combination of i) events and their consequences and ii) associated uncertainties (will event occur and what outcome will the consequences take).

Risk could be expressed in descriptive and quantitative ways. When risk is expressed quantitatively, it is usually taking use of the probability and consequence to the equation:

$$\textbf{\textit{Risk=probability}} \times \textbf{\textit{consequence}}$$

The risk is unknown as the probabilities and consequences of an undesirable event are unknown, and must be identified through systematic risk analysis. which is done by first identifying hazards, where a hazard is anything that is a potential source of harm related to human injury, damage to the environment, damage to property or loss in production (ISO(2000)).

In COSL, hazard is used to express a potential to cause harm or damage, and the risk is usually be defined as the likelihood of a hazard occurring. In this thesis, the word “risk” is used to express the combination of potential probabilities of undesirable events and their consequences led to QHSE and cost aspects during the offshore operation.

2.2.2 Risk analysis

Risk analysis is to systematic use of information and data to identify initiating events, causes and consequences of these events, and then express risk(Aven, 2008). The information and data includes expert experience, historical failure data, design data, operation procedures, and concerns of the stakeholders… which could be used to identify sources and estimate the possible consequences of undesirable events.

The objective of risk analysis is to provide possible information to support decision making. By conducting risk analysis, one can establish a risk picture, compare different alternatives and solution, identify factors, and demonstrate the effect of measures on risk(Aven, 2008). These provides a basis for decision maker to be able to balance different concerns, and then choose the most cost-effective and cost-efficient solutions to reduce the risk to as low as reasonably practicable (ALAPR) level.

The results of risk analysis are screened based on the combination of the probability of failures and potential consequences of failures using risk matrix. The analysis could be qualitative, quantitative or semi-quantitative (semi-qualitative) based on the requirement of results and the available information:

- The qualitative analysis is often used for the coarse analysis which mainly based on experts' judgment and experience;
- The quantitative analysis has a deeper analysis using logic models to simulate the probability and consequences;
- The semi-quantitative way is to both use the descriptive information and simulation models to present the risk.

The common used methodologies of risk analysis are bow-tie, event tree analysis (ETA), fault tree analysis (FTA), hazard and operability analysis(HAZOP), failure mode, effects, and criticality analysis (FMECA), root cause analysis (RCA)…(see detail in(Aven, 2008)).

The most common risk analysis method used in COSL is Job Safety Analysis (JSA), which is an analysis of the accurate and detailed description of each job in terms of duties, tools, methods, operation and work environment to identify the methods reducing work risk. Conducting a JSA before every critical operation is one of basic requirement of COSL's QHSE management.

2.2.3 The process of risk analysis

The main steps of risk analysis include planning, risk assessment and risk treatment (Aven, 2008, Aven, 1992):

✧ **The planning phase includes following activities**

- define the problems are analyzed;
- gather the information and data needed;
- select multi-disciplinary employees;
- choose the analysis method;
- arrange the activities;
- define the objective of the risk analysis;
- Set up the acceptable criteria.

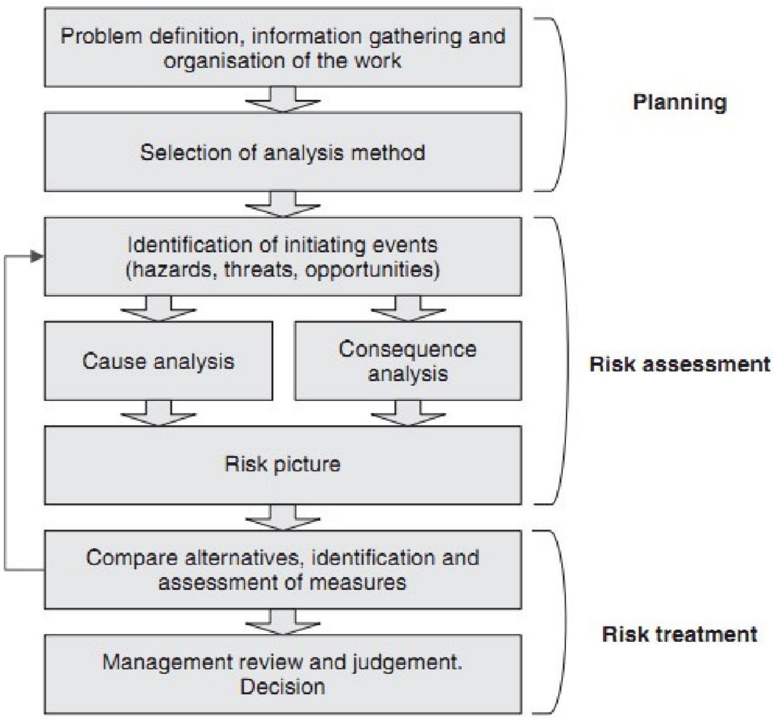

Figure 5 the main steps of risk analysis process: source from(Aven, 2008))

PLANNING	Objectives Definition of activity (subject of analysis) Time planning Organization of work
EXECUTION	Description of activity (subject of analysis) Identification of undesirable events Assumptions and suppositions Cause analysis Consequence analysis Data collection and analysis Presentation of results
USE	Risk evaluation/safety evaluation Decisions

Figure 6 Panning, execution and use of risk analysis: source from (Aven, 1992)

✧ **Risk assessment**

It is the execution part of risk analysis, and it intends to establish a risk picture. It has careful analysis to find out what could cause harm or damage and to search what can be done to prevent. In this part:

- the initiating events are identified;
- the causes and consequences of these are analyzed;
- A clear picture of risk is expressed.

Risk treatment is to provide possible alternatives and solutions to prevent the undesirable events and consequences from occurring, separately or both.

The risk analysis process could also be categorized in planning, execution and use of risk analysis as the following figure 6.

2.2.4 Risk Matrix:

Risk matrices are common used tools for risk categorization in qualitative and semi-quantitative risk assessment. As per the risk concept, the consequences of failure and the likelihood of failure are arranged in a matrix to present the risk level (seeing in the following figure 7: the Risk Matrix example). Usually, the risk levels are categorized in three regions presented in matrix—high, medium and low risk.

- The high risk level is presented in the upper right-hand corner and color scheme red;
- the low risk level is presented in the lower left-hand corner and color scheme yellow;
- The medium risk level is present in medium region of matrix with yellow color.

Consequence of Failure	High	Risk Level 2	Risk Level 1	Risk Level 1
	Medium	Risk Level 3	Risk Level 2	Risk Level 1
	Low	Risk Level 3	Risk Level 3	Risk Level 2
		Low	Medium	High
		Likelihood of Failure		

Figure 7 Example of risk matrix: source from (API, 2008)

According to NORSOK Standard Z-013 "Risk and emergency preparedness assessment", the decision maker will have different actions for the corresponding risk level(NORSOK, 2010) :

- High risk (red region): risk reduction, high management attention or more detailed assessment is necessary;
- Medium risk (yellow region): risk reduction based on ALARP principle;
- Low risk (green region): broadly acceptable risk;

2.2.5 Reliability

✧ The definition of reliability

Reliability: a characteristic of the ability of a component or a system to perform a specific function(Aven, 1992). The reliability could be described in different ways, such as average lifetime or functional probability of component or system, the probability or frequency of failures, etc.

✧ Reliability analysis

Reliability analysis is a systematic use of information to analyze the reliability of a technical system. It provides the information for the decision maker to understand how to undertake the measures and activities to maintain the reliability of the technical system.

✧ Reliability analysis process

The main steps of reliability analysis consist of planning, execution, and use. The detail process is clearly presented in figure 8(Aven, 1992):

PLANNING	Objectives System definition Time planning Organization of the work
EXECUTION	System description Definition of system failure Assumptions Cause analysis Data collection and analysis Presentation of results
USE	Reliability evaluation Decisions

Figure8 the main steps of reliability analysis(source from:(Aven, 1992))

The planning phase: the objectives, the system and limitation of the analysis must be defined, the activities of analysis should be well scheduled and the working group must be well organized.

The execution phase: the system should be well described for being clear of the system failure; then the cause of failure will be analyzed based on the model and the data collected; the results of analysis should be presented comparing with the acceptance criteria. During the analysis process, some assumptions and suppositions should be made when the data and information is not available or incomplete.

Use of reliability analysis: the results of reliability will be used to design possible alternatives, modifications, and solutions to improve or maintain the reliability of the system, and then these will be ranked for the decision maker based on the cost-effective and cost-efficient evaluation.

2.2.6 The risk and reliability analysis

The objective of reliability and risk analysis is to provide a basis for decision regarding choice of solutions and actions(Aven, 1992). As per the process of risk and reliability analysis, it is obviously that the reliability analysis process is similar with the risk analysis process:

- At First, both of them include the similar planning process and execution process to analysis of system failures, and their causes;
- Secondly, the common used methods of reliability analysis are FTA, FMEA, and ETA, which are the main methods of risk analysis;
- Furthermore, the reliability can be expressed by the probability or frequency of failure, which is same with risk.

So the risk analysis and reliability analysis can be integrated into one single analysis process. That provides the basis for the integration of RCM, RBI and RBM.

2.2.7 Risk management approach

The risk management approach is based on applying a structured approach and making the best use of available knowledge towards assessing, mitigating to an acceptable level and monitoring of risk(DNV-PR-G101). When the risk management approach is applied in maintenance management, risk levels and proposed solutions of technical system will be screened as per NORSOK standard Z-008—criticality analysis for maintenance purpose. Then the maintenance decision will be made based on the priorities of solutions with cost-effective and cost-efficient evaluation to reduce the risk to as low as reasonably practicable (ALARP) level in a constraint cost.

For example, if a drilling platform has several hazards need be resolved, but the budget is limited, the senior manager of asset management department will consider reducing the risk as much as possible with the budget constraint. However, which one be monitored, which one be inspected, and which one be maintained could reduce the risk in cost-effective and cost-efficient way should be based on results of risk and reliability analysis. So the risk management approaches give the manager the opportunities to control the cost of facilities failures without compromising the risk.

For a complex technical system likes the drilling platform, the maintenance management should use different risk approaches according to different kinds of equipment, and RBI, RCM, SIL (safety integrity level) and RBM are the common used risk approaches. The RBI is mainly used for the inspection of static equipment like the structure of the platform, and pressure tank and pipe line; the RCM is mainly used for the condition monitoring of dynamic equipment, such as the vibration, pressure, temperature of a mud pump; the SIL is mainly used for the electric system to see if the system has any safety functions missed(not included in this thesis); the RBM is mainly used for the maintenance decision making according to the result of the other approach.

In COSL, although some risk management methods are used to reduce the business risk, such as JSA is used to reduce the risk during the operation work executed, STOP cards to discover the unsafe behavior and conduct a risk analysis before new project. But for the maintenance management, COSL wants to reduce the risk of failures and improve the reliability by utilizing the PMS system to plan the maintenance activities. But the PMS reminds the maintenance activities based on predefined time interval and recommendation of manufactures, the risks and uncertainties of facilities are dynamic, the maintenance activities should optimized by applying risk management approach in maintenance management. The recommended approaches are risk based inspection (RBI), reliability centered maintenance (RCM) and risk based maintenance (RBM), which will be discussed in the next chapter.

3 Literature Review of RBI, RCM and RBM

This chapter will introduce the risk approach based methodology of RBI, RCM and RBM, and study the application procedures for maintenance management in the current offshore oil and gas industry.

3.1 Risk based inspection:

This part will generally illustrate what is RBI, the key elements and the implement of RBI.

3.1.1 RBI introduction

The Risk based inspection (RBI) is a proven decision-making technique to optimize inspection planning for static mechanical equipment. RBI has been one of the many dedicated activities within offshore asset management that contribute to controlling and minimizing offshore risk(DNV-PR-G101). Since the mid 1990 RBI has been applied by DNV for decision making of preventive maintenance for containment equipment(DNV, 2009). And DNV already developed several tools such as PHAST, SAFETI, LEAK, SOQRATES, WOAD, Orbit SIL and **Synergi** used to support risk based decision making. Synergi risk based inspection software is one of tools used to support RBI analysis for the offshore oil and gas industry in Norwegian continent.

