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Optimization of Maintenance Performance for Offshore Production Facilities

By

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Abstract

New technologies are becoming advanced and complex for offshore production facilities. However this advancement and complexity in technology creates a more complicated and time consuming forensic processes for finding causes of failure, or diagnostic processes to identify events that reduce performance. As a result, micro-sensors, efficient signaling and communication technologies for collecting data efficiently, advanced software tools (such as fuzzy logic, neural networks, and simulation based optimization) have been developed, in parallel, to manage such complex assets. Given the nature and scale of ongoing changes on complexities, there are emerging concerns that increasing complexities, ill-defined interfaces, unforeseen events can easily lead to serious performance failures and major risks.

To avoid such undesirable circumstances, 'just-in-time' measures of performance to ensure fully functional is absolutely necessary. The increasing trend in complexity creates a motivation to develop an integrated maintenance management framework to get real-time information to solve problems quickly and hence to increase functional performance (help the asset to perform its required function effectively and efficiently while safeguarding life and the environment). Establishing "just-in-time" maintenance and repairs based on true machine condition maximizes critical asset useful life and eliminates premature replacement of functional components.

This thesis focuses on developing an integrated maintenance management framework to establish 'just-in-time' maintenance and to ensure continuous improvements based on maintenance domain experts as well as operational and historic data. To do this, true degradation of components must be identified. True level of degradation often cannot be inferred by the mere trending of condition indicator's level (CBM), because condition indicator levels are modulated under the influence of the diverse operating context. Besides, the maintenance domain expert does not have a precise knowledge about the correlation of the diverse operating context and level of degradation for a given level of condition indicator on specific equipment. Efforts have been made in here to identify the true degradation pattern of a component by analyzing these vagueness and imprecise knowledge.

Key words: *effective and efficient maintenance strategy*, *'just-in-time' maintenance*, *condition based maintenance, P-F interval.*

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I finally would want to dedicate this thesis to my wife, Tsigereda Elias Kindaya, for her support morally and spiritually. I love you!

Contents

Abbreviations

CBA	Cost benefit analysis
CM	corrective maintenance
DNV	Det Norske Veritas
ESD	emergency shutdown
FIS	fuzzy inference system
FMECA	failure mode and effect and criticality analysis
FTA	fault tree analysis
HAZID	hazard identification
HAZOP	hazard and operability study
HSE	health, safety and environment
GMC	generic maintenance concept
MF	main function
NCS	Norwegian Continental Shelf
NPV	net present value
NPD	Norwegian Petroleum Directorate
PM	Preventive maintenance
PSA	petroleum safety authority Norway
OEM	original equipment manufacturer
OLF	The Norwegian Oil Industry Association
QRA	quantitative risk analysis
RAC	risk acceptance criteria
RBI	risk based inspection
RCFA	root cause failure analysis
RCM	reliability centre maintenance
STEP	sequential time event plotting

Table of Contents

List of Tables:

List of Figures:

CHAPTER 1

Project Description and Formulation

1.1 Introduction and Background

Wear and tear is an unavoidable part of normal and aging of equipment and components. Besides design weakness and operational environment (human errors, unskilled personnel, over load etc) worsens the situation. Maintenance is therefore of key importance to maintain availability and functional performance.

The maintenance of industrial assets has continued to develop and has moved from the former “fault repair” mentality to “fault prevention” strategy i.e. from reactive to proactive. Over the last few years, maintenance practices have significantly changed, from time/use based to condition based, relying on monitoring the condition of the equipment to determine the most cost effective frequency.

By continuous monitoring the integrity of offshore production platform, the condition and performance of the industrial asset can be controlled leading to maximum production regularity at ‘minimum’ maintenance cost. Increasingly important, is the enforcement of HSE as set in company goals and national and international regulations. This means “optimization of maintenance” does not refer to “cutting down maintenance costs to save money”; it is rather means balancing between fulfilling HSE requirements and maximizing production regularity.

Development of integrated frame work for effective and efficient maintenance strategies (reactive/proactive, need based/opportunity based, failure/time/condition based, offline/online, RCM, RBI etc) involve the determination of what needs to be repaired when it needs to be repaired as well as prioritizing maintenance for each component/equipment in a complex, advanced and integrated production facilities.

Maintenance programs for offshore installations are developed based on preventive maintenance routines recommended by the OEM manufacturers, using the experience of operators and by identification of best practices. In most of the cases the preventive maintenance schedules are either calendar based or based on the machine’s run time. The method of determining the maintenance activities in this case may not be optimal. These days energy companies are under increasing pressure to reduce overall life cycle costs as well as maximize profit generated over time(i.e. maximize ROI); meet performance goals with respect to functional capability, capacity, quality and availability; comply with standards, regulatory requirements, and enhance the use of their organizational assets(to operate nearly at 100% asset utilization).

Offshore production systems are becoming more advanced and complex by providing better functional performance than before. These high performance production facilities represent high capital investment, new levels of complexity, shortage of experienced technical personnel and spare components. In addition to this, factors such as stringent regulatory requirements, and the ability to predict and prevent failures and to make informed decisions based on consolidated equipment health and performance data becomes critical. However such advanced, complex and integrated systems result in complex failure modes, which are more difficult to diagnose and repair, and becoming more complex to operate and maintain.

In parallel With the development of new advanced and complex for offshore production facilities, micro-sensors, efficient signaling and communication technologies for collecting data efficiently, software tools (such as fuzzy logic, neural networks, and simulation based optimization) have been developed to manage such complex assets. However, this complexity creates a more complicated and time consuming forensic processes for finding causes of failure, or diagnostic processes to identify events that reduce performance. Given the nature and scale of ongoing changes on complexities, there are emerging concerns that increasing complexities, ill-defined interfaces, unforeseen events can easily lead to serious performance failures and major risks.

The challenges remain to address includes:

- Optimizing performance, integrity and safety of critical equipments
- To identify influence of failed components on other components in the system as the interdependency is complex.
- Fully utilization of an asset i.e. nearly 100% availability(uptime/(uptime +downtime))
- Financial management -risk, cost and benefit (ROI). Cost, the level of risk and the benefits from risk control are closely linked, and hence cannot be evaluated separately.
- Diminishing and limited personnel expertise in a demand growth environment

Key question for researchers to address such challenges should be “What is the optimum preventive maintenance time interval?” Too short intervals would lead to unnecessary prevention costs; no preventive maintenance would lead to breakdowns, which may affect production, and inflict money losses on the firm as discussed previously; and too long intervals would result in both inconveniences, as they will involve preventive maintenance actions and would lead to uncontrolled breakdowns. A comprehensive overview helps to overcome unforeseen events and incidents that might lead to catastrophe.

Optimization of maintenance strategies to addresses such complex operating context is critical. There is a room for maximizing asset performance, prolonging effective operating time, minimizing repair costs and minimizing consequences of unplanned downtime, by maximizing the interval between scheduled maintenance services according to the equipment’s real condition and by eliminating the reoccurrence of the root cause of failures. Determinations of actual mean time to failures (MTTF) or loss of functionality (partial/full) of critical components, combines real time data (or near real time data) with operational and environmental factors, to define the true condition. Including RCM analysis, FTA, FMECA, RBI, and RCFA etc. will provide an understanding of failure, incipient failure, catastrophic failure and the underlying root causes. For this, relevant data indicators and design of instrumentation to collect data is critical. From data, algorisms can be developed to build equipment profiles, define normalcy, interpret conditions of interest and provide an overall understanding of the health or condition of the critical equipment and hence failures can be prevented or warned about in advance (detecting potential failures).

In fact, even though some degraded components are replaced during PM activities, effects of the failed components on other parts of the system may go unnoticed and worsen the condition of the relative parts, and the system as a whole. Integrated approach to maintenance activities help to see the unnoticed incidents that might lead to catastrophe. Establishing “just-in-time” maintenance and repairs based on true machine condition maximizes critical asset useful life and eliminates premature replacement of functional components.

A set of KPIs should be defined for monitoring and follow up of functional performance. The advances in sensor as well as inter communication technology (ICT) have enabled availability of useful information related to equipment condition and functional performance. This information provides some opportunities to diagnose and prognose critical components/equipments. Usually, there is no shortage of data and information. However, utilization and integration of realistic time data and to translate the data in to information and from information to knowledge, so as to make right decisions to choose and prioritize maintenance activities, remains as a challenge.

Furthermore, managing functionality and technical performance of equipment connected to the safety functions is a key challenge faced by the operator companies on offshore Oil & Gas industries (e.g. Norwegian Continental Shelf,NCS). The regulatory requirements are stringent to maintain and improve the technical condition of safety critical equipment. Any effort to reduce the corrective maintenance and/or optimize the maintenance programs will contribute greatly in the offshore O&G industry.

On the NCS the maintenance programs are developed and maintenance activities prioritized based on the coarse consequence classification of equipments/subsystems (NORSOK Z008 rev. 2). This approach does not take into account individual failure modes of the equipment. To achieve the desire of achieving highest production regularity and ‘zero damages’ to HSE due to equipment failures, it will be necessary to perform the maintenance activities that prevent unexpected equipment failures. Furthermore, the frequency of conducting maintenance activities has to be linked to realistic mean time between failures. Moreover, functionality and true performance degradation of the equipment has to be monitored in a manner that sufficient time is available for the maintenance managers to plan and organize selected maintenance activity execution, (Panesar et al., 2008), at the equipment level to develop optimized maintenance strategies.

1.2 Maintenance Management Process

The term maintenance management is defined in EN3306 as *"all activities of management that determine objectives, strategies, and the responsibilities and implement them by means such as maintenance planning, maintenance control and supervision, improvement of methods in the organization including economical aspects."* The basic maintenance model, based on PSA, 1998, proposed as industry best practice is shown in Appendix Figure A-1.

The basic Maintenance management loop has been illustrated as a superior process in the offshore O&G production facilities where products are produced with low HSE risks and high production regularity. On an overall level there are input factors called resources, processes called management of work processes and outputs named as results. This process model served to illustrate the dependencies and interactions among diverse set of knowledge areas. In this frame work, outputs from one management process become inputs to another in a subsequent hierarchy. We can summarize the loop as:

1. Define resource requirements(organization, material , documentation and IT)
2. Define corporate goals and objectives clearly
3. Develop 'just-in-time' maintenance program to achieve those goals and objectives
4. Plan efficient maintenance program
5. Execute the maintenance
6. Asses the technical condition (e.g. using condition monitoring techniques)
7. Report technical condition results
8. Analyze the results
9. Define improvement measurements required to avoid reoccurrences, after which the process returns to step 1 to complete the loop.

1.3 Problem Formulation

In practice, the choice of the optimum maintenance strategy is not a simple task. Implementation of such philosophy for complex installations is a difficult and a complex task. Key question to address such challenges should be "What is the optimum preventive maintenance time interval?"

This thesis focuses on developing an integrated maintenance management framework (Figure 1) to establish 'just sufficient' &'just-in-time' maintenance and to ensure continuous improvements based on maintenance domain experts as well as operational and historic data.

To establish 'just-in-time' maintenance true degradation of components must be identified. True level of degradation often cannot be inferred by the mere trending of condition indicator's level (CBM), because condition indicator levels are modulated under the influence of the diverse operating context (normal, marginal, hostile, operating complexity, etc). Besides, the maintenance domain expert does not have a precise knowledge about the correlation of the diverse operating context and level of degradation for a given level of condition indicator on specific equipment. Advanced software tools, like fuzzy logic, considers these vagueness and imprecise knowledge (better than the conventional statistical modeling) to quantify imprecise and uncertain information.

1.4 Main Objectives and Sub-objectives

1.4.1 Main Objectives

- To develop a methodology to optimize maintenance performance

1.4.2 Sub-objectives

1) To develop effective and efficient maintenance strategy

2) To identify true component degradation pattern

3) To explore how to enhance continues analysis and improvements

1.5 Project Activities

1) Develop integrated maintenance management framework. Develop a methodology that establishes a clear link between the identified failure modes and maintenance activities. Evaluate generic failure modes and failure frequencies of the various equipment groups so as to develop the basis for realistic consequence classification.

2) Assess P-F curves for major equipment groups, identify failure mechanisms and develop the condition-monitoring needs linked to failure mechanisms to find true degradation.

3) Propose an analyses model that integrates historical maintenance data as well as operational data and provides basis for continuous improvement of maintenance programs. Improved root cause analysis of failures, event analysis and trends should be clearly linked.

1.6 Research Methodology

An integrated maintenance management framework has been built to establish 'just-in-time' maintenance activities to improve potential maintenance performance. The factors contributing to improve system performance (HSE, productivity, economy) have been discussed using HTO integration. The uncertainty/vagueness related to true degradation of components is modeled using expert synthesis of information. To reveal the underlying physical, human, machine or latent causes for unwanted event, improved Root Cause Failure Analysis (RCFA) has been used. By learning from these underlying causes, proper actions can be taken at the 'right time' and the right measures implemented in order to prevent future reoccurrences of unwanted related events (continues improvements).

1.7 Research Limitations

The thesis is based on advanced and complex offshore Oil and Gas production facilitates. The study focuses on the basic maintenance management loop developed by PSA in 1998 to improve the potential maintenance performance. The developed framework is based on basic concepts, and hence efficiency might be limited to some extent. Full implementation is not possible because the cost-benefit analysis is not done due to limited data, tools and time frame. Cost-benefit analysis is out of scope at this stage.

CHAPTER 2

Integrated Maintenance Management

2.1 Introduction

Integrating the diverse knowledge across the integrated maintenance management frame work increases flexibility and robustness. This integrated framework helps to get real time information, which enables to quickly identify events (including hidden events) that lead to functional failures. Updates in knowledge can be accommodated within the frame work by integrating personnel, technology and the organization. Leadership capabilities should be built in all levels to accommodate the updates.

It is believed that by implementing Expert System tools and methods, such as Fuzzy Logic can significantly improve maintenance performance by identifying the true degradation of components and performing 'just-in-time' maintenance and hence saving the system from unwanted downtime. The improved RCFA is also another input to the integrated maintenance management model to create improvement opportunities for the future.

In the following chapters, detail descriptions and discussions of the different elements in the maintenance management process model is given. Those elements where risk assessment, use of consequence classification and probability for failure assessment are important and are further described in the following sections.

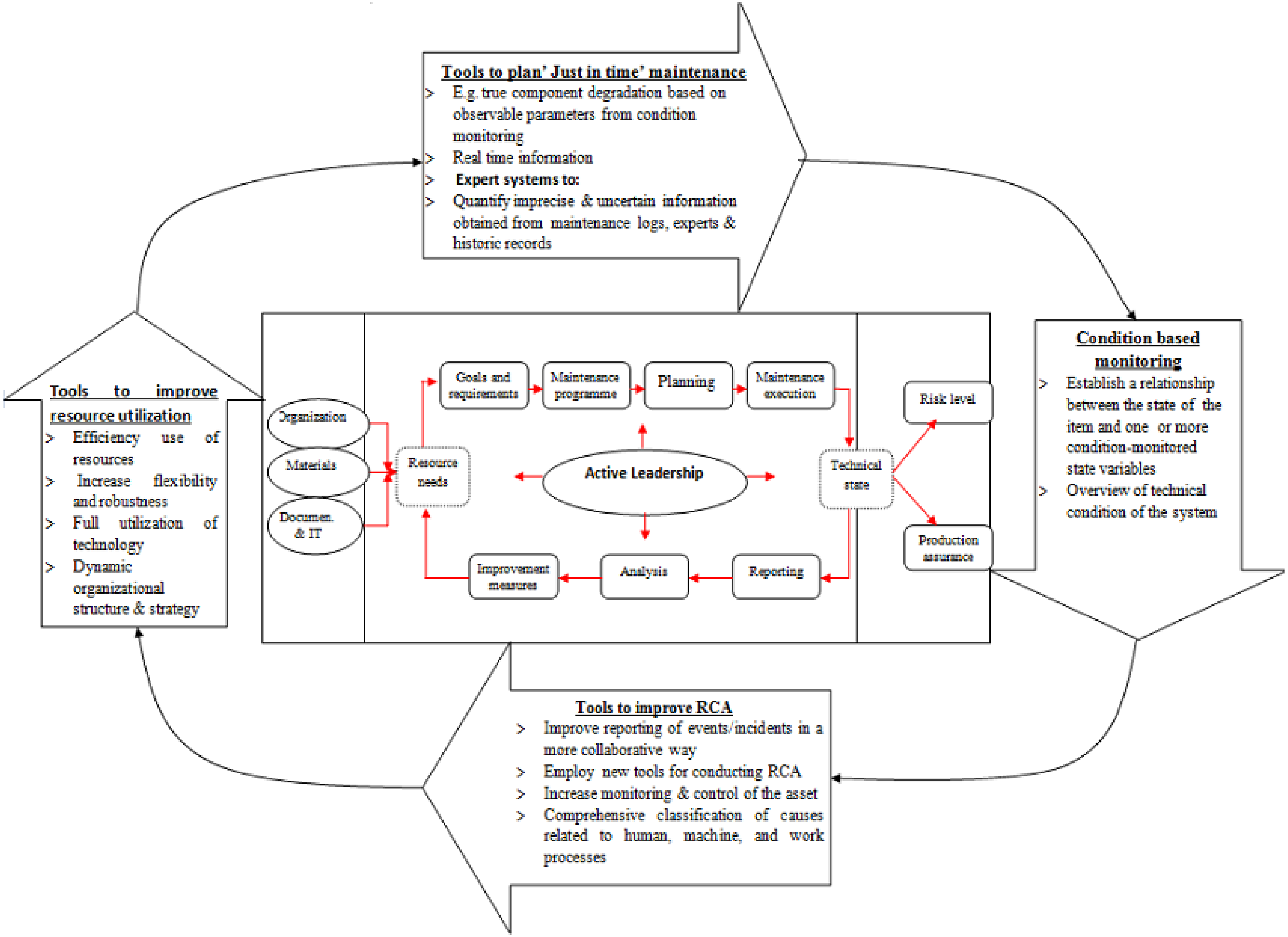

Figure 1: integrated maintenance management process model

2.1.1 Maintenance Inputs/Resources

To develop efficient and effective integrated maintenance management process, goals have to be established clearly that commit the organization to realizable level of performance (in long or short period). In general the goals of maintenance management focuses on ambition level of;

- Risk, production and cost
- Regulatory requirements
- Technical condition of the facility in particular the performance level of safety systems and critical processes
- Improvement of overall maintenance process
- Operational efficiency

To meet these organizational goals optimally, effective use of maintenance resources (organization, materials, documentation and IT systems) is a necessity. For this, there should be a comprehensive integrated link among these elements. Maintenance organization refers to setting up the organizational structure, strategy and human power for organizing the work; materials refer to issues regarding purchase, storage and usage of the spare parts; and documentation and IT systems refer to collecting, processing, storing and disseminating data in the form of information needed to carry out the functions of maintenance management.

For example, a Computer Maintenance Management system (CMMS) helps to maintain a computer database of information about an organization's maintenance operations. This information is intended to help maintenance personnel do their jobs more effectively & effectively.

CMMS facilitates fast access to vital information, quick handling and storage of large amount of data and information. It is a tool for maintenance planning and control which helps to reduce lead time problems associated with ordering of parts in addition to reducing losses associated with downtimes for inspections and repairs. CMMS provides 'just-in-time' maintenance program by monitoring the equipment failure rates and histories thereby allowing for effectiveness in coordination of labour and spare parts needed for maintenance. This has the effect of minimizing maintenance costs (improved cost control) and improving maintenance efficiency.