The objective of RBI is to determine what incident could occur in the event of an equipment failure, and how likely is that incident could happen(API, 2002). RBI analysis prioritizes risk level based on the combination of assigned probability and consequences in the line with different failure mechanisms. Then the inspection plan is redesigned according to the risk levels within the resources constrain.

RBI analysis provides a better linkage between the mechanisms that lead to equipment failure and the inspection approaches. If the failure mechanisms or degradation is predictable or detectable, then RBI could provide the information needed to determine where, what, how and when to inspect, to reduce the uncertainty in the predicted deterioration and/or as a means of identifying deterioration before it becomes critical (API, 2002, Faber, 2002). The non-destructive testing (NDT) techniques are usually used for the prioritized inspection.

3.1.2 Process of RBI

The figure 9 presents a typical risk based inspection process recommended by API. In similar, the DNV devided the RBI process into five stages:

- Information gathering
- Screening assessment
- Detailed assessment
- Planning
- Execution and evaluation.

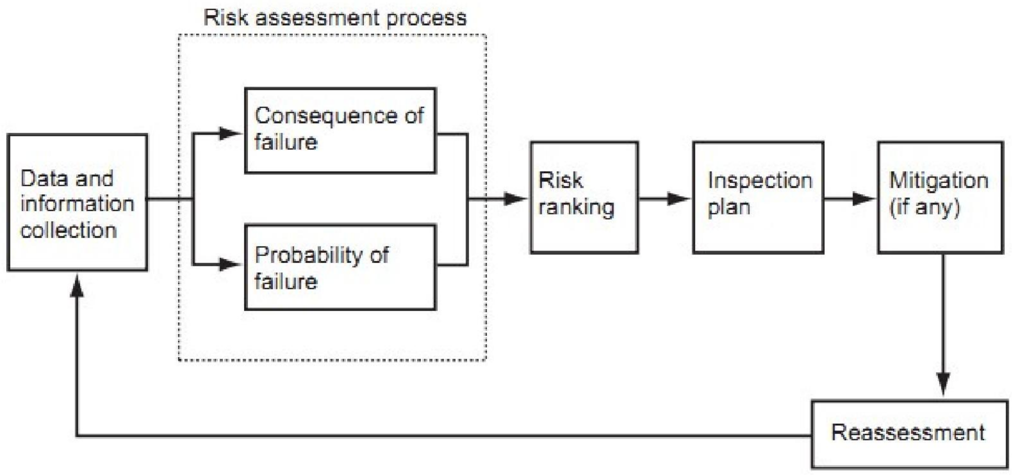

Figure 9 the recommended process of RBI: source from(API, 2002)

As per the above recommended process of RBI, it is a continuous process:

- Before the risk assessment process, the required data and information should be collected (the detailed level of information depends on the level of risk or the complexity of system);
- the consequence of failure and probability of failure are assigned based on the collected data and information and experience;
- Then the risk can be ranked using risk matrix;
- The inspection plan is designed according the priority of risk, and inspection activities are schedules;
- After execution of inspection activities, the technicial status of the system will indicate if any mitigation has be achieved.
- the analysts will reassess the system based on updated technicial status to see if

possible have any modification or more improvement .

3.1.3 Working process

In order to prepare a risk and cost-effective inpsection plan, the DNV developed a working process for RBI, as showing in the figure 10.

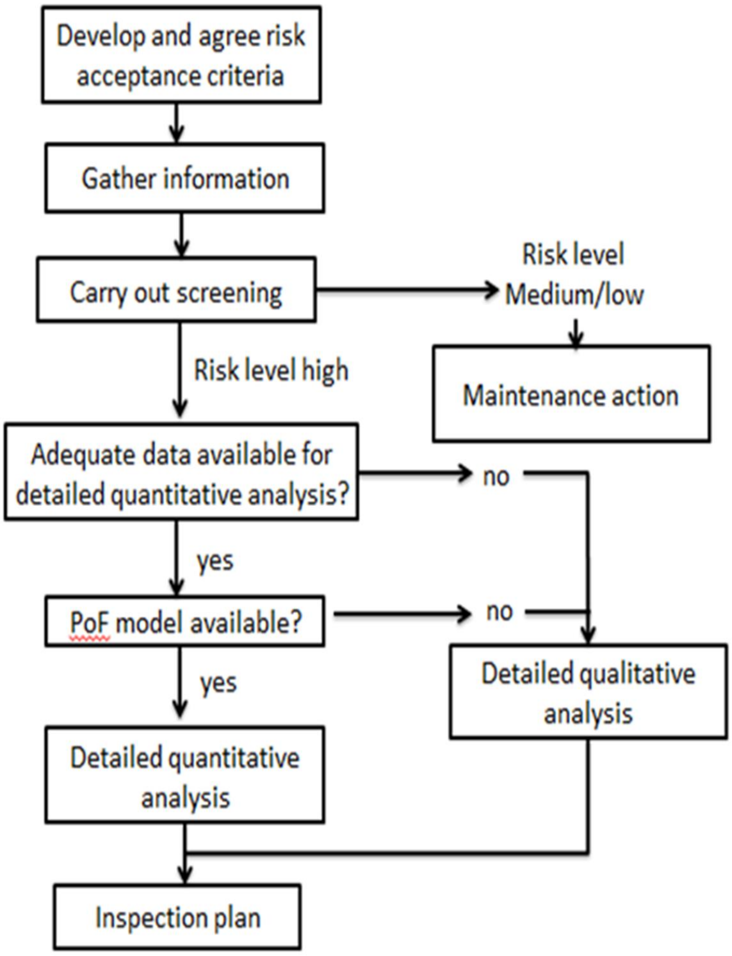

Figure 10 the working process of RBI:source from(DNV, 2009)

With the different levels of risk, the required data and information and alternatives of RBI could vary accordingly:

- For the low risk level, a qualitative analysis with little data and information may be enough to define the causes, and then only corrective maintenance needed to solve the failures;

- For the medium risk level, a semi-quantitative analysis will be used to discover the causes of the failures with appropriate data and information, and preventive maintenance actions will be considered;

- For high risk level, a detailed quantitative analysis model will be developed, which requires increased level of data and information and detailed analysis, and the condition monitoring action will be used to provide detail of information to varify the model and guide further plan and execution of inspection.

When the result of risk analysis is gained, the failure cause and effect and critical of a defined component could be identified. Then the inspection planer could take cooresponding inspection plan:

- For different types of failure modes, different kinds of NDT techniques or condition monitoring tools could be used;

- For different risk levels and degradation mechnism of different equipment, the inspection frequency is defferent: some needs periodic inspection, some needs continuous monitoring.

3.1.4 Benefit of RBI

As the figure 11 showing, when inspection is optimized by RBI analysis, more risks will be reduced comparing with typical inspection. For both inspection programs, the levels of risk will reduce with the level of inspection activity increased. But when the frequency exceeded, the risk level of typical inspection program will increase.

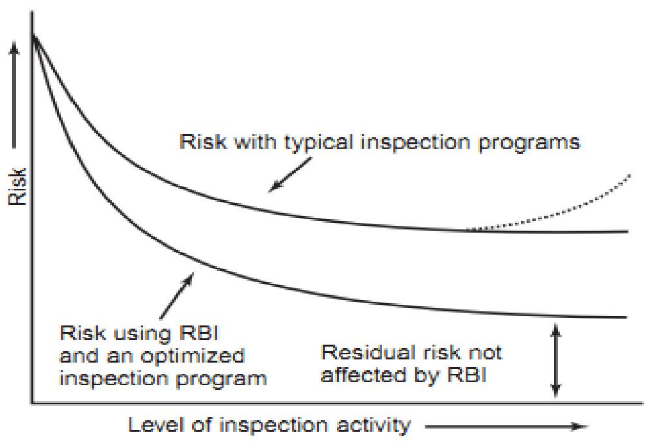

Figure 11 Management of risk using RBI(API, 2002)

However, the optimized inspection program by RBI will not be affected. So the RBI not only provides the right approach for the inspection, but also the cost-effective and cost-efficient frequency.

3.2 Reliability centered maintenance

3.2.1 Definition of RCM

The reliability centered maintenance (RCM) is a widely used method to optimize preventive maintenance tasks for dynamic equipment. This methodology was firstly applied in aircraft industry in 1980s to achieve safety and reliability of operation in cost-efficient and cost-effective ways, and then utilized in the many other industries including nuclear power station, and offshore oil and gas industry. RCM is defined as "a process used to determine what must be done to ensure that any physical asset continues to do whatever its users want it to do in its present operating context"(Moubrey, 1997, Moubray, 2001). The main objective of RCM is to reduce the maintenance cost, by focusing on the most important functions of the system, and avoiding or removing maintenance actions that are not strictly necessary(Rausand, 1998). It focuses on the functionality of equipment to determine what preventive maintenance may be needed to improve the reliability of process equipment (John T. Reynolds). Smith (1993) summarized the four unique features of RCM as following:

- Preserve system function;
- Identify failure modes that can defeat the functions;
- Prioritize function needs (via the failure modes);
- Select only applicable and effective PM tasks.

3.2.2 RCM analysis

The RCM analysis can be simply divided into two parties: the first part is to identify the operating condition of the equipment using FMECA; the second part is to optimize maintenance tasks based on the results of FMECA. During the process, the RCM methodology cannot optimize the preventive maintenance tasks without illustrating the following aspects:

- Functional states
- Failure modes
- What causes the system fail
- What can be done to predict or prevent each failure

- What should be done if a proactive task cannot be found

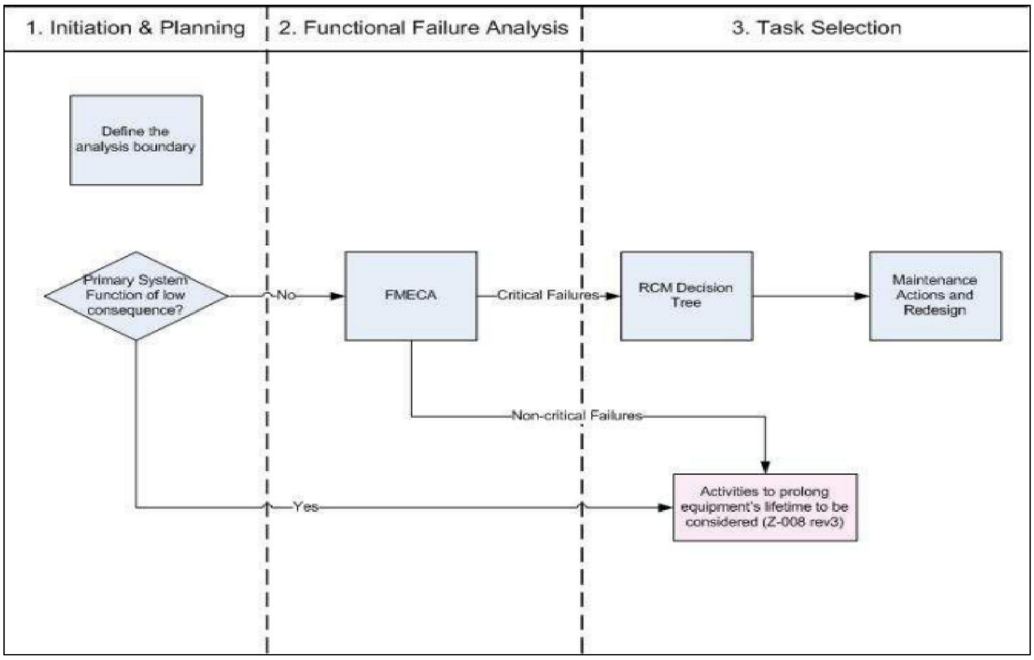

Figure 12 the work process of RCM (Jovanov, 2010)

In the line with how the RCM optimize the PM tasks, the main steps of RCM are as following(Moubray, 2001):

- The first step is to define the function of each asset, together with the standard of performance. That helps the analysts to understand the primary function and second function of system, how the equipment actually works and the acceptable criteria of performance.