As maintenance management is a multi-faceted discipline which includes maintenance engineers, accountants, inventory managers, human resource personnel and so on, integrating the diverse knowledge across the frame work increases flexibility and robustness. This integrated framework helps to get real time information, which enables to quickly identify events (including hidden events) that lead to functional failures. Updates in knowledge can be accommodated within the frame work by integrating personnel, technology and the organization. (I explain in detail about human-technology-organization in section 3)

A typical CMMS package deals with some or all of the following modules:

- Equipment identification and bill of materials;
- Work order management: Manages the opening of a new order, its cost estimate and its development.
- Planning and scheduling: Deals with time for various tasks and resources needed.
- Deals with the material, time and cost requirements of PM.
- Monitors inventory in store and in use.
- Provides a record of special events in the equipment life cycle and other events like repairs, downtimes, overhauls, labor and cost.

Keeps record of individuals, their skills, certifications to cater for the labor requirements of maintenance activities. (Gardiner, 2005)

2.1.2 Maintenance Management Process: Building Leadership Capability

People are the most important assets of any organization. Most maintenance companies focus on improving process and Technology, yet they lack the tools to efficiently identify, integrate, and engage the unique talents of their people. Competent (with knowledge, skills and attributes) leaders should define roles and responsibilities and within the area of maintenance. Leadership capabilities should be built at all levels of the maintenance department. They should possess knowledge related to risk based maintenance management and make sure that the main work flow is followed.

A set of KPI's should be defined for monitoring and follow up performance, and act up on deviations from set corporate goals and objectives. Besides the leaders should plan and institute audits of the organization, suppliers and contractors. Integrating from top to lower level improves to get real time information to solve problems quickly. Maintenance strategies for offshore facilities are defined to meet the clearly defined set of goals. (See ISO14224 for examples of KPI). The most common KPI's relevant for offshore maintenance strategies, for example, is discussed below.

- Technical related maintenance KPI's such as:
  - Time used on PM/total maintenance time
  - Time used on unplanned CM/total maintenance time
  - Total planned maintenance time/total maintenance time
  - Waiting time for spare parts/total maintenance time
  - Production down time/total production time

- KPI's comparing actual executed work orders against planned work orders (Backlog). This is a good indicator of maintenance work efficiency, but does not give indication of how effectively the work is carried out in planning, execution and follow-up. Deviation in measured performance may be due to any of the following factors:

> Poor planning, wrong work orders
> Lack of efficiency in execution of work orders
> Lack of human power
> Lack of spare parts
> Too much corrective work in the period and insufficient staff to do the PM works.

- Criticality safety compliance KPI's. This gives a confirmation whether the required SIL (safety integrity level) is achieved. This KPI implicitly assumes that the planned tests are an accurate of system performance and reliability without considering the characteristics of the system measured or the risk failure. the true performance should include measurement of :
  > maintenance performance
  > Management performance

- Safety system performance KPI's: these KPIs relate to the specific HSE critical equipment and systems and for which performance standards be defined. The KPIs can be managed as follows:
  > Measurement per safety function group
  > Count of number test failures per HSE equipment
  > Remedial actions are assessed based on system performance.
  > Failure statistics for all safety systems must be compiled on a yearly basis to assess development over time, identify bad factors, etc.

- Organizational maintenance KPI's:
  > Number of internal maintenance personnel/total internal employees
  > Planned and scheduled maintenance man hours /total maintenance man hours available
  > Internal man-hrs used for continuous improvement/total internal maintenance personnel man-hrs.
  > Number of injuries to maintenance personnel/total maintenance personnel etc.

- Economical maintenance KPIs:
  > (Input maintenance cost) total maintenance cost/output maintenance
  > Availability related to maintenance/total maintenance cost
  > Total maintenance cost/asset replacement values etc.

2.1.3 Output: Technical State (risk level and production regularity)

The result of 'just-in-time' maintenance action will give us an improved technical condition of the system. (i.e. performance and risk level should be in acceptable limit and regularity). The performance of the output measured uses as a feedback to the maintenance loop and update the process accordingly. The risk level is a result of the

O&M work done to the asset. Risk can be measured as HSE performance, barrier reliability status or related indicators. The plant's production regularity is a result of the activities implemented to achieve and maintain a performance that is at its optimum in terms of the overall economy and at the same time consistent with applicable framework conditions. An indicator of this would be the achieved production availability.

CHAPTER 3

Maintenance Strategy Development

3.1 Introduction

Defining maintenance goals and formulating strategies is an important aspect of an integrated maintenance management within a company. Pinjala and Pintelon (2004) defined maintenance strategy as a series of unified and integrated pattern of decisions made in four structural and six infrastructure decision elements to achieve maintenance goals.

According to Pinjala and Pintelon (2004), the four decision elements (maintenance capacity, maintenance facilities, maintenance technology, and vertical integration) can be viewed as the maintenance resources. They are termed as structural, because decisions made in those areas are generally assumed to be fixed. For instance, a company outsourcing its entire maintenance activities cannot revert immediately to in-house maintenance. The majority of the maintenance budget is consumed by these structural elements.

The six infrastructure elements (maintenance organization; maintenance policy and concepts; maintenance planning and control systems; human resources; maintenance modifications and maintenance performance measurement and reward systems) can be viewed as maintenance management elements.

These structural and infrastructure elements are interrelated. For instance, effective utilization of maintenance resources depends upon the decisions taken in the infrastructure elements (Panesar and Markeset, 2006). Over a period of time decisions must be made in all of these maintenance strategy elements. The way these elements are managed or utilized can have a major impact on the maintenance function's ability to implement and support the company's manufacturing and business strategies. Companies mainly differ in their maintenance strategies by the combination of decisions taken in these elements. Several operating aspects and business requirements influence these decisions.

The effectiveness of maintenance can be known only if one is able to identify and evaluate a given maintenance strategy. An effective maintenance strategy is one that fits the needs of the industry. The process of formulating an effective maintenance strategy for a company can be a difficult task of quite daunting complexity. Furthermore, evaluating such a strategy can be much more complex. For example, performing maintenance activities in the offshore oil and gas production facilities is quite challenging and highly risky (due to adverse operating environment).

Even it becomes more difficult, expensive and challenging when it comes to the Norwegian Continental Shelf Oil and Gas industry, because many of the fields are located in a deep, remote as well as harsh environments(e.g. Arctic zone). Thus there is a requirement of increased focus on developing an integrated maintenance approach for effective and efficient maintenance strategies that create value by improving the safety, reliability, availability, technical integrity, regularity, quality and functional performance of the production facilities.

3.2 Issues for Developing an Integrated Maintenance Management Framework

The formulation and establishment of an integrated frame work for maintenance strategy requires understanding the operational and maintenance objectives; the technical and functional system characteristics; the administrative and organizational issues; the system functions and performance targets; the internal and external resources; the geographical location; statuary requirements; as well as the support services(see as an example in Table 1). Therefore, one has to examine the types of resources (organization and level of competence (knowledge, skills, attributes, motivation)) available.

Table 1: Issues to be considered in the development of an integrated frame work for a maintenance strategy (based on Markeset, 2003)

Types of issues	Examples
Operational objectives	Customer needs, wants and preferences, production objectives, production schedules, plant operating pattern, , uptime, availability, etc
Maintenance objectives	Cost and performance optimization, regulatory requirements, etc
Technical and functional system characteristics	Reliability, maintainability, supportability, availability, etc.
Administration and organization	Maintenance and operational organization, shift and personnel rotation, planning and scheduling, reporting and continuous improvements, etc
Statutory requirements	HSE, standards and regulations
Geographical location	Infrastructure, culture, political stability, weather conditions, etc
Support services	Training, modifications, upgrading, warranty, expert assistance, diagnostics, remote support, etc
Internal resources	Competence level, facilities, tools, and methods, labor costs, etc
External resources	Service providers competence and capabilities, availability of service provider, support logistics, support quality, etc.

In Oil & Gas industry corporate goals of ensuring the highest possible HSE level, highest possible production regularity, and highest possible cost effectiveness are the three main issues. A comprehensive integrated maintenance program should contribute to achieving these goals. Achieving the highest HSE level means that the production facilities are operated and maintained in such a manner that HSE risks are ‘eliminated’ to zero level.

Optimizing production regularity means that production facilities are operated and maintained in such a manner that production up times are optimized and production down times minimized (Markeset, 2003). This means to optimize production regularity, to ensure optimum capacity utilization, to minimized unplanned shut downs, to minimize maintenance interventions and to minimize unplanned maintenance works.

Achieving cost effectiveness means that the resources should be utilized in the best possible manner and equipment failures that could cause productions losses or could result in high repair/replacement costs should be prevented or reduced to an acceptable level(see also NORSOK ZOO8 rev. 2; NORSOK ZO16). HSE, production regularity and cost effectiveness therefore, can be considered as the three main concerns for development of efficient and effective maintenance strategy.

An important matter to realize is that these three important issues are interrelated. That means no change can be made without affecting the other two issues. For instance increasing production up times may affect HSE risk level and/or maintenance related cost. Furthermore, one needs to realize that to optimize maintenance performance, one need to optimize and integrate the technological, organizational and the human performance to quickly identify the underlying root cause for the failures (i.e. human error, organizational or technical error). Therefore these (also depicted in Figure 2) are also the key issues to be considered when one needs to develop efficient and effective maintenance strategies. Integrating personnel, technology and organization optimizes our decision capabilities, and hence improves maintenance performance.

3.3 Human-Technology -Organization (HTO) Integration

The aim of HTO integration is to increase maintenance performance (innovative performance, efficiency, effectiveness, employee satisfaction etc) and to get real time information to quickly identify the underlying cause for failures to solve problems. Human-technology-organization integrated approach gives a chance where to create a better value for the organization. The objective is to create a work situation which contributes as much as possible to realizing efficient and safe operations, and which takes into account people's capabilities, limitations and needs. Even the most sophisticated technologies, when designed and implemented without proper consideration of user needs and requirements, may not achieve optimal maintenance performance.

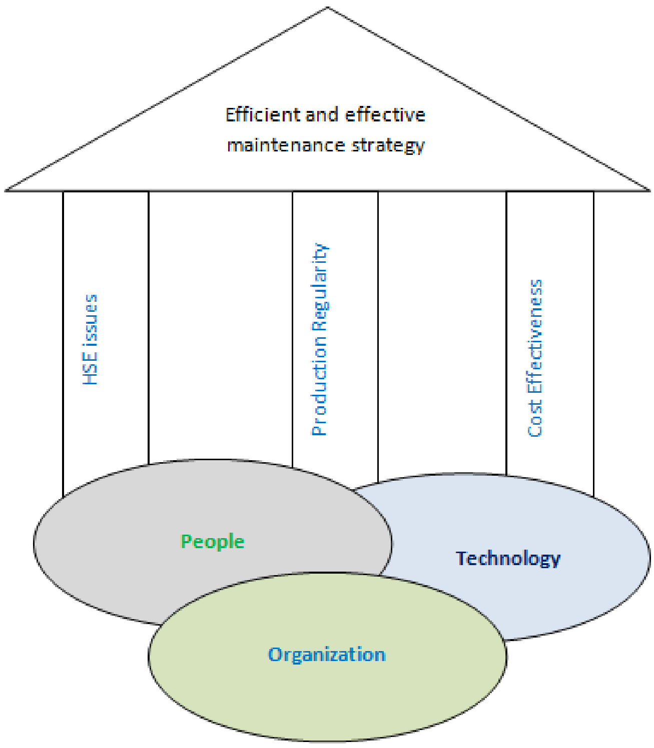

Figure 2: Integration of human-technology-organization to improve maintenance performance

Integrated socio-technical consideration ensures full functionality and fail-safe system. Comprehensive overview enables to overcome unforeseen events that might lead to total collapse of the complex production facility (Liyanage and Eirik, 2010). This integration will specially help to manage complex and high risk assets like O&G industries. Over the last couple of years, several serious incidents have highlighted the connections between factors which are important to both a good working environment and operational safety (PSA, 2010). Increased knowledge of the interaction among technical, organizational elements and the people using these is, therefore, critical in understanding the underlying causes of incidents (i.e. human, technical or organizational error).

Human factors (HFs) knowledge provides a basis for deeper understanding of what causes human errors. However, in a statistical sense, human errors are predictable, and may also be caused by a number of factors outside the control of the individual. Focusing on human errors gives an opportunity to develop and improve system performances. For instance, we can make a system to be able to handle errors by taking human capabilities and limitations into account when designing equipment and technology. Therefore, it is critical to maintain an inclusive focus on factors which influence human behavior.

In this HTO integration approach to facilitate the avoidance of human error, the most important aspect is to keep in mind that people are rational, dynamic, solve problems, make systems which are more robust and flexible and that they are irreplaceable in many systems. If we do this, we will contribute to creating the best environment for improving the potential maintenance performance.

In modification projects, for instance, which involve installation of new equipment, it is important to have a clear understanding of the entire work situation, and consider the combined mass of equipment as one system to create conducive environment for maintenance activities. Complex and safety-critical activities will always depend on human actions, which are the precondition for better decision makings, safe operations and handling of unplanned failures. Even though people may make errors, the people in the system are more advantageous, as humans are rational and adaptable.

The competence (knowledge, skill, attributes, motivation, etc) of managers and employees, as well as their ability to improve, are thus critical in re-establishing a safe condition following an unexpected course of events (maintenance activities). There is, therefore, a clear connection between factors which are important for both a good working environment and maintenance operational safety. Increasing knowledge of the interaction among human, technology and organization (HTO) - is therefore essential to understanding the underlying causes of incidents, and for optimized maintenance in the integrated maintenance management.

The biggest challenge in adoption a new technology is the mindset of managers and their attitude. Technology is viewed as physical asset (mechanistic dimension, while disregarding or attempting to eliminate the human side. In this view, it is to reduce reliance on human inputs (both the quantity of labor and variance (errors)). Due to this sophistication in maintenance technology appears to be under-utilized.

Organizational change to keep a pace with the technological change is another challenge. The current operational setting and functional characteristics are still not fully fail-safe assured nor perfect in all senses. It obviously has brought a number of issues to be seriously considered further, for example, new forms of partnerships for cooperation, shared responsibilities and roles, contract redesign, risk-gain sharing schemas, security and reliability of infrastructures, etc., that are important to ensure fully-functional fail-safe activities.

The biggest concern therefore is that the accelerated change triggered by the miracle of the technology and the success of technology implementation efforts may easily undermine the hidden problems, where ill-defined interfaces and increasing complexities of systems and data solutions can lead to unforeseen events which lead to high consequences. It implies that complex interfaces of the emerging socio-technical system need serious considerations to avoid maintenance hazardous incidents with heavy losses.

The underlying issue here is that the current development trends, which have substantial faith on pure technological solutions (technical dimension of technology), can easily over calculate human and organizational capacities and limitations.

In fact in most cases human and organizational aspects are seen largely deviated from main-stream change and thus the pace of development of sub disciplines take place at different rates and scales. Since this setting can directly contribute to various levels and forms of complexities within an integrated maintenance environment, the E&P industry, for example, has begun to look relatively more seriously on a development path that will contribute to establish a more harmonized socio-technical setting (Liyanage and Eirik, 2010). Therefore human should be viewed as central part of the maintenance management system. Human factors consideration should be integrated throughout the life cycle of maintenance management system development.

By specifying and designing the system to accommodate human capabilities and limitations, we can improve maintenance performance.

The emerging socio-technical-organizational system in the Oil and Gas industry, as a consequence of systematic growth towards integrated maintenance approach, is in fact seen very complex. It involves different levels in the socio-political hierarchy, ranging from policy levels to more maintenance operational levels. It also involves different maintenance organizations that need to play active roles in implementation of techno-managerial solutions (e.g. technology experts, maintenance service providers, asset operators, service providers, etc.) (Liyanage and Eirik, 2010). The nature of vertical and/or horizontal interactivity between those different sources is a defining factor of the future of integrated maintenance operations.

Despite the obvious complexity of the emerging setting, there still is an absence of a comprehensive overview and a deeper insight into the sensitive interfaces that is critical to mitigate operational risk. Liyanage and Eirik (2010) argue that the very socio-political level acts, rules, regulations, and guidelines represent important components to establish a well-defined top-down interface.

Even though there is a vacuum in that respect between the policy-making and operational levels of the emerging system, the change processes at the operational level takes place regardless. Systematic integration of human, technology, organizations, and work processes are the basis to improve/optimize maintenance activities. In fact the effects of such explicit or implicit integration is very synergistic, and has begun to place numerous demands on the need for more clear guidelines, procedures, recommendations, references etc. to help reducing the operational risk exposure.

3.4 Development Process of Effective and Efficient Maintenance Strategy

By integrating the diverse knowledge areas and different issues, an effective and efficient maintenance strategy can be developed. Figure 3 illustrates a process for maintenance strategy development (Panesar et al., 2008). According to Panesar et al (2008) two engineering companies follow this process when developing maintenance strategy for O&G operator companies active on the Norwegian Continental Shelf. In addition to that different NORSOK standards are used. Such as Z008 rev. 2-Critacallity Analysis for Maintenance Purposes, Z013-Risks and Emergency Preparedness Analysis, Z016-Regularity Maintenance and Reliability Technology, Z002-Coding System and DNV RP G-101-Risk Based Inspection, etc. both the engineering companies extract production facilities equipment data from CMMS of the operator companies.

The process starts with extensive collecting data, information and documentation from asset maintenance logs, history records, and experts about offshore productions facilities and then followed by developing technical and functional hierarchy.

Criticality analysis (also known as Consequence classification) is then done with respect to overall company requirements (HSE, production regularity and economics consequences) (Panesar et al, 2008). The consequence classification is done to set up priority of maintenance activities while developing ‘just sufficient’ and ‘just-in-time’ maintenance program, to specify common spare part strategy for equipment of equal importance, to decide the extent and quality of technical documentation as well as to decide the priority of corrective maintenance activities .

Here the uncertainty with respect to prioritize the maintenance activity is improved my increasing our knowledge to understand the interaction among the technical, organizational and the people. This helps to quickly look the underlying causes for incidents (human error, organizational or technical) and improve our decision making to make ‘just-in-time’ maintenance. This is done by integrating human-technology-organization.

The consequence classification is done based on analysis of functional failure consequences. Very high consequence requires a RCM approach or redesign to avoid failure. Safety systems are also redesigned if failures are classified as highly critical. Failures of sub-systems which have less serious failure consequences are classified in the low criticality category. For these systems one defines planned corrective or first line maintenance activities.

For systems in which failures have medium or high consequences one first screens and then after analyses using for example FMECA, or fuzzy logic, methodology to identify failure modes, failure effect, potential mitigating activities etc (Panesar et al, 2008). In chapter 4, I try to show, with an example, the advantage of fuzzy logic to improve the traditional FMECA methodology to prioritize maintenance activities in a better way. Discussion of main parts of the process model for the development of efficient & effective maintenance strategy is made in the following sections.