- The second step of RCM is to identify what functional failures—the failed states make the asset unable to fulfill an acceptable level of performance.

- The next step is to try to identify all the events—known as failure modes, are reasonably to cause the functional failures.

- The fourth step is to entail listing failure effects—what happens when failures mode occurs. The failure effects are used to support the evaluation of failure consequences.

- When the functions, functional failures, failure modes and failure effects are identified, a detailed analysis is conducted to assign the consequences of failures, including the consequences related to hidden failure, safety, environment, operation and non-operation.

- All these consequences are evaluated, and then corresponding tasks and actions are planned to optimize the PM task to prevent these consequences form occurring.

During the risk analysis steps, the failure mode effects and criticality analysis (FMECA), fault tree analysis (FTA) and event tree analysis (ETA) are often be used. The FMECA is used to identify the undesirable event; the FTA is used to identify the cause and likelihood of the event; the ETA is used to identify the consequences of the event and quantifying risk.

3.2.3 Benefits of RCM

RCM could offers five types of maintenance for a system:

- Predictive maintenance tasks;
- Preventive maintenance tasks;
- Detective maintenance tasks;
- Run-to-failure;
- On-time changes to the system.

In addition to traditional preventive maintenance, RCM mainly focuses on the predictive maintenance which is based on condition monitoring techniques. According to the result of the RCM analysis, the analyst could know the failure is predictable or not based on the criticality, the failure mechanism and available techniques. The inspection, testing and monitoring are commonly used to predict the failure. In case maintenance personnel want to know whether a bearing is overheated or not: for a motor less than 55kw, an inspection temperature inspection using potable thermodetector may be enough; for a turbine generator, it is necessary to mount temperature, vibration and some other sensors to have a continuous temperature monitoring.

RCM also optimizes the operation procedures, changes maintenance frequency, removes unnecessary maintenance activities, priorities maintenance tasks, and considers of economic resources. All of these activities are aimed to keep the system functional without comprising risk and cost. So the benefits of RCM cannot be simply measured for the remaining or reducible work(Gurumeta et al., 2007). It can gain diverse achievement as following(see detail in (Moubray, 2001)):

- Greater safety and environmental integrity;
- Better operating performance;

- Greater maintenance cost-effectiveness;
- Extended useful life of expensive items;
- Amount of comprehensive data base;
- Greater motivation of individuals;
- Better teamwork.

3.3 Risk based maintenance

3.3.1 Risk based maintenance

Risk based maintenance (RBM) methodology was introduced first in the chemical engineering and petroleum refining fields. It provides a tool for maintenance planning and decision making to reduce the probability of failure of equipment and the consequences of failure(Arunraj and Maiti, 2007). The main aim of the RBM is to reduce the overall risk of facilities. It focuses on the most important areas and to prioritize the factors that are critical to success, and then allocates the resources and scheduling maintenance activities in the line with the priority of failure and budget constrain.

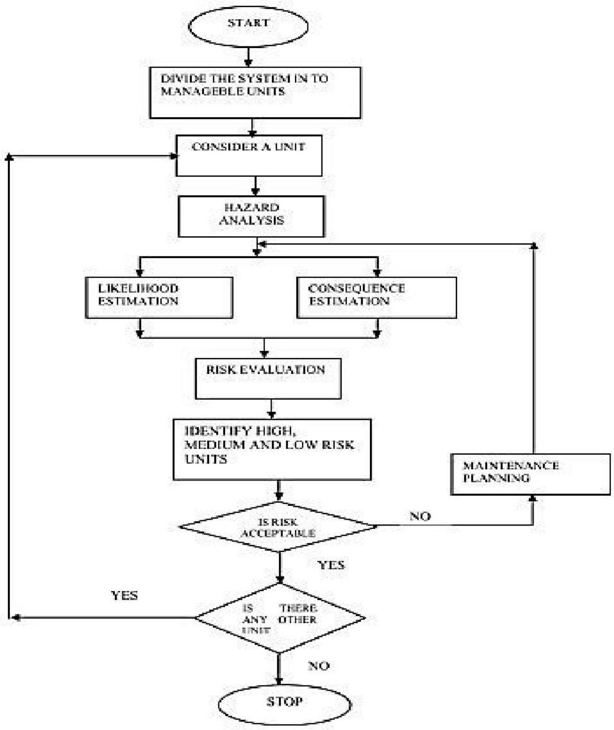

Figure 13 the typical working process of RBM(Arunraj and Maiti, 2007)

3.3.2 Process of RBM

Similar with the process of RBI and RCM, the process of RBM is based on two aspects: risk assessment and maintenance planning based on results of risk assessment. It can be seen from the recommended process by Arunraj and Maiti (2007) in the figure 12.

3.3.3 The relationships of RBM with RBI, RCM

As the risk based inspection and maintenance (RBIM) encompasses the RBI and RCM(CEN, 2008), and the general definition maintenance management encompasses the inspection activities and maintenance activities, the risk based maintenance should compass the RBI and RCM. The RBI is mainly used for static equipment, and the RCM is mainly used for dynamic equipment, the SIL is mainly used for the electric equipment, the RBM is used to prioritize the results of RBI, RCM and SIL to have an overall maintenance activities plan. Their relationships are as the figure 13 presenting:

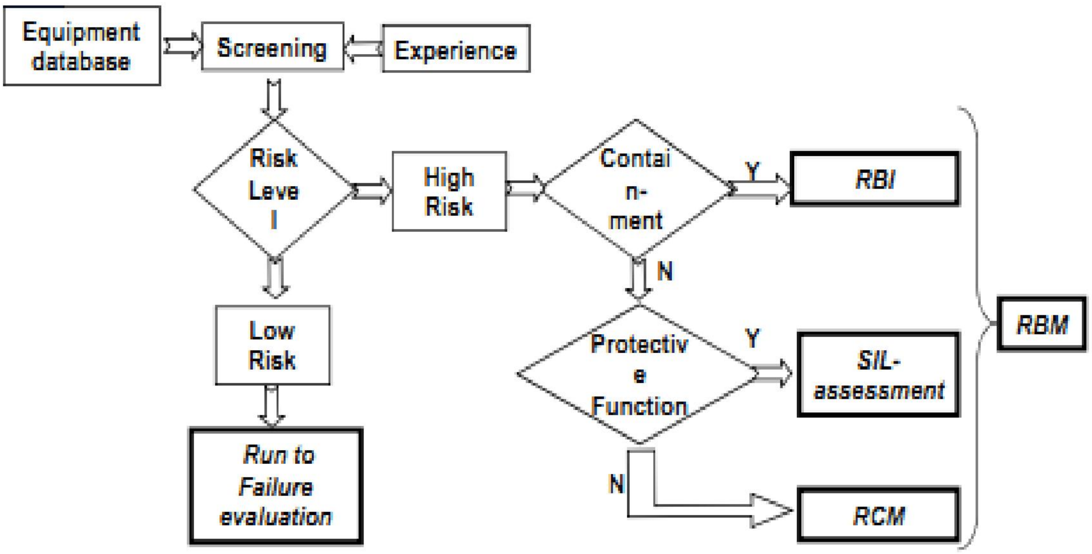

Figure 14 the relationship of RBI, RCM and RBM(Markeset, 2012)

3.4 Limitations of RBI, RCM and RBM

The primary work products of the RBI, RCM and RBM are plans that address alternatives and solutions to manage risks on an equipment and system. These equipment and system plan highlight risks from a safety/health/environment perspective and/or from an economic standpoint (API, 2002). In these plans, cost-effective actions for risk mitigation are recommended along with the resulting level of risk mitigation. The application of RBI, RCM and RBM has been popular in many industries, and the API, DNV, and NORSOK have recommended some practical guidelines for the application. However, the work is complicated, and the risk and reliability processes are dynamic. They still have some limitations affecting the effectiveness of the RBI and RCM and RBM methodologies(API, 2002):

- Inaccurate or missing information and data;
- Inadequate designs or faulty equipment installation;
- Operating outside the acceptable design envelope;
- Not effectively executing the plans;
- Lack of qualified personnel or teamwork;
- Lack of sound engineering or operational judgment;

4 Application of RBI, RCM and RBM

This chapter will integrate the application of RBI, RCM and RBM into one unified process.

4.1 The RIMAP

The DNV has recommended a working process for the maintenance management as the figure 4 showing. The maintenance management is a closed cycle and continuous process. The integration of the risk management approach and maintenance management will continuously update the inspection and maintenance plans according to the risks. In 2008, CEN (2008) has developed a RIMAP procedures for the application of Risk-based inspection and maintenance combining with the maintenance management process , seeing in figure 14.

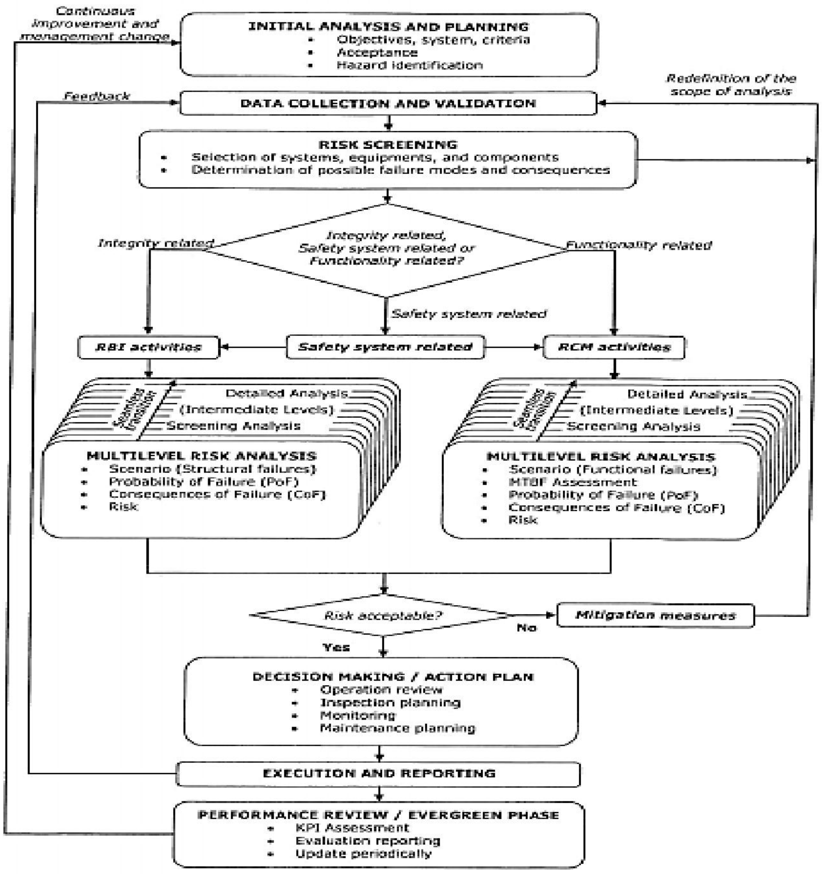

Figure 15 the RIMAP procedures (CEN, 2008)

These RIMAP procedures have well integrated the RBI and RCM into the inspection and management maintenance. The intent of this thesis is to development process for the application of RBI, RCM and RBM in one system, based on the procedures of RIMAP. The RIMAP procedure includes the following main steps:

- Initial analysis and planning
- Data collection and validation
- Multilevel risk analysis
- Decision making and action planning
- Execution and reporting
- Performance review

This RIMAP procedure is applicable to different types of equipment, such as static equipment, rotating equipment, safety systems and electrical equipment.