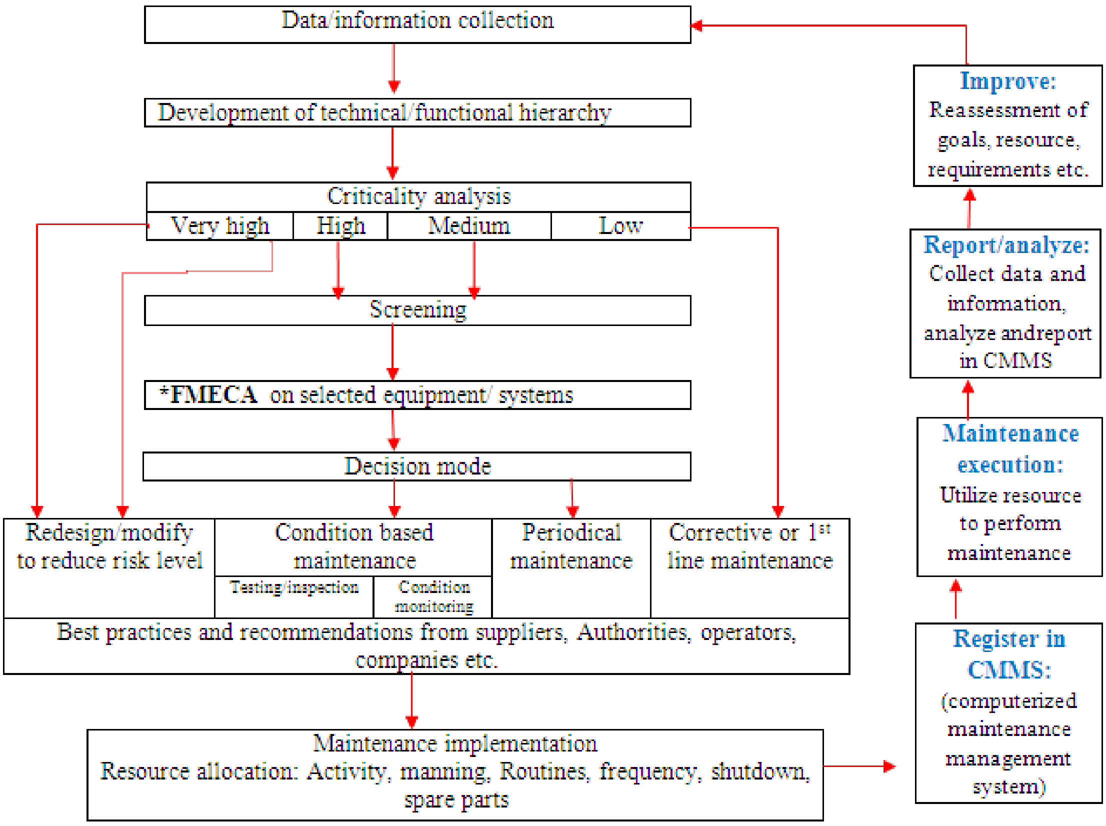

Figure 3: maintenance strategy development process (adapted from Kumar and Markeset, 2005)

**: the shortcoming of FMEA [based on RPN analysis] is that various sets of failure Occurrence probability [Pf,], severity [S] and detestability [Pd] may produce an identical value, however, the risk implication may be totally different which may result in high-risk events may go unnoticed. The other drawback is that it neglects the relative importance among Pf, S and Pd. To address these shortcomings related to traditional FMEA, tools such as a fuzzy logic theory, with gearbox as an example is provided in chap. 4 to prioritize the failure causes.*

3.4.1 Technical and Functional Hierarchy to Develop an Efficient and Effective Maintenance Strategy

To develop an efficient and effective maintenance strategy, it is important to develop a functional and technical hierarchy for each sub-system/component. NORSOK Z008 & Z0016 recommend that the complex and advanced production facilities can be divided in to technical and functional hierarchy for conducting maintenance analysis. In this section a detail description (using as an example) will be given to show the technical hierarchy and how this is connected to the functional hierarchy which is used for consequence classification. The technical hierarchy is established at an early phase to give an overview of all the tags/equipments and how they are related.

The technical hierarchy describes the technical structure of the installation. The hierarchy provides an overview of equipment units that belong together technically, and shows the physical relationship between main equipment, instruments, valves, etc. for example, a lube oil pump will be placed under lube oil tank and the motor is placed under the pump. Other technically connected equipment, for example heating element and filter are placed at the same level as the pump or under a corresponding package tag.

The functional hierarchy is a logical diagram linking all the complex production facility functions noted as main functions (MF) and sub functions. Each system is split into main functions, for example power generation, heat exchange, pumping etc. the main functions are split in to sub-functions based on the function performed by each component. At the component level the function could be process shutdown, equipment shutdown, indication, alarm, etc, the components, based on their functional hierarchy, are placed on various hierarchal levels.

The level on which the maintenance objects are established is governed by practical execution and the individual need to monitor and control the different maintenance programs. For corrective maintenance where the work orders can be assigned to any tagged equipment, the cost will be traceable to a lower level, but even this costing should be possible to summarize to the same level as for the maintenance objects used for the preventive maintenance programs.

This information is a part of the data needed to perform an evaluation and optimization of the maintenance strategy. If the data is linked to the lowest level, the hierarchy will make it possible to summarize this information to the appropriate level, which could be the maintenance object or MF as shown in Figure 4.

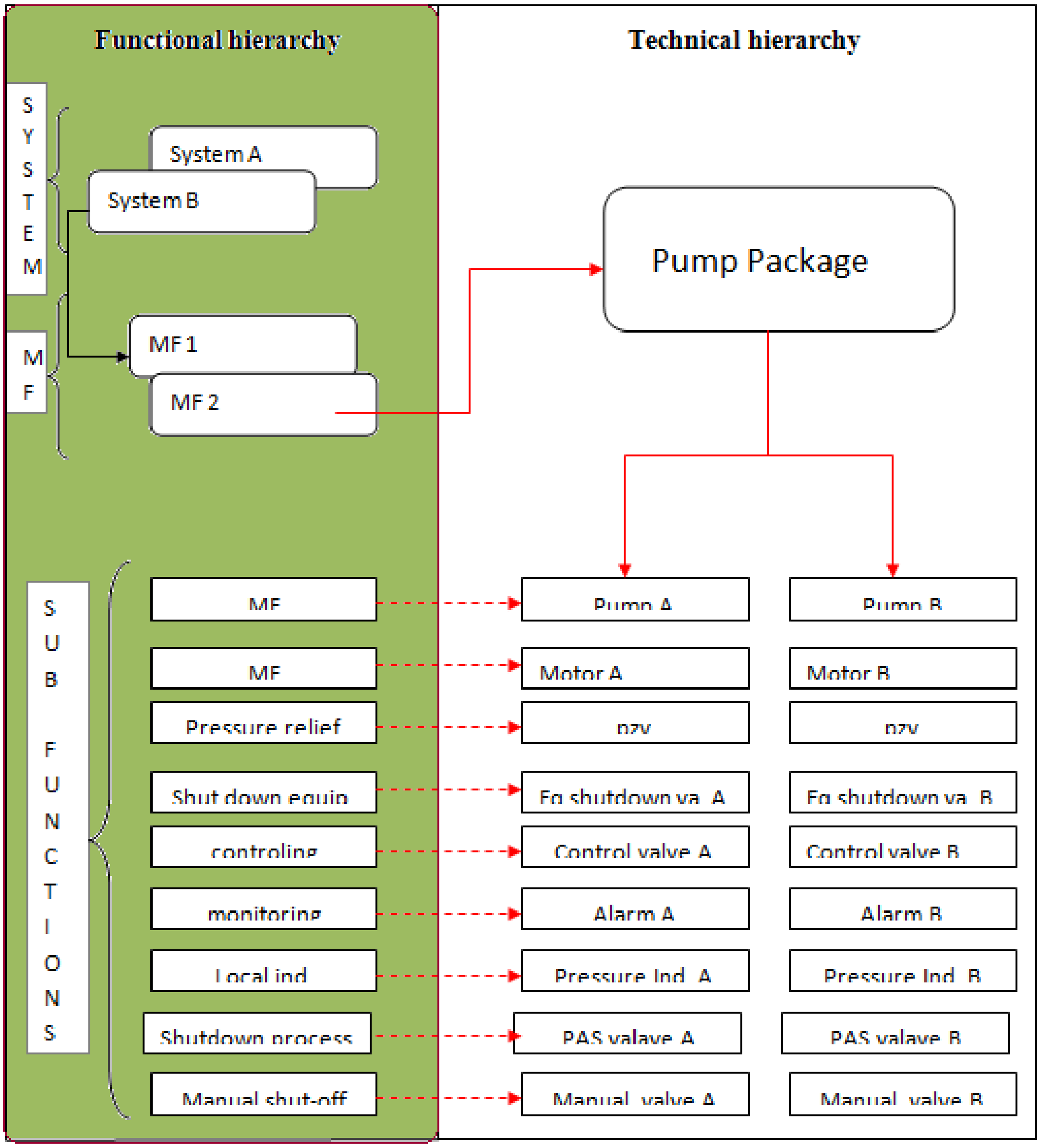

Figure 4: illustration of the link between functional and technical hierarchy (NORSOK Z008 rev. 3)

3.4.2 Consequence Analysis for Prioritizing Maintenance

A Consequence classification of the whole system is made with respect to the maintenance of failure of any of the functions on the three main concerns (i.e. HSE, production regularity and economics).

This classification is to underscore what effect a functional failure can have on HSE, production and economics. This classification together with the other key information and parameters (HTO and RCFA) gives input to the following activities and processes:

- Selection of equipment where detailed RCM/RBI/FMECA analysis is recommended

- Establish preventive maintenance programme (time/age/condition based)
- Preparation and optimization of GMCs
- Design evaluations
- Prioritization of work orders
- Spare part evaluations

Figure5 below shows the overall work flow related to classification

- The functional classification is done to identify safety critical functional failures and link tags to this function

- All systems and/components related to an installation should be classified using the same classification scale

- The classification feeds in to a common risk model used for operational decision making as a result they need to be similar.

- The containment function consisting of pipes, vessels, valves are normally consequence classified via and RBI analysis. The containment has a dual function, i.e. safety system with a performance standard and a production system with its production functions. Equipment with a containment function has two inputs in to the classification process as illustrated in the Figure 5

- Safety critical systems are defined via safety analysis (e.g. QRA) in the design or amendment process. As such these systems are already identified and its function defined.