4.2 Simple unified process of RBI, RCM and RBM

In order to have a good understanding and execution of RBI, RCM and RBM in COSL, this thesis simple divides the technical systems of an offshore platform into two types: static equipment and dynamic equipment. The static consists of pressure tanks, non-pressure tanks, pipelines, loading structures …, such as the boiler tank, high pressure mud pipeline, the derrick structure, the main hook; the dynamic equipment mainly consists of rotatable equipment, such as the diesel engines, motor, generators, bearings, pumps…

Combining with the relationship of RBI, RCM and RBM and the RIMAP process into maintenance management process, this thesis developed a simple unified process for application of RBI, RCM and RBM as following figure 15 showing:

Similar with the RIMAP in CEN (2008), this application process divided into six phase:

- Initial analysis and planning
- Data collection and validation
- Risk assessment
- Decision making and planning
- Execution and reporting

- Review and evaluation

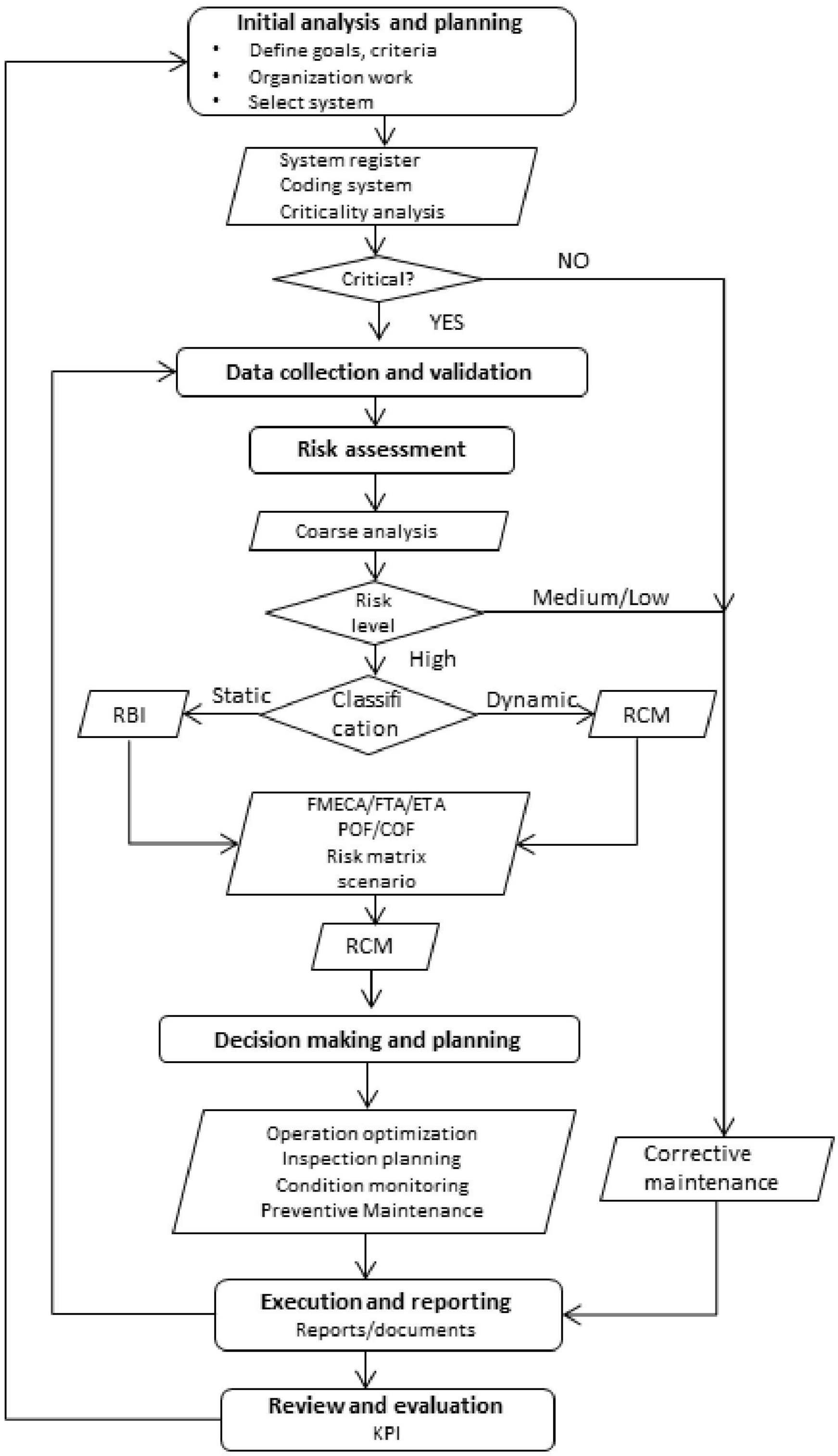

Figure 16 the unified process for the application of RBI, RCM and RBM

4.2.1 Initial analysis and planning

The initial analysis and planning is the first step of application. In this phase, two main activities should be done: the planning work and initial analysis.

✧ **The planning work**

During the planning work, the senior management would define the description and scope of the analysis, set up the measurable objectives, and then the following work would be done: management support, activities schedule, team leader assignment, team selections, training …

✧ **The initial analysis**

The initial analysis is mainly about to choose the desired system the analyst team want to analyze. As the coding system is the foundation of maintenance management, the components and sub-components of the selected technical system should registered, and then the criticalities of registered components will be evaluated refer to NORSOK STANDARD NTC (2001). If the components are not critical, only run-to-failure or corrective maintenance needed; if the components are critical, it is necessary to conduct further risk analysis.

4.2.2 Data collection and validation

The collected data are mandatory prerequisites to any form of risk analysis(CEN, 2008). For critical components, it is necessary to collect some more data for the further analysis if the data sources are available. The normally available data are the design data, operation data, historical maintenance and inspection records, failure modes and effects, and cost information (CEN, 2008). And before the data collection, the quantity of required data should be estimated by the analysts.

However, as per the limitation of risk based approach—inaccurate data could produce inaccurate results of analysis—the collected raw data should be validated, to make sure these data are relevant and representative data.

4.2.3 Risk assessment

The risk assessment involves multilevel risk analysis ranging from coarse risk analysis to detailed risk analysis, which depends on the complexity of system. Accompanying with the increased multilevel risk analysis, the decreased number of components of system involved.

✧ Coarse analysis

The coarse analysis is mainly conducted by quality analysis using descriptive information. It is mainly used for screen the risk levels. If the result of coarse analysis is low or medium risk level, the corrective maintenance may be enough to resolve the failures; if the result is high risk level, it require further detailed risk analysis to make maintenance and inspection decision.

✧ Equipment classification

In this thesis, the equipment is simply classified into dynamic equipment and static equipment (not including the electric diagram system). Then RBI can be conducted for static equipment and RCM for dynamic equipment.

✧ RBI, RCM and RBM analysis

For the different types of equipment, the RBI and RCM could be conducted separately. It takes use of the detailed data and information, to analyze the failure modes, causes and effects using FMECA method, and then to have ETA and FTA analysis to assign the POF and COF for corresponding failures. When the POF and COF have been assigned, the detailed risk levels of failures can be ranked using risk matrix and relevant scenarios can be evaluated to reduce the potential risks of static and dynamic equipment to the ALARP level.

All the alternatives will be evaluated by RBM analysis, the high risk area will be highly prioritized with the consideration of budget constrain, available techniques and time limitation. The cost should be controlled without compromising the risk.

4.2.4 Decision making and planning

As per the alternatives providing by the risk assessment, then the senior manager can make a decision on the maintenance activities. For different equipment and different failures, different maintenance decision should be made to reduce the risk and optimize the operation condition. And the activities should be planned. The decision includes:

- operation optimization

- inspection planning
- condition monitoring
- maintenance optimization
- Preventive maintenance

4.2.5 Executing and reporting

The output of decision making and planning is the plans and schedules for the inspection and maintenance work of the facilities. Then the activities in the plan should be executed to mitigate risk through the execution of the following work:

- Monitoring
- Performance testing
- Optimized procedures of operation and maintenance
- Inspection
- Modification
- Repair
- Replacement

During the execution process, the work is documented and reported. These documents could present the technical condition of the technical system, and could provide the data which is be helpful for the further analysis and continuous improvement.

4.2.6 Review and evaluation

The review and evaluation process is to review and evaluate the process of application of RBI, RCM and RBM to assess the effectiveness and efficiency of this risk based approach. And then it is used to define the area where could modified and improved. Some key performance indicators will be used(CEN, 2008):

- Number of overall safety and environmental incidents
- Equipment effectiveness
- Utilization rate of equipment
- Return on investment
- Production throughout

- Cost per unit
- Maintenance cost
- Etc.

The above process of application will be illustrated using case study in the chapter 6.

5 Requirements of the application of RBI, RCM and RBM

This chapter is mainly aimed to present the necessary requirements for successful application of RBI, RCM and RBM based on the real condition of COSL.

The implementation of RBI, RCM and RBM require well-developed procedures and strict standards to ensure the work is well conducted and the risks are reduced to the reasonable level in cost-effective and cost-efficient ways. The RBI, RCM, and RBM are based on the risk and reliability analysis. But the risk and reliability processes are complicated and dynamic, without clearly predefined requirements the results of assessment and evaluation may deviate from the intend goal. This chapter focuses on the requirements which are needed for the application of RBI, RCM and RBM according to the practical situation in COSL and refer to the reference literature-Risk based inspection and maintenance procedures in European industry.

5.1 General requirements

According to the process of RBI, RCM, and RBM, the general requirements are:

- The application of RBI, RCM and RBM cannot be well executed without the management supports from the senior managers and stakeholders. Senior management team should promise to invest enough resources on the implementations.

- Before the risk and reliability assessment, cost-effective and cost-efficient evaluations, the acceptable risk level and criteria must be clearly defined by the related departments.

- In order to gain the real information of the failures to conduct accurate results, the results of risk and reliability assessment should not be the evidence of punishment.

- The applications of RBI, RCM and RBM are based on team efforts of multi-disciplinary employee. The senior management should allow the team leader to select the multi-disciplinary employee with required competence from the different departments.

- During the assessment, the required level of data and information should be available. The organization should have a good information system and documentation management to ensure the required support and information are accessible. And the employee related the assessment should cooperate with the team members freely.

- All the activities should comply with the applicable legal and regulation, and company's standards. Especially in the international area, the procedures should yield to the local laws and requirements and international standards.

- The methodologies and techniques selected should be able to conduct in organization, and they should be able to provide results the analyst team desired.

- For better utilization of resources, the detailed level of assessment and evaluation should be conducted in the line with the criticality of the facility or system.

The above requirements are only the general requirements should be meted during the application process. The more detailed requirements will be discussed in the following contents.

5.2 management support requirements

The application of RBI, RCM and RBM in COSL cannot be successful without the management supports from board of directors and senior management. The assessment and evaluation are usually time and resources consuming processes, and they require the cooperation of different departments:

- financial department;
- QHSE department;
- asset management department;
- operation department;
- HR department, etc.

The supports from the senior management could ensure the cooperation of different departments during the implementation. The senior manager should promise that the results of assessment and evaluation should only be as the information for improving the inspection and maintenance management, not the excuse to punish the related employees.

In COSL, the QHSE department is to conduct safety management independently. They are familiar with the QHSE standard and risk and reliability analysis methods and techniques. It is better that the team leader be assigned to the one from safety department. They should be responsible for providing specialist help in assessments and evaluation process, and other analysis tools or software. COSL should improve the capability of QHSE with respects to risk and reliability analysis, and the knowledge of operation and asset management.

The operation management department and asset management department are the main cooperators during the execution: they are more familiar with the condition of the equipment and system the team assessed, and could provide the required information during the operation and maintenance processes. The operation department should have a clear operation schedule and ensure all standard operation procedures are well defined, no activities scheduled until risks have been assessed, all operation records are available. The asset management department should have a good quality control for the facilities, and set up SOP for maintenance and inspection, train the maintenance personnel for required skills to maintain and inspect equipment, record, store, report all maintenance and inspection activities. These two departments are responsible to provide detailed information for the specialist during assessment. So in COSL, operation management and asset management should set up unified procedures for management with details records.

The HR department should ensure the convenience that the competent employees are available and provide the corresponding training. Choosing skilled employees and training the employees are the most important responsibilities for the application of risk based approach. The training should at least include the skills of operation, maintenance, and the ability of utilizing special tools or software for analysis.

The financial department should provide the necessary finance to ensure the activities of the team members will not be delayed or stopped due to the lack of finance. During the process, some software, tools, for example ERP and risk analysis software should be invested under the approval of financial department.

5.3 competence requirements of team members

As the application of RBI, RCM and RBM require multi-disciplinary experience and technologies. The team members should be experienced personnel who are competent to execute the work process. When the team leader select the team members, it is better to keep the skills and backgrounds of members in mind. If necessary, it is possible to invite relevant experts from the outside of COSL. According to the risk-based inspection and maintenance procedures in European industry(CEN, 2008), the team should be with the competence of the following aspects:

- QHSE standards and regulation
- Equipment or system operation and process

- Inspection and maintenance issues
- Risk and reliability assessment
- Specific equipment disciplines(e.g. materials, corrosion, electrical, fixed and rotating equipment)

As the inspection and maintenance activities are often regulated or guided by some standards or guidelines, for example the ISO standard and CCS standard，the team members should be clear with the relevant standards and regulations. In addition, if these activities are conducted in the international area, the implementation should comply with the local and international rules and legislation, and the industry standard.

According to the above competence requirements, the team members should include at least:

- An experienced safety supervisor or quality control engineer, who should be familiar with the standards and regulations with respects to QHSE;
- An experienced driller or a toolpusher, who should be familiar with the operation procedures, technological process and work environment;
- An electrical engineer, who should be expert in the electrical equipment principle and inspection and maintenance of electrical equipment;
- A mechanical engineer, who should be expert in the mechanical equipment principle and structure of equipment and inspection and maintenance of equipment;
- A material engineer, who should be expert in materials, knowing degradation process of materials and inspection and protection of materials;
- Risk analyst and reliability engineer, who should be expert in the risk assessment, and reliability analysis and calculation;
- A lawyer if necessary, who should be familiar with the international rules and local legislation.

For COSL, employees such as QHSE personnel, maintenance engineers, operators are easily available. However, the risk analyst and reliability engineer are lack of. The personnel involved in the analysis process should have a clear system thinking to conduct risk and reliability analysis by having a systematic training.

5.4 requirements for the probability assignment

- The methods used to assess the probability of failure and reliability should be generally used and accepted by COSL or the offshore oil and gas industry;
- Various methods could be used according to the level of detail or criticality;
- Qualitative, quantitative, and qualitative-quantitative approaches should be used according to the depth of plant. The results of simplified analysis should yield higher or equal average score of probability of failure compared to a more detailed analysis;
- The results of assessment should be reliable and validate;
- The probability of failure and reliability should avoid averaging and unrealistic value;
- The results should be ranked according to the different failures;
- All the results and assessment process should be well informed and documented;

In COSL, currently used approaches are almost qualitative, some quantitative models to conduct quantitative analysis. For example, JSA, HAZOP, FMECA are common qualitative methods utilized in COSL, but some other quantitative methods such as ETA, FTA, root cause analysis, should be imported. Quantitative models are difficult to be developed by any company themself. The most meaningful data and value are based on the international data collection and experience of the O&G industry. For better utilization of the application of risk based approaches, some mature software or models can be directly imported form DNV, which can be used for quantitative, qualitative and semi-quantitative analysis, such as PHAST, SAFETI, LEAK, SOQRATES, WOAD, Orbit SIL and Synergi. The software could use the vast amount of value and data directly form the world wide, that will save much time to analyze and the results can be reliable and validate.

5.5 requirements for consequence assignment

- The consequence assessment should include the safety, health, environment, financial aspects;
- The assessment should consider the processes and material produced or released during these operation process, which could have immediate or long term effects;

- All the results and processes of consequence assignment should be documented for the inner or outer audit in future;

- The assigned consequence of safety should be comply with the relevant regulations ;

- The assigned consequence of failure on health should consider the effect on people both in short term and long term;

- The impacts on environment should include the effects on soil, air, surface water and ground water;

- The impacts on the business and financial should be documented for the further cost-effective and cost-efficient evaluation of alternatives.

Similar with the probability assignment, the consequences assignment should also refer to examples of the whole world wide offshore oil and gas industry. These recommend DNV software will be helpful.

5.6 risk and reliability assessment requirement

- The detail level of assessment should be based on criticality of the equipment or system, referred to NORSOK Z-008-criticality assessment for maintenance purposes;

- The acceptable risk and reliability level should be predefined before the assessment;

- The results of risk and reliability assessment should be reliable and validate;

- The failures modes and mechanism should be well discovered;

- The risk mitigation and reliability enhancement solution should be correspondent to the failure modes and system function;

- Each failure mode should develop a correspondent solution to reduce the risk or improve the reliability;

- the criteria could depend on the company standard and the industry average, national requirement;

- If in the international area, the criteria should be multi-international or meet the local requirement.

For COSL, as some basic data and information which could clearly indicate the risk and reliability of components is lack of, it is better to take use of advanced risk analysis software using in the O&G industry. For example, COSL has data and information which could define the failure and consequences of high pressure pipeline leakage, but has not information to verify the probability of failures and severity. So COSL should improve the basic data and information record, and it is better take use of software to apply risk and reliability analysis. And the software will ask for defined data and information, which will help COSL to improve the basic management of maintenance and inspection, as well as the data and information management.

6 Case Study

This chapter chooses a Top Drive of a drilling platform as the technical system to conduct the case study, to present how to apply the risk based approaches in maintenance management and combine the use of ERP system.

6.1 Background

A Top drive is one of critical equipment used for drilling and workover operation. It is a substitute of rotary table used to hang drilling strings and provide clockwise torque. The use of a top drive system provides the operator substantial benefits over traditional Kelly drilling (NOV):

- It uses triple or two drill pipes as one stand, that means fewer drill pipe connections and safer, saving drilling time by up to 30%;
- It provides quicker tool orientation through better control of directional drilling tools;
- It could reduce the capability of drill pipe stuck in down hole by circulating mud and rotating while tripping;
- It could extend the life of the drill pipe by having a well control of make-up torque;
- It could stab and close IBOP at any time;
- Etc.

As the top drive is critical system during the drilling operation, the failure of Top drive system will directly affect the drilling downtime. This thesis chooses the TD 500PAC system which has been used on LD5-2 DPP (drilling and production platform) in Bohai Bay for drilling and operation since 2004. It is an electric, variable frequency, 1,100 horsepower AC motor driven top drive with 500 tons pipe hoisting capability, and pipe handling system with a 500 ton, at 100rpm, API rated hoisting capacity(NOV, 2003).

In 2009, the TD 500PAC was used for the extra 30 wells of LD5-2 DPP after overhaul. However, during the drilling operation, the maintenance of the top drive system was not optimized according to the real condition. The unscientific maintenance caused a lot of downtime. The following figure of downtime statistics, the TD 500 PAC's downtime was the main part of drilling operation downtime. It brought more pressure on the safety operation and operation efficiency.

Downtime statistics (from Oct-09—Jul-10)		
Time	Top drive system	Other equipment
Oct-09	2.25	3
Nov-09	4	6
Dec-09	6.75	17
Jan-10	1	12.25
Feb-10	2.5	0
Mar-10	8.75	5.5
Apr-10	18.25	11.8
May-10	0	0
Jun-10	6.5	8.25
Jul-10	27.75	31.75
Sub total	77.95	95.55

Figure 17 The downtime statistics of LD5-2 DPP (from oct-2009—Jul-2010)

From the above statistics, almost 45% of the total downtime came from the top drive system (source from the LD5-2 DPP drilling operation efficiency report). So it will be meaningful if the downtime could be reduced. That is why this thesis chooses this system to conduct the application of RBI, RCM and RBM.

6.2 Initial analysis and planning

- **Define goals, criteria**

The goal of risk based approach is to maximizing availability and profit without compromising safety (to personnel and environment)(DNV-PR-G101). DNV recommends that the risk acceptance for maintenance management should be based on management targets related to the availability, profit and safety. The acceptable criteria could be defined by the acceptable limit of personnel safety risk, environmental risk and economic risk(DNV-PR-G101).

Every year COSL will define the QHSE target including the criteria of PLL (potential loss of life), accident with/without personnel injuries, economic loss and environmental pollution. Every department in COSL will define the QHSE requirement in the line with the COSL's target. That could be the goal and criteria of the risk analysis.

One platform also needs define the acceptable criteria. Right now, most of business divisions have criteria, but the platform has no defined criteria apply with the criteria of divisions. For the application of RBI, RCM and RBM on platform, it is necessary for COSL to have clearly acceptable criteria for the platform management

✧ Organization work

In order to have a good analysis of the top drive system, at least the following professional personnel should be in the analyst team:

- Safety supervisor, who is familiar with the QHSE target, safe operation and knows well the risk analysis and reliability calculation;

- Driller or tool pusher, who is familiar with the top drive operation procedures and downhole condition and operation environment;

- Mechanic engineer and electric engineer, who are good at the theory, principle, and maintenance of the Top Drive system and available techniques of inspection and maintenance;

- Material person who is knows well the cost and availability of spare parts for the top drive system, as well as the degradation of materials;

- If necessary, the expert from the top drive company could be invited.

It is better that the mechanic engineer and electric engineer, driller or tool pusher should be selected from the LD5-2DPP. However, maybe the above personnel are not available or not experienced enough, and then relevant training should be issued. For example the ERP training, to make sure these engineers are well skilled to use ERP to register components and record and print maintenance activities. But in this thesis, all these work are just simulated, so the analysis process is conducted by the author. So some experience and consumption will be used.

✧ System selection

For the system selection, it is better to choose the facility that is in the infant or aging period during the life cycle of facility, which has more risk of failure and the optimized maintenance management will be more meaningful for saving cost without compromising safety. That is why this thesis chooses TD 500 PAC top drive system, it caused more downtime and waste much cost.

✧ System registers

The facilities can be registered as functional hierarchy or technical hierarchy(NTC, 2001). In COSL, the system usually registered in the ERP system as functional hierarchy. The system is registered according to the system, main function, sub function, and parts. The TD 500 PAC top drive system consists of the following main system: Top drive assembly, control and power system, service loop, rig interface, guide track assembly, and transport assembly (seeing in figure 18 and 19). According to the downtime statistics, the main downtime of this top drive system caused by the failure of the top drive assembly, so this thesis not register the whole of the top drive system, but the top drive assembly(seeing in the figure 20).

However, COSL has not registered the system in components and parts levels, only the system, main function and sub function are registered. So COSL should create more layers to register the components and parts level of one technical system for more detailed analysis.

Figure 18 TD 500 PAC

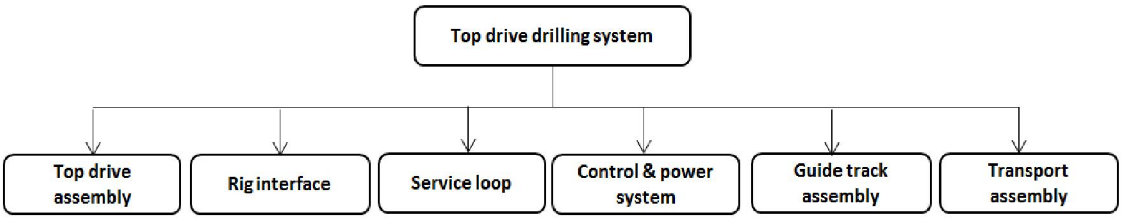

Figure 19 the main part of top drive drilling system

SYSTEM		MAIN FUNCTION		SUB FUNCTION	
Description	Code	Description	Code	Description	Code
TOP DRIVE ASSEMBLY	1	Motor cooling system	11	Blower assembly	1101
		Swivel assembly	12	Motor assembly	1201
				Goosneck assembly	1202
				Washpipe assembly	1203
				Spray head nozzle assembly	1204
				Spray head nozzle assembly	1205
				Downpipe assembly	1206
		Hydraulic system	13		
		Electrical assembly	14	Encoder assembly	1401
				Power distribution block	1402
				Junction box	1403
		Brake assembly	15		
		Dolly assembly	16		
		Pipe hander assembly	17	Link clamp assembly	1701
				Back-up wrench assembly	1702

Figure 20 system register of top drive assembly

✧ **Coding system**

In the ERP system of COSL, every system, main function and sub function have their own function locations, which is one kind of code to indicate one unique system, main function or sub function. The operator could find any one through the unique function code. The following figure is one example of system register and coding system for mud pump unit of LD5-2DPP.