- The outcome of the classification will be a set of attributes assigned to each component tag. The set of parameters should be aligned to the decision model. Examples of information to be assigned to each component tag are:
  - Safety function indicator
  - Leakage HSE consequence
  - HSE functional failure consequence
  - Production consequence
  - Cost consequence
  - Redundancy

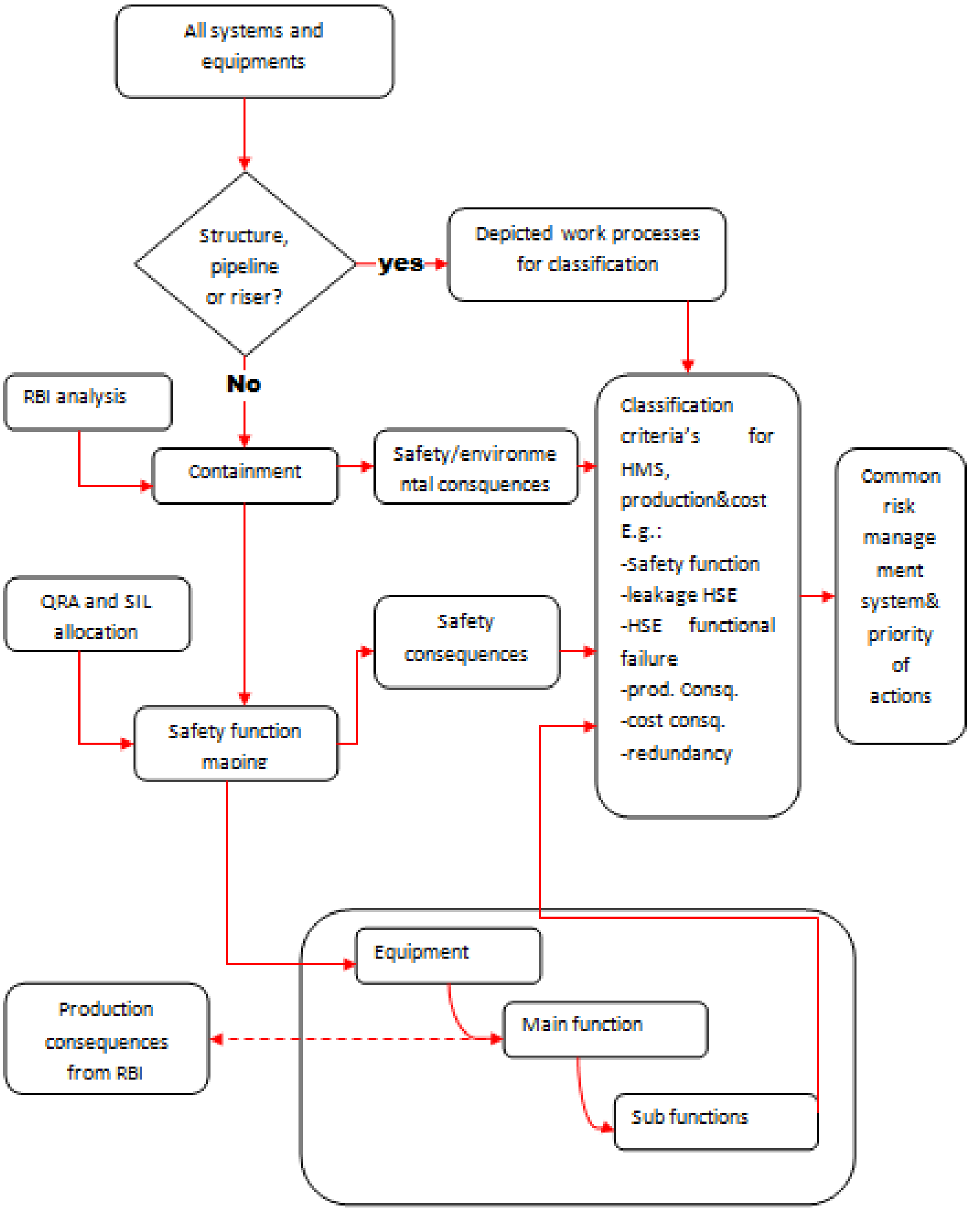

Figure 5: consequence classification process (source: NORSOK-Z008, rev. 3)

In developing effective and efficient maintenance strategy, it is important to clearly identify, define and document the systems/equipments with their boundaries by the use of the engineering numbering system. Selection criteria could be based on maintenance cost, main contributors to functional failure/unavailability and safety related incidents. For the consequence analysis which assesses the consequences of failures and the degree of functional redundancy, the consequence classes have to be properly defined prior to performance of the analysis.

The definition of the consequence classes must be done in accordance with overall company criteria for safety and environment, and reflect the actual plant operation when it comes to functional failures. To classify the most serious effect of functional failures, the consequence classes defined in Table 2 is applied, unless otherwise specified. Note that the loss of functional failure should in monetary value comply with the corresponding cost limits specified for 'Cost' within each class. (NORSOK-Z008)

Table 2: General consequence classification (NORSOK-Z008 rev. 2)

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

Loss of 'Containment "for example, i.e. external leakage, requires a separate evaluation to reflect best practice for inspection planning. This applies for consequences to HSE while the consequences to production loss and other costs are similar for all kinds of failures. Table 3 gives guidelines for assessment of the consequences to workers safety, while the consequences to the external environment differ significantly depending on the chemical composition of the released substance, volume and the recipients (open sea, shore, earth or atmosphere). The consequence classification related to containment is proposed as a prioritization of static mechanical equipment for establishing an inspection program.

Table 3: Consequence classification for containment (NORSOK-Z008 rev. 2)

Class	Health, safety and environment (HSE)	Production	Cost (exclusive production loss)
High	When substance is: • Hydrocarbons (highly ignitable gases and un stabilized oil) and other flammable media. • Liquid/steam, exceeding 50 ºC or 10bar. • Toxic gas and fluids.	As for production, class 'High' in Table 2.	As for cost, class 'High' in Table 2.
Med.	When substance is: • Stabilized oil, diesel and other less ignitable gases and fluids. • Liquid/steam, less than 50 ºC and 10 bar • Toxic substance, small volume. • Diesel	As for Production, class 'Medium' in Table 2.	Moderate cost b/n Z–YNOK(specify cost limits)
Low	When substance is: • Non-ignitable media. • Atmospheric gasses and fluids harmless to humans and environment. • Negligible toxic effects.	As for production, class 'Low' in Table 2.	As for cost, class 'Low' in Table 2.

In Offshore Oil & Gas industries, the production facility is usually complex and is divided into a number of main functions covering the entire system, such as heat exchanging, pumping, separation, power generation, compressing, distributing, storing, etc. Each MF is given a unique designation consisting of a number (if appropriate a tag number) and a name that describes the task and the process. A comprehensive integrated assessment for each main function helps in developing effective and efficient maintenance strategy.

As an example, main function (MF) redundancy grade assessment of all the equipment is specified in a with respect to loss according to Table 2&3. The level of redundancy within one MF is classified by the codes as in Table 4.

Table 4: Classification of redundancy

Redundancy	**Redundancy degree definition**
A	No redundancy i.e. the entire MF is required to avoid any loss of function(no unit can fail without disturbing the MF)
B	One parallel unit can suffer a fault without influencing the function.
C	Two or more parallel units can suffer a fault at the same time without influencing the function.

Assessing the consequences of the most serious faults preferably is carried out by experts with experience in risk and reliability evaluations in collaboration with personnel experienced in operations and maintenance and with sound understanding of the production process and the technical equipment. The entire MF is assessed in terms of the most serious effect of a fault. In this assessment any redundancy within the function is disregarded, as the redundancy will be treated separately.

With this approach, the most serious effect of a fault be identified and the influence on the performance of the MF can be quantified according to Table 2. The optimal time from the fault occurring, until it affects the system/plant functional performance be estimated, see Table 3, column for ’Production’. When the fault affects more than one of the categories (HSE, production and cost), this is identified and described so that it is evident from the text how the effect takes place.

Based on the consequence and redundancy grade assessment, a matrix can be developed. See Table 5.

Table 5: Criticality and Redundancy Matrix (H=high; M=medium; L=low)

HA	HB	HC
MA	MB	MC
LA	LB	LC

The criticality and redundancy matrix gives a classification of component/equipment in various groups and helps the decision makers to decide the most efficient maintenance strategy for the component/equipment in these groups. The equipment that falls in the high criticality-redundancy group (HA) is generally recommended for RCM actions or the product need to be redesigned/ modified to reduce the risk with respect to cost and production loss. The equipment that falls in the medium criticality-redundancy group (LA, HC, MA) is generally recommended for planned corrective maintenance activities or to follow the maintenance activities recommended by the OEM supplier. Safety criticality equipment is always considered of very high criticality (based on NORSOK Z008 rev. 2)

Moreover, for deciding the most effective and efficient maintenance strategy for components, maintenance concepts are developed. The basic principle for maintenance concepts is to group similar equipment, operating in similar conditions, for conducting similar maintenance activities. In other words, the maintenance concepts enable standardizing maintenance activities for equipment with the same criticality and operating in similar conditions. The maintenance concepts also take in to account the corporate strategy to facilitate inclusion of operator and maintenance personnel's experience, supplier recommendations, historical data, company/authority regulations, etc.

A criticality based maintenance analysis enables to define and prioritize maintenance activities, the resources required, the spare parts required, etc. and to develop 'just-in-time' maintenance programs for the complex productions facility. The maintenance activities at the component level are uploaded in the CMMS of an O&G operator company for generation of work orders

In order to simplify the consequence assessment and enable work to be carried out with sufficient accuracy with minimum use of resources, the sub function level can be 'standardized'.(See Appendix B).

3.5 Maintenance program

Failure modes, failure mechanisms and failure cause that can have a significant effect on HSE and production and cost will be identified and the risk determined. Taking compressor as an example, the failure modes could be: failure to start on demand, to stop on demand, high output, low output, external/internal leakage, vibration, noise, overheating, plugged/choked, parameter deviation and tec. The failure mechanism could be: mechanical, material, instrumental, electrical, external failures and etc. these have to be in to further details.

For example, material failure could be detailed further as; cavitations, corrosion, erosion, breakage, wear, fatigue etc. failure cause could be: design-related causes; fabrication/installation-related causes; failure related to operation/maintenance; failure related to management and others.

The classical way of establishing a maintenance program is using RCM analysis. However, this standard calls for using generic maintenance concepts in combination with more detailed RCM methods. It is important that the generic concepts are adjusted to local operational conditions, for example, Norwegian Continental Shelf (NCS) as well as the local risks associated with the advanced, complex production facilities. (Look, for instance, Appendix C, maintenance program as recommended by NORSOK-Z008)

The most common effective and efficient methods to establish maintenance program are briefly described in the following sections.