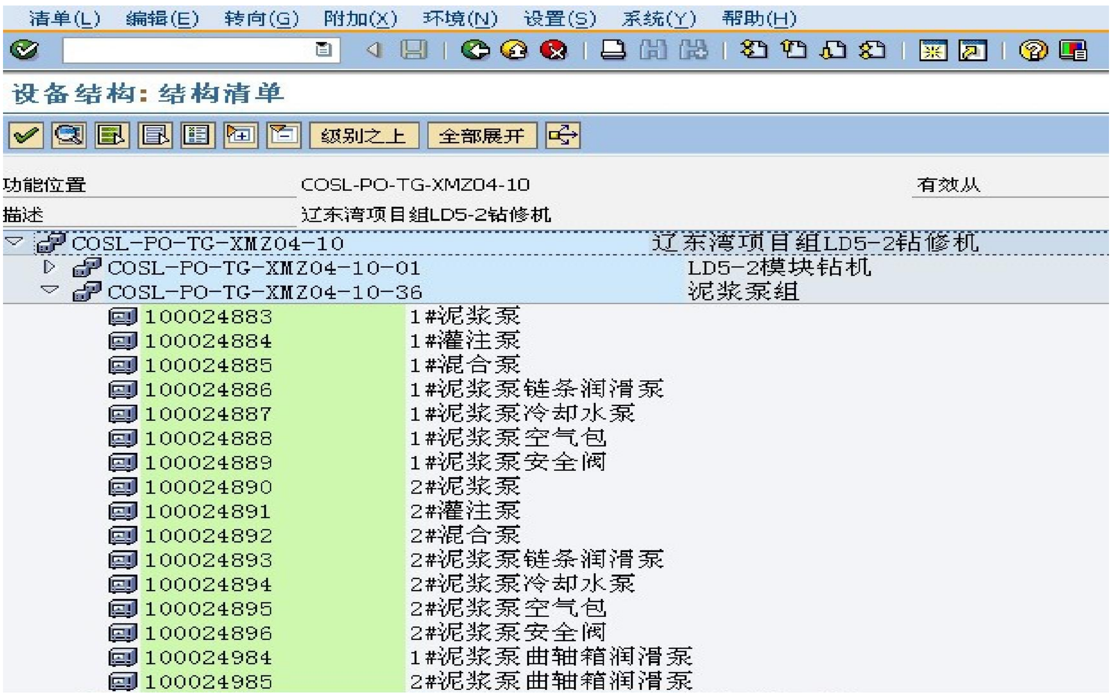

Figure 21 the system register and code example in ERP

However, the system is in Chinese language. So in this thesis, the system register and coding system are just stimulated. The top drive assembly divided into sub system and sub components, and one component should be registered with unique code. It is convenient to describe the component and present the relationship of component and system using code (Seeing in the above figure 20).

✧ Criticality analysis

COSL usually classifies the system in general facility, important facility and critical facility. But in this thesis, the criticality of a component is based on the consequences of failure with respects to HSE, production and cost aspects and redundancy degree of component(NTC, 2001).

The classification of criticality and consequences could be presented by: 1=low, 2=medium, 3=high.

The redundancy degree could be presented by the number of spare parts: A=no spare part, B=one spare part, C=two or more spare parts.

The following figure presents a simple criticality analysis result of the top drive assembly.

Code	Function Description	Consequences	Redundancy	Criticality
1101	cool the main motor	3	A	3
1201	provide rotate and torque	3	A	3
1202	provide passageway for mud by connecting flexible hose and washpipe	3	A	3
1203	provide passageway for mud by connecting goosneck and rotating top drill stem	3	B	3
1401	calculate rotate speed	2	A	2
1402	distribute electric power	3	A	3
1403	cable connection	3	A	3
1701	hold the drilling stem	3	B	3
1702	transmit torque to torque tube	3	A	3

Figure 22 the criticality analysis of top drive assembly

(Notice: the analysis is conducted to assemblies, so the redundancy degree is based on spare assembly number, not on spare parts number of assembly.)

From the above analysis, most sub functions of top drive assembly are high criticality excepting 1401(the encoder assembly are medium criticality). For the medium criticality components, corrective maintenance will be issued. So the 1401 will be replaced when failed. The reasons are following:

- At first, if the encoder failed, the consequence is that rotate speed is not indicated or not accurate, and will not cause much QHSE and cost consequences, but the other assembly will cause the top drive assembly does not work directly or in short time;

- At second, the rotate speed could be calculated by the PLC in the VFD system of TD 500 PAC.

According to the analysis, these component of the system are critical, there are needs to collect more information of the components for further analysis.

6.3 Data collection and validation

As mentioned above, the data and information are prerequisites to risk and reliability analysis. Before the data collection, it is necessary to estimate how much and what kind of the data and information required for analysis(CEN, 2008). After data and information is collected, it will be validated to make sure it is accurate and can be used to analysis (the detail of validation is not included in this thesis). For the top drive assembly, it is necessary to collect the drawings, spare parts, the maintenance requirement, the historical record of failures and maintenance, system safety, cost, etc. However, the above is not available because of no defined system to record all related data and information. Most of these data and information are recorded in different departments. Actually, they can be recorded in ERP system, but COSL needs to improve the utilization of ERP system. That needs a long way to go.

In this case study, the sources of data and information of top drive assembly are:

- the specification document, operation and maintenance manual, drawing, and spare parts manual provided by NOV accompanying with the top drive system;

- the maintenance and inspection historical record of the top drive;

- the running hour and downtime report;

- interview of top drive expert and operators;

- The author's experience.

6.4 risk assessment

✧ **Coarse risk analysis**

A coarse risk analysis is to analyze the initiating event with modest effort usually using checklist to present the cause and consequence. The flowing figure is the coarse risk analysis result of some selected high criticality components as per the above criticality analysis.

No	Event	Causes	Consequences	Probability	Risk level
1	no or low cool air pressure from	No power supplied, blower fan stucked, air intake stucked, motor broken down,	D	3	3
2	no rotate torque provided from main motor	No power supplied, power connected with ground, motor overheating, motor broken down,	C	3	2
3	Goosneck leakage	rupture, erosion	B	2	2
4	Washpipe leakage	grease fitting failed, seal failed, corrosion	E	5	3
5	Back-up wrench failed to hold pipe	solenoid valve failed, no or low pressure hydralic oil,	D	5	2

Figure 23 coarse risk analysis of top drive assembly

(The categories of consequences and probability of the event are in the line with the categories of CNOOC. See detail in appendix A.)

From the above result of coarse risk analysis, the main motor, gooseneck and back-up wrench are high risk. For the gooseneck, although the probability of failure is low, the consequences may be serious, so the result of risk is high; for the back-up wrench, the consequences may be not serious, however the probability is high, so the combination of consequences and probability is high.

✧ System classification

Based on the result of coarse risk analysis, this thesis selected three high level risk components for the further detailed risk analysis: main motor, gooseneck and back-up wrench. In the selected components: the main motor and back-up wrench are dynamic, the gooseneck is static. For the further detailed risk analysis, the gooseneck should use the RBI method; the main motor and back-up wrench should use RCM approach.

✧ RBI analysis for gooseneck

As mentioned in the function description, the gooseneck is a bended structure used as a passageway between wash pipe and flexible hose. It can be considered as a high pressure pipeline which the drilling mud will go through. As per the DNV-PR-G101 ()during the drilling operation, the drilling mud is at high pressure and temperature, the degradation mechanism of gooseneck can be considered as chemical. The chemical should be corrosive or toxic, and the failure mechanisms of gooseneck could be corrosion and erosion.

In the RBI analysis process, the initial event is assumed as the erosion of gooseneck, and then an ETA method is conducted to estimate the possible consequences and the possibilities.

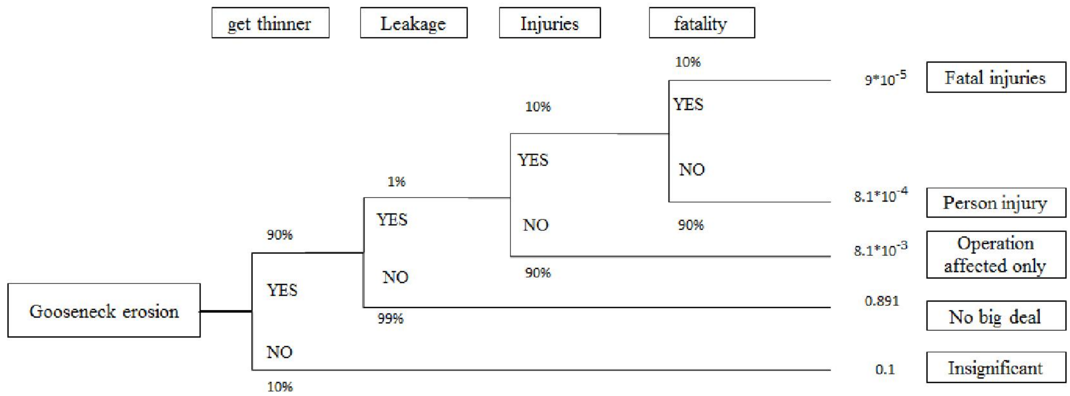

Figure 24 ETA analyses for gooseneck

According to the above ETA analysis result, the risk of can be compared with the acceptable criteria which has been defined before risk conducted. As per the experience, it should be reminded that the probability of leakage will increase with the increasing using life. So even if the risk is acceptable at the beginning, it will increase to unacceptable level.

According to the operation and maintenance manual, the history record of inspection and maintenance activities, the flexible hose changes at a defined time interval and other high pressure pipelines of mud pump system have annual magnetic inspection. However, there is no any record or recommendation to inspect the condition of gooseneck. So it is necessary to schedule inspection activities and take some barriers to prevent the person being injured when leakage occurred.

The erosion of gooseneck could be inspected to record the changes of thickness using non-destructive testing techniques, such as visual inspection, X-ray, eddy current, liquid penetrant, ultrasonic and magnetic. However, as the gooseneck is coated by painting, combined with the cost and availability of NDT tools, the magnetic inspection is recommended. The alternatives to reduce the risk of gooseneck leakage:

- Conduct a visual when it is possible;
- Conduct an annual inspection with other high pressure pipelines;

- Reduce the operation close to the gooseneck: for example, the derrick man should go away when the top drive travelling close to the monkey board.

✧ **RCM analysis**

As the main motor and back-up wrench are dynamic components, the RCM method will be utilized to conduct risk analysis. For a better practice, in this thesis FEMCA and Root cause analysis will be used individually—Root cause for main motor, FEMCA for back-up wrench.

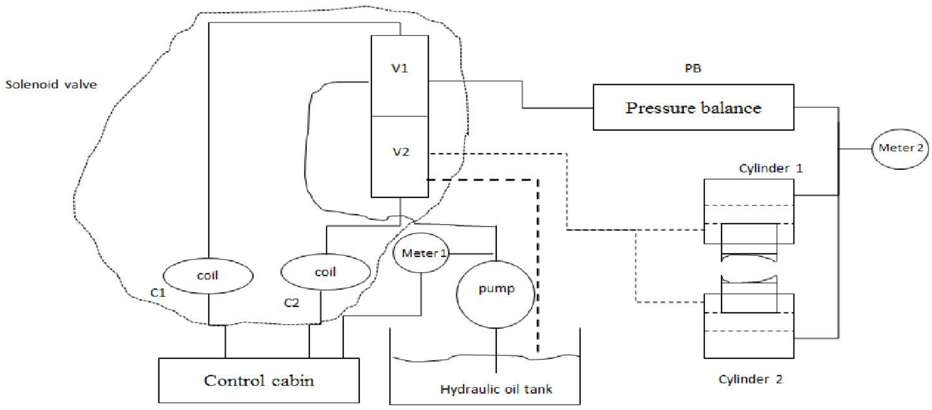

Figure 25 the sketch map of back-up wrench system

The above figure is a simple function diagram of the back-up wrench system. In order to have a systematic study of the back-up wrench system, FMECA method is used to analyze the failure and rank the criticality of the various failures of the system. The result of the analysis as the following figure showing:

No	Function	Operational mode	Failure mode	Failure cause or mechanism	Effect on other subsystem	Effect on the system function	Failure rate	Failure effect ranking
1	C1	Povide force to move V1	No force to move V1	Coil is burned out	V1 cannot open, Cyliner cannot move out	Back-up wrench can not work	5	1
2	C2	Povide force to move V2	No force to move V2	Coil is burned out	V2 cannot open, Cyliner cannot move back	Back-up wrench can not work	5	1
3	V1	provide passageway to PB	can not open or close	stucked	V1 cannot open, Cyliner cannot move out	Back-up wrench can not work	4	2
4	V2	provide passageway to tank	can not open or close	stucked	V2 cannot open, Cyliner can not move back	Back-up wrench can not work	4	2
5	Pump	provide pressure hydraulic oil to selenoid valve	cannot provide hydralic oil	motor pump failed,	cylinder cannot move	Back-up wrench can not work	3	3
6	PB	Balance the pressure to cylinder	No ballanced pressure	balance ball does not work	Cylinder cannot work at the same time	low efficience	1	5
7	m1	Indicater the pressure of hydraulic system	no pressure indicated	broken	operator cannot know the pressure of hydraulic system	stop work and check the pressure	3	4
8	m2	Indicater the pressure of back-up wrench cylinder	no pressure indicated	broken	operator cannot know the pressure of cylinders	see the torque data when working	3	4

Figure 26 the FMECA analysis for the back-up wrench system

Seeing from the result, the solenoid valve is the most critical parts. As the status can be monitored and inspected using the pressure value and resistance value, the recommended solutions are as following:

- Weekly test for the resistance using multi-meter: it will record the resistance changes to indicate the status of coil, if the resistance becomes low, maintenance actions should be taken to increase it, then the life of solenoid valve will be extended;

- Monthly function test for the valve of solenoid valve: to check whether the valve has any stuck phenomenon, if the piston cannot move freely, should be changes or milled, then the life can be extended;

- Install pressure sensor for hydraulic system and cylinder to indicate the status in the control cabin: it will help the operator to know the cylinder has worked or not, and help the maintenance people to estimate the cause of failure, which will reduce down time.

The analysis for main motor system:

Main motor is to provide the rotate torque to the drilling stem. But if the main motor cannot rotate, the main function will lose. So during this analysis process, the root cause is analyzed at first. The simple analysis results are as following figure presenting.

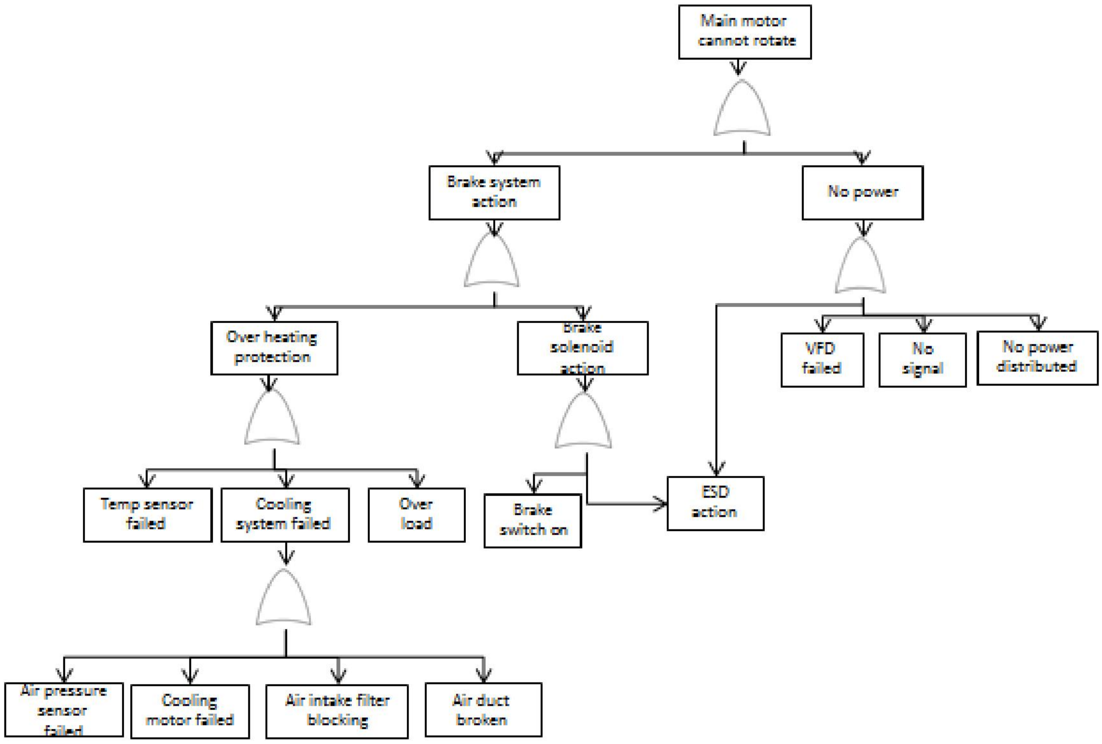

Figure 27 the fault tree analysis for main motor

Base on the analysis result and the experience, the most possible causes of failure are the overheating and wrong operation of ESD and brake solenoid switch. So the alternatives recommended are as following:

- The ESD button and brake switch should be check before operating main motor: to make sure they are in right position;
- Temp sensor should be checked through comparing the indicated temperature with value tested by the portable thermometer every day;
- A pressure sensor should be installed to indicate the pressure of cooling air: to make sure enough cooling air for main motor;
- Monthly clean the air intake filter: to ensure enough air can be in taken by blower motor.

If the above alternatives can be executed, the reliability of main motor could be improved. In the line with the logic relations in root cause figure, if it is translated into reliability block diagram, it should look like the following figure showing (some elements have been deleted to simplify the reliability calculation):

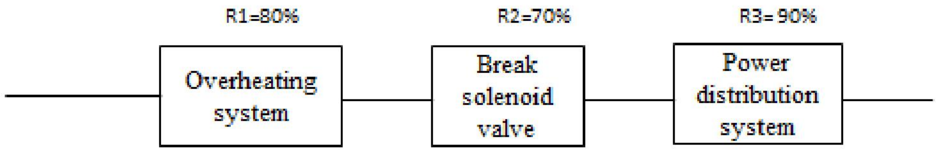

Figure 28 Simple reliability block diagram of main motor

Before the maintenance and operation procedures are optimized, the reliabilities are assumed to be 80%, 70% and 90% individually. Then the reliability of the system should be:

$$Reliability = R1 * R2 * R3 = 0.8 * 0.7 * 0.9 = 0.504$$

However, if make an assumption that the reliability of overheating system increased to 90%, break solenoid valve increased to 90%. Then the reliability should be:

$$Reliability' = R1' * R2' * R3 = 0.9 * 0.9 * 0.9 = 0.729$$

Comparing with the reliability before and after optimization, the reliability of the system increased 0.225(22.5%).

If the increased reliability is calculated separately, the increased reliability of system could be calculated, then the more reliability increased, the more critical the sub system will be.

For example, if only optimizes overheating system, the increased reliability will be:

$$Io = R1' * R2 * R3 - R1 * R2 * R3 = 0.9 * 0.7 * 0.9 - 0.504 = 0.063$$

If only optimized brake solenoid valve, the increased reliability will be:

$$Ib = R1 * R2' * R3 - R1 * R2 * R3 = 0.8 * 0.9 * 0.9 - 0.504 = 0.144$$

It is obviously that Ib>Io, so brake solenoid valve is more critical than overheating system, it should be optimized at first if budget is not enough to optimize both.

✧ **RBM analysis**

As the RBM method provides a tool to allocate the resources for the prioritized failures, which could mostly affect productive capability of physical assets by reducing production, increasing operating costs and interfering with customer services(Arunraj and Maiti, 2007). So all the above suggested solutions should been screened to rank the priorities. The priorities should be based on the how much risk is reduced or reliability increased and available techniques, personnel, cost, lead time. It will take use of the risk analysis methods as above analysis processes used to analyze the effectiveness and efficiencies of the solution to the whole area. And then the most critical area will be allocated resources at high priorities. (As the RBM will use similar risk analysis methods as RBI and RCM, so here will not present the detail analysis, just describe a general guideline.)

6.5 Decision making and planning

Based on the result of RBM analysis, inspection and maintenance decision will be made to the area which could reduce the risk or increase reliability most effectively. For example, the brake solenoid valve is more critical to the reliability of system, and the cost is not much, it should optimized as it will more effective to reduce the risk and increase the reliability. Then the detailed activities could be scheduled, for example to modify the standard operation procedure, training the operator, take action to prevent the brake switch and ESD button from mistake during operation, paste operation notice on the control cabin to remind the operator, etc.

So, after the series of risk and reliability analysis, the senior managers could have the decision of corrective maintenance, condition monitoring, inspection, preventive maintenance.

When these maintenance decisions and plans are made, the operators could record these activities in the PM module of ERP system.

6.6 Execution and reporting

When the activities scheduled, then the maintenance personnel, operator or some other relevant people will execute the activities with respects to the schedule. During the execution process, the activities should be well recorded and stored, and then the process and results should report to the senior management. Based on the report, the senior management could assess if the defined criteria has been achieved or not, and then have a decision to have further action or not.

All these execution are reminded by the ERP system, and recorded and reported in the ERP system.

6.7 Review and evaluation

QHSE department should review and reevaluate the analysis periodically to determine their continued effectiveness. For example, when the operation of brake solenoid valve optimized, the analyst should reviewed the assessment process to see if the original decision and assessment is right or not, or to see if there is any space to increase the accurate the result of analysis. These review and evaluation are a good way to summarize the valuable experience and lesson, which could be used on other place.

7 Conclusion

The maintenance management process should be a cycle loop based on Deming's' PDCA loop (plan, do, check and act), which could continuously improve the maintenance management for the life cycle of facilities (Panesar et al., 2008). The aim of the thesis was to study how to develop a unified process of the application of RBM, RBI and RCM to reduce the risks in maintenance and inspection management with COSL. From the study of this thesis, by applying the risk based approach in the life cycle of facilities, the maintenance and inspection activities can be better planned, executed, reviewed and improved for different periods of the facilities. That could help COSL to allocate the scare resources to the most critical area, achieve excellent QHSE achievement while not cause much cost, and enhance the competitiveness in the marketing.

However, COSL wants to have a better practice on applying risk based approach in the maintenance and inspection management, the following activities should be conducted to improve the practice of RBI, RCM and RBM methods:

- Conduct a more comparative study to integrate RBI and RCM into RBM for carrying out maintenance and inspection activities. The main analysis process of the three method are similar, they could share database, use the similar method to evaluating consequences of failure, assign the probability of failures, and take the same risk ranking principle to select maintenance and inspection activities. If these methodologies could be more clearly integrated, a simpler unified process could be developed and the efficiency and effectiveness could be improved.

- Enhance the utilization of maintenance management software and some other risk and reliability analysis software. COSL should improve the ERP operation training and take full utilization of ERP system, which can help COSL have better execution and records of maintenance activities. And professional risk and reliability analysis software should be introduced in COSL to have a professional analysis, which could also lead COSL comparing the criteria and standard of the international operators, and then improve own management and standard. That can help COSL improve the planning and schedule of maintenance activities.