3.5.1 Reliability Centered Maintenance (RCM)

RCM is a process of systematically analyzing a system to understand:

- Its functions(i.e. the focus is on functional failures not equipment failures)
- The failure modes and failure effects and failure causes of its equipment that support these functions
- How to choose an optimal maintenance to prevent the failure modes from occurring or to detect the failure mode before failure occurs (true condition monitoring)

The objective of Reliability Centered Maintenance (RCM) is to achieve highest reliability for all of the operating modes of a system. All results and decisions are logged during the RCM process so that results can be re-evaluated later. The result will be an effective system to ensure reliable and safe operation of an engineered system. The standard IEC 60300-3-11/7/ describes in detail how to perform an RCM analysis.

3.5.2 Risk Based Inspection (RBI)

RBI techniques have been applied for developing preventive maintenance (PM) program for containment functions. The methodology is developed by DNV. Doing an RBI analysis involves assigning probability and consequences to all important failure modes within the containment functions as well as setting risk reduction measures in the form of inspection, maintenance and condition monitoring. (See sec. 3.6.1 for details on risk assessment)

3.5.3 Generic maintenance concept (GMC)

According to NORSOK-Z008 rev.3, a generic maintenance concept is a set of maintenance actions, which demonstrates a cost efficient maintenance method for a defined generic group of equipment functioning under similar frame and operating conditions. The use of the generic maintenance concept ensures that all defined HSE, production, economics and other operating requirements are met. The concept includes relevant design and adverse operating environments (normal, marginal, hostile). Appropriate performance indicators and the corresponding acceptance criteria are defined for safety critical functions.

NORSOK-Z008 rev. 3 recommends generic maintenance concepts in order to:

- Reduce the effort in establishing the ‘just-in-time’ maintenance program.
- Ensure uniform and consistent maintenance activities.
- Facilitate analysis of component/equipment groups.
- Provide proper documentation of selected effective maintenance strategies.

A generic maintenance concept may be utilized when:

- The group of components has similar designs.
- The components have similar failure modes and failure frequencies.
- The amount of similar equipment justifies a generic concept.

3.5.4 Update Maintenance Program

As the aim is to improve potential maintenance performance, a maintenance program needs updating at intervals. The indicators for such updating could be:

- The observed failure rate (e.g. based on observable parameters based on condition monitoring) is significantly different from what was expected, i.e. higher failure rate./lower failure rate is observed requiring a change in maintenance strategy
- The complex operational context has changed causing different consequence and failure rate;
- Cost of maintenance different from expected
- New technology that could make the maintenance more efficient(CBM technologies) is available
- Updated rules and regulations
- Information from original equipment manufacturer(OEM)

The evaluation is based on historical data and best practices and expert's recommendations. A process diagram model, to update a MP for example, is shown in the Figure 6 below. If it is a safety system, an evaluation of number of failures per tests and performance standard requirements is performed. If there is a significant change in the safety system stated in the performance standard (PS), this information is used back to the overall risk assessment for the plant. For non-safety systems a cost benefit analysis based on best practices and personnel recommendations is performed. Based on this evaluation maintenance program and GMC is updated, and implemented in the maintenance plan to improve maintenance performance.

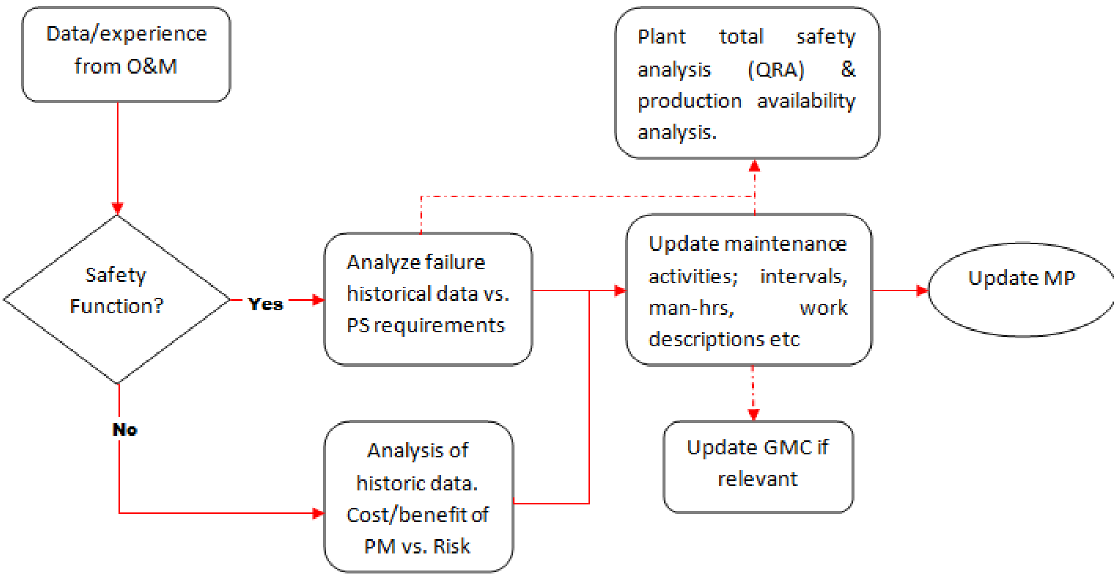

Figure 6: work processes for updating maintenance programs (NORSOK-Z008 rev. 3)

3.6 Maintenance Planning

An overall plan has to be prepared for the advanced offshore production facilities for the conduct of 'just-in-time' maintenance program .The results from the criticality analysis classification are useful when defining criteria for prioritizing work orders. Prioritization of maintenance (using FMECA or Fuzzy Logic) should be done based on the risk the failure represents, described as consequence and failure impact/probability of failure. Continues improvements on accurate planning can be made by getting updated inputs from improved root cause failure analysis and human-technology-organization (HTO) integration.(Look also Appendix C, prioritization of corrective maintenance recommended by NORSKO-Z008 rev. 3, based on the risk the failure represents, described as consequence and failure impact). Criticality of failures can be classified based on Table 6.

Table 6: Failure impact scale (adapted from NORSOK Z008 rev. 2)

Term	Definition	Note
Failure impact	Impact of failure of equipment's function(s) or on the production facility plant	On equipment level, failure impact can be classified in three classes (critical, degraded, incipient)
Critical failure	Failure of an equipment plant unit which causes an immediate cessation of the ability to perform a required function.	Includes failures requiring immediate action towards cessation of performing the function even though actual operation may continue for a short period of time. A critical failure results in an unscheduled repair.
Degraded failure	Failure that does not cease the fundamental function(s), but compromises one or several functions	The failure may be gradual, partial or both. The function may be compromised by any combination of reduced, increased or erratic outputs. An immediate repair can normally be delayed, but in time such failures may be developed into a critical failure if corrective actions are not taken
Incipient failure	Imperfection in the state or condition of an item so that a degraded or critical failure may/may not eventually be the expected result if corrective actions are not taken	

3.6.1 Risk Assessment Criteria

An example of risk decision matrix (based on DNV, 2009) is shown below (Table 7) for use in consequence classification, maintenance planning, inspection planning and for prioritizing work orders. It uses three classes for consequences (C1, C2, C3), four classes for probability (frequency) and four classes for risk (H: high; M: medium; L: low; VL: very low)

The risk for decision making is as important as the risk scale. An example table 8 below shows a set of criteria for prioritizing time to repair connected to complete repair and the mean time to failure (MTTF)

Table 7: example of priority to repair based on risk

risk	Priority/time to repair	Comment
H	5days	Always highest priority for functional failure
M	60days	
L	200days	
VL	365days	

Table 8: example of Risk matrix used for consequence classification and for decisions (modified from DNV, 2009)

Loss of function leading to:	Personnel consequences	No injuries	Minor injuries	Injuries with absence	Serious injuries	Fatality
	HC release to environment	<1 tons	1-10 tons	10-100 tons	100-1000 tons	>1000 tons
	Production loss	0.1mill$	0.3mill $	1 mill $	3 mill $	>10 mill$
Frequency per yea	MTBF(year)	Risk/priority time				
>1	0-1	L/6m	M/1m	H/1w	H/1w	H/*
1-0.3	1-3	L/1y	L/6m	M/1m	H/1w	H/*
0.3-0.1	3-10	VL/2y	L/1y	M/6m	H/1w	H/1w
<0.1	Long	VL/3y	VL/2y	L/1y	M/1m	H/1w

*): special considerations, w: week; m: month; y: year

The decision criteria for what to do is in the form of a time period until the case is repaired or brought back to original function. Some criteria may apply:

- For safety related barrier equipment, the priority must in any case be high as function of these systems is fundamental for operation. Usually a time to repair is in the order of one week. In the mean time, risk reducing measures can be instituted

- The risk associated with a full functional failure is determined by the consequence only as probability 1. The upper part of the matrix then be appropriate.

- For cases where the notification is related to starting degradation (incipient or degraded failure impact) the time to full functional failure has be assigned. The time to repair should be smaller than the time to failure. The safety factor may be used till repair, but for low consequences, 80% of time to failure (TTF) can be used.

- The priority times in Table 8 point to different times to repair depending on the combination of consequence and probability. The matrix is basically developed by means of the formula; time=f(consequence)*TTF. For simplicity, one set of times vs., risk can also be used, like High=1week, Medium=1month, Low=6months, and Very Low=1year

- Practical aspects like access to the systems, availability of spare parts and tools and personnel should not have, in principle, influence on the priority (integrating the organizational strategy, logistics and materials help optimize to the resource utilization). These factors will obviously play a role in the practical planning, and will affect the actual time to finalize the work. But the assigned risk and priority must remain the same.

- The process for identifying priority be implemented in the integrated maintenance management system, i.e. default priority with due date is set when creating a failure report/notification. The priority for offshore production facilities is possible to change due to e.g. adverse operational information on the actual failure mode. If the priority is changed, a reason for the change should be documented. This is done by using improved root cause failure analysis (RCFA) techniques.

The actual maintenance work can be organized in two ways.

- As daily activity using permanent employees
- As maintenance campaigns where the maintenance activities are performed by dedicated team which may specialize and cover maintenance activities for several plants.