- Take a full utilization of technology and scientific information management system. One of the challenges for COSL to have a good utilization of the risk based approach is lack of accurate basic data. As per the "garbage in, garbage out" principle, if the collected data and information is "garbage", then the results of analysis could also be "garbage". Then the risk and reliability analysis could be meaningless. So for COSL, a better utilization of technology and scientific information management system is necessary. The proper technology could improve the accurateness of the quantity data; the scientific information management system could improve the availability of data and information when the analysts want to take use of. And a better information management system can help the QHSE department to review and evaluate the analysis process for further improvement.

- Take a full utilization of training program to improve the ability of the employees. The application of risk based approach is a comprehensive process. That has a high requirement for the knowledge, experience and ability of the employees who selected into the analyst team. Necessary training programs should be conduct to make sure these employees could meet the requirement of analysis.

Reference

API 2002. API Recommended Practice 580: Risk-based Inspection.

API 2008. API RP 2SIM : Recommended practice for the structureal integrity management of fixed offshore structure.

ARUNRAJ, N. S. & MAITI, J. 2007. Risk-based maintenance—Techniques and applications. *Journal of Hazardous Materials,* 142**,** 653-661.

AVEN, T. 1992. *Reliability and risk analysis*, Elsevier Applied Science.

AVEN, T. 2008. *Risk analysis: assessing uncertainties beyond expected values and probabilities*, Wiley.

CEN 2008. Risk-based inspection and maintenance procedures for European industry(RIMAP).

COSL. 2010. *Company Profile-COSL is a leading integrated oilfield service provider* [Online]. Available: http://www.cosl.com.cn/ens/CompanyP/About/2010-06-04/76.shtml.

DNV-PR-G101 Risk based inspection of offshore topsides static mechanical equipment. *DNV-RP-G101*

DNV 2009. report for JIP-Best practice for maintenance management, DNV-managing risk.

FABER, M. H. 2002. Risk-based inspection: The framework. *Structural engineering international,* 12**,** 186-195.

GROOTE, P. D. 94. Trends In Maintenance Management In Europe.

GURUMETA, E. M., CIDE, I. S. & FACTORY, E. N. Reliability Centered Maintenance. 9th International Conference Electrical Power Quality and Utilization, 2007.

GUSFRE, D. 2010. *Implementing condition based maintenance within an asset management framework,* Stavanger, D. Gusfre.

ISO(2000) ISO 17776, Petroleum and natural gas industries–offshore production installations–guidelines on tools and techniques for hazard identification and risk assessment. 1-45.

JOVANOV, A. 2010. *Development of an integrated inspection and maintenance strategy.* Master Degree, university of stavanger.

KUMAR, U. Risk based maintenance strategies for mechanized and automated systems. University of Stavanger.

MALMHOLT, O. Maintenance objective, strategy, and organization, EUREKA project, UTEK.

MARKESET, T. 2012. MOM460-Operations and miantenance management.

MARKESET, T. & KUMAR, U. R&M and risk-analysis tools in product design, to reduce life-cycle cost and improve attractiveness. Reliability and Maintainability Symposium, 2001. Proceedings. Annual, 2001. IEEE, 116-122.

MOBLEY, R. K. 2002. *An introduction to predictive maintenance*, Butterworth-Heinemann.

MOUBRAY, J. 2001. *Reliability-centered maintenance*, Industrial Press Inc.

MOUBREY, J. 1997. Introduction to Reliability-centred Maintenance. *Relability centered maintenance.* 2nd edition ed. Oxford, England: Butterworth/Heinemann.

NORSOK 2010. Z-013 Risk and emergency preparedness assessment. *Z-013.*

NOV. *TOP DRIVE SYSTEM* [Online]. Available: http://www.nov.com/Drilling/Top_Drive_Systems.aspx.

NOV 2003. TD500PAC Top Drive Drilling System--Care and operating manual Model

NTC 2001. NORSOK STANDARD Z-008 Rev. 2:Criticality analysisi for maintenance purposes. Oslo: Norwegian Technology Centre.

PANESAR, S. S., KUMAR, R. & MARKESET, T. 2008. development of maintenance strategies for offshore production facilities,. *the proceedings of the 3rd world congress on engineering asset* *management and intelligent maintenance system(WCEAM-IMS 2008).* Beijing International Convention Center.

PIET, K. 2001. Procedure for preparation and operation of risk control measures and safe system of work.

PINTELON, L., GEDERS, L. & PUYVELDE, V. 2000. *Maintenance Management*, Acco.

RAUSAND, M. 1998. Reliability centered maintenance. *Reliability Engineering & System Safety,* 60, 121-132.

SANTOS, A. D. & HAJRI, A. A. A. 2000. Risk Based Inspection - A Valuable Approach. *Abu Dhabi Interntional Petroelum Exhibition and Conference.* Abu Dhabi, United Arab Emirates: Copyright 2000, Society of Petroleum Engineers Inc.

SCHEFFER, C. & GIRDHAR, P. 2004. *Practical machinery vibration analysis and predictive maintenance*, Newnes.

SMITH, A. M. 1993. *Reliability-centered maintenance*, McGraw-Hill New York.

WILKINS, D. J. 2002. *The Bathtub Curve and Product Failure Behavior: Part One - The Bathtub Curve, Infant Mortality and Burn-in* [Online]. Available: http://www.weibull.com/hotwire/issue21/hottopics21.htm.

Appendix A

The categories of consequences and probability and risk matrix used in this thesis are based on the recommendation of Piet (2001).:

Risk matrix:

INCREASING PROBABILITY

	Potential Severity	People	Assets/ Production	Environment	Reputation	1 Never heard of in Industry	2 Has occurred in Industry	3 Has occurred in Company	4 Occurs several times a year	5 Occurs several times a year at	Action Priority Rating
INCREASING CONSEQUENCE	F	No injury	No damage	No effect	No impact	Low					4
	E	Slight Injury *(FAC, MTC)*	Slight Damage *(<$10,000 & no disruption to operation)*	Slight Effect *(within fence, no exceedance)*	Slight Impact *(public awareness)*						3
	D	Minor Injury *(LTI 4 days or less, RWC)*	Minor Damage *(<$100,000 & brief disruption)*	Minor Effect *(temporary contamination/ single exceedance)*	Limited Impact *(local public/ media)*		Medium				2
	C	Major Injury *(LTI, PPD > 4 days)*	Local Damage *(<$500,000 & partial shutdown)*	Local Effect *(recoverable environmental loss/repeated exceedance)*	Considerable Impact *(region/state public/media)*			High			0/1
	B	Single Fatality	Major Damage *(<$10,000,000 & partial operation loss)*	Major Effect *(severe damage recoverable /extended exceedance)*	National Impact *(extensive adverse media)*						
	A	Multiple Fatalities	Extensive Damage *(>$10,000,000 & substantial operation loss)*	Massive Effect *(widespread, chronic effects constant high exceedance)*	International Impact *(extensive adverse media)*			Intolerable			

Score for probability:

1 = never heard of industry

2 = has occurred in industry

3 = has occurred in CNOOC

4 = occurs several times a year in CNOOC

5 = occurs several times a year at the location

Consequences categories:

HARM TO PEOPLE

No.	Description
E	Slight injury or health effects (including first aid case and medical treatment case) - Not affecting work performance or causing disability
D	Minor injury or health effects (Lost Time Injury) - Affecting work performance, such as restriction to activities (Restricted Work Case) or a need to take a few days to fully recover (Lost Workday Case). Limited health effects that are reversible, eg. skin irritation, food poisoning
C	Major injury or health effects (including Permanent Partial Disability) – Affecting work performance in the longer term, such as a prolonged absence from work. Irreversible health damage without loss of life, eg. noise induced hearing loss, chronic back injuries
B (HPI)	Single fatality or permanent total disability - From an incident or occupational illness (poisoning, cancer)
A (HPI)	Multiple fatalities - From an incident or occupational illness (poisoning, cancer)

ASSET DAMAGE

No.	Description (100% costs, $US)
E	Slight damage - No disruption to operation (costs less than 10,000)
D	Minor damage - Brief disruption (costs less than 100,000)
C	Local damage - Partial shutdown (can be restarted but costs up to 500,000)
B (HPI)	Major damage - Partial operation loss (2 weeks shutdown costs up to 10,000,000)
A (HPI)	Extensive damage - Substantial or total loss of operation (costs in excess of 10,000,000).

No.	Description - COMPANY examples
E	Minor oil spill - (<20L inshore, <80L offshore) contained within facility boundary Non water based drilling fluid spill (<80L) Gas release (0.3-10t)
D	Small oil spill - (20-100L inshore, 80-200L offshore). Non water based drilling fluid spill (80 – 1,000L) No impact on sensitive environmental resources e.g. mangroves, corals, mud flats. Single accedences of oil in water max. discharge limit. Accedences of license conditions - oil in water, dark smoke, NOx, sulphinol. Unplanned gas release (10-100t).
C	Moderate oil spill - (100-1,000L inshore, 200-10,000L offshore); e.g. refueling incident. Non water based drilling fluid spill (1,000 – 10,000L) Minor/localised impact on sensitive environmental resources e.g. adjacent to OTP. Repeated accedence's of discharge limits. Unplanned gas release (100-1,000t).
B (HPI)	Large oil spill -(1,000-10,000L inshore, 10,000-100,000L offshore); e.g. loading hose, flow line failure, vessel grounding. Non water based drilling fluid spill (10,000 –100,000L) Regional impact on sensitive environmental resources e.g. National marine Park Extended accedence's of discharge limits. Unplanned gas release (>1,000t). Uncontrolled release of hazardous wastes
A (HPI)	Massive oil spill - (>10,000L inshore, >100,000L offshore); e.g. trunkline rupture, well blowout, tanker grounding. Non water based drilling fluid spill (>100,000L) Widespread impact of sensitive environmental resources.

IMPACT ON REPUTATION

No.	Description
E	Slight impact - Public awareness may exist, but there is no public concern
D	Limited impact - Some local public concern. Some local media and/or local political attention with potentially adverse aspects for company operations.
C	Considerable impact - Regional public concern. Extensive adverse attention in local media. Slight national media and/or local/regional political attention. Adverse stance of local government and/or action groups
B (HPI)	National impact - National public concern. Extensive adverse attention in the national media. Regional/national policies with potentially restrictive measures and/or impact on grant of licences. Mobilisation of action groups.
A (HPI)	International impact – International public attention. Extensive adverse attention in international media. National/International policies with potentially severe impact on access to new areas, grants of licences and/or tax legislation

ACTION PRIORITY RATING

0	Action items that reflect a level of risk exposure which is intolerable and for which no temporary risk mitigation measures are possible or appropriate or yet implemented. They are therefore of such a serious nature that immediate shutdown of the affected facility is required. Restart of that facility can only be taken once risk levels are reduced to an acceptable level and the appropriate authority to restart has been obtained.
1	Action items that reflect a level of risk exposure which is intolerable but it is possible or appropriate to take temporary compensatory actions that reduces the risk to tolerable levels while permanent remedial action is being implemented. Such measures are to be agreed to at the Business Unit Manager Level. The facility may then continue operation.
2	Action items that have potentially high consequences and could result in serious safety, health or environmental or other production critical situations. However, the likelihood, by virtue of other 'bow-tie' barriers, is such that the perceived risk within the time frame of the Action Item closeout is tolerable. Nevertheless, Category 2 items should not be outstanding for an extended length of time.
3	Action items that are either mandatory or have a CBR greater than 1.5. Mandatory in this case means items that are required by an external regulatory or statutory authority, are required by legislation, or have been directed internally by senior COMPANY Management.
4	Action items that have a cost benefit ratio (CBR) of less than 1.5 but greater than 1 or judgmentally appears to be worthwhile. Items in this category should be scheduled after all Category 0-3 items have been scheduled or, an opportunity exists to complete an item in conjunction with a higher category. Note: An action priority rating must be given for each incident or hazard. This rating must be entered in the priority column, on page two of the report form.