Experience has shown that about 50% of the corrective work may not be done immediately and are suited for the campaign team (DNV, 2009). Extensive use of integrated operations (IOs) technology can make this process effective and efficient. The day-to-day workers will do work that need immediate attention, like corrective work for safety critical equipments. This set up has many companies shown to be a cost effective method to perform the required maintenance tasks. (Refer also Appendix E for reporting recommendations by ISO 14224)

CHAPTER 4

Optimization of Maintenance Interval

4.1 Optimization of Maintenance Activities

By identifying the root cause for the failure, achieving the desired system performance, e.g. reliability, availability, is determined in system design and development, but also through implementation of efficient and effective maintenance strategies. The overall objective of maintenance process is to increase the profitability of the business in a total life cycle cost (LCC) perspective without compromising HSE. As indicated in the Figure 7 below, the life of a project is extended by improving maintenance performance. Optimization of maintenance strategies is therefore expected to provide a basis for development of cost effective maintenance strategies which minimizes the consequences related to HSE and economy.

There are different types of maintenance, of which the main types are preventive maintenance (PM) and corrective maintenance (CM). Furthermore PM can be grouped in to two.

a) Age/time/condition based; and
b) Opportunistic based

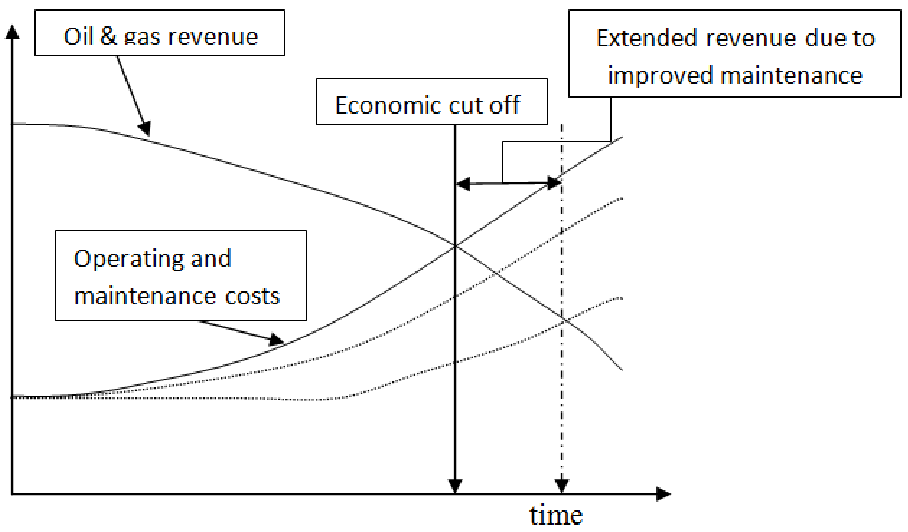

Figure 7: enhancing revenue through optimizing maintenance

The specific nature of the maintenance requirements depends on the nature and function of the systems/subsystem/equipments and the external environmental conditions, and should be balanced towards requirements of reliability (availability).

Condition-monitoring is already an integral part of the condition-based maintenance (CBM) strategy of existing onshore production facilities and is assumed to be cost-effective for offshore production facilities, due to higher loss of revenue, longer downtimes (due to harsh weather and long transport distance), and larger, heavier and more costly components for larger capacity rated facilities.

Access to the offshore is limited, and most of the maintenance activities have to be conducted from May to September. This implies that use of condition-monitoring techniques, implemented with fault detection systems (FDS), will be even more important for remote offshore production facilities than for onshore. If potential failures are detected early enough, it is possible to plan for the maintenance action when the component is still on uptime. However, due to the limited window of opportunity for doing maintenance on the (remote) offshore, planning ahead implies a rather long time horizon. When deterioration and faults are detected during the summer season, decisions have to be made whether to replace and repair immediately, or wait until next summer.

A key question for researchers concerned with preventive maintenance for offshore facilities, for example, is then "What is the optimum preventive maintenance time interval?" Too short intervals would lead to unnecessary prevention costs; no preventive maintenance would lead to breakdowns, which may affect production, and impose money losses on the firm as discussed previously; and too long intervals would result inconveniences, as they will involve preventive maintenance actions and would lead to uncontrolled breakdowns.

In order to exploit the information from condition monitoring into maintenance decision making, it is necessary to establish a relationship between the state of the item (or system) and one, or more, condition-monitored state variables, denoted by say, $X(t)$. The relationship between the state of the item and $X(t)$ can be determined by using mathematical models or expert judgments to predict the behavior of the deterioration process. It is often of interest to find the probability of failure based on the value of the condition-monitored state variables, $X(t)$.

Different subsystems and components will have different deterioration processes and measures, depending on their construction, materials, usage, and exposure to external adverse conditions. Deterioration may be modeled based on physics of failure and characteristics of the operating environment; i.e., modeling deterioration in terms of a time-dependent stochastic process. Relevant models are, for example, the P-F interval (Moubray, 1997), proportional hazard modeling (PHM)-which is multivariate regression analysis and Markov-processes. Since, the operation of (deep-sea) offshore implies condition-based maintenance strategies and temporal variability of deterioration, stochastic process models, such as Markov processes, may be more applicable.

On the NCS the maintenance programs are developed and maintenance activities prioritized based on the coarse consequence classification of equipment (NORSOK

Z008 rev.2). This approach does not take into account individual failure modes of the equipment. To achieve the ambition of achieving highest production regularity and zero damages to HSE due to equipment failures, it will be necessary to perform the maintenance activities that prevent(or minimize the probability of occurrences) unexpected equipment failures.

Furthermore, the frequency of conduct of maintenance activities has to be linked to realistic mean time between failures. Moreover, functionality and performance degradation of the equipment has to be monitored in a manner that sufficient time is available for the maintenance managers to plan and organize selected maintenance activity execution. This implies that for selected equipment a detailed analyses needs to be conducted at the equipment level to develop optimized maintenance strategies.

In practice, the choice of the optimum maintenance strategy is not a simple task. Implementation of such philosophy for complex installations is a difficult and a complex task. This thesis focuses on developing integrated maintenance framework to implement more effective work processes to develop optimized maintenance strategies and to ensure continuous improvements in maintenance strategies based on maintenance as well as operational historic data.

4.2 Concept of Maintenance Optimization-mathematical approach

Cost of maintenance is weighted against the cost of the expected failures (DNV, 2009)

$$C_t = \frac{C_m}{\tau} + \sum_{k=1}^{n}(f_k C_k)$$

C_t=total expected cost per unit time
C_m=total cost of maintenance activities
τ=interval between maintenance activities
f_k=frequency of "qualitative consequence"
n =the number of "qualitative consequence"
C_k=the expected cost of the "qualitative consequence"

After we estimate the total cost, the economic optimal maintenance interval (see figure 9 below) can be found by: $\frac{dC_t}{d\tau} = 0$

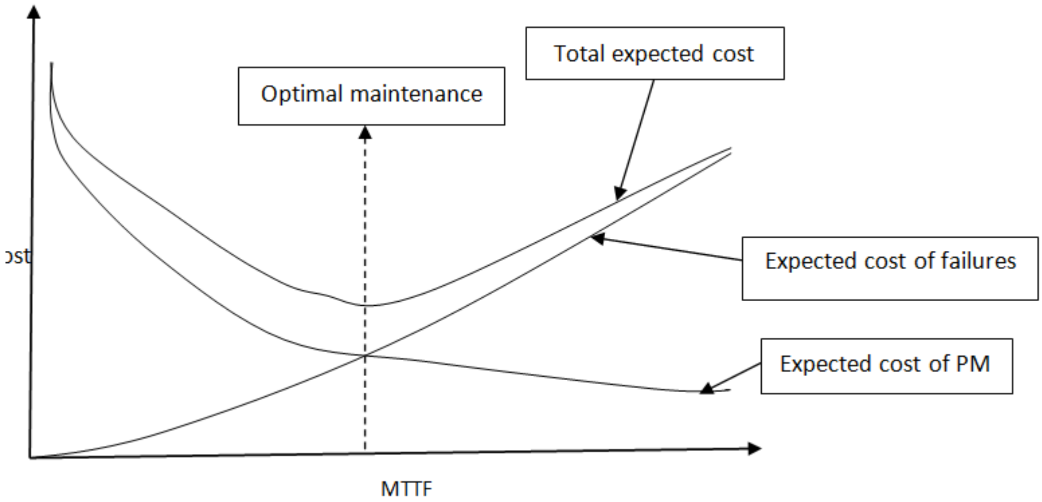

Figure 8: maintenance optimization

Optimizing costs related to maintenance (see Figure 8 above) may be related to the production facility subsystem's or component's effective failure rate, as a function of the inspection intervals and the threshold values. For (deep) offshore facilities, the window for performing inspections and maintenance will be limited and it will be difficult to inspect some equipment during long time periods of a year. Thus, opportunistic maintenance may be economically practicable.

Operation and maintenance cost elements consist of operation costs, preventive maintenance (PM) costs, and corrective maintenance (CM) costs. The operation costs are related to scheduling site people, monitoring overall operation (e.g. through SCADA), responding to component fault events, etc. Preventive maintenance (PM) costs include periodic inspections of the equipment, oil and filter changes, calibration of sensors, and replacement of consumables, such as seals and brake pads. The frequency of the PM tasks is usually recommended by the OEM supplier.

The direct costs related to corrective maintenance are associated with the labor and equipment required to repair and replace, component costs. Indirect costs are due to lost revenue due to system downtime. The downtime depends on the repair time, including detection, getting access to the components, diagnosis, labor and spare part mobilization, and weather conditions. Costs of major overhauls and major component replacement over the life of components constitute an additional cost element. Figure 9 shows important factors influencing the system performance (uptime, availability, etc.), O&M costs, and thereby maintenance management.

These factors have to be taken into consideration over the system's entire life cycle in order to optimize performance. Assuming that the activities in the diagram that corrective maintenance is more expensive to carry out than PM. PM and CBM are advantageous compared to strategies merely based on corrective maintenance (CM) actions.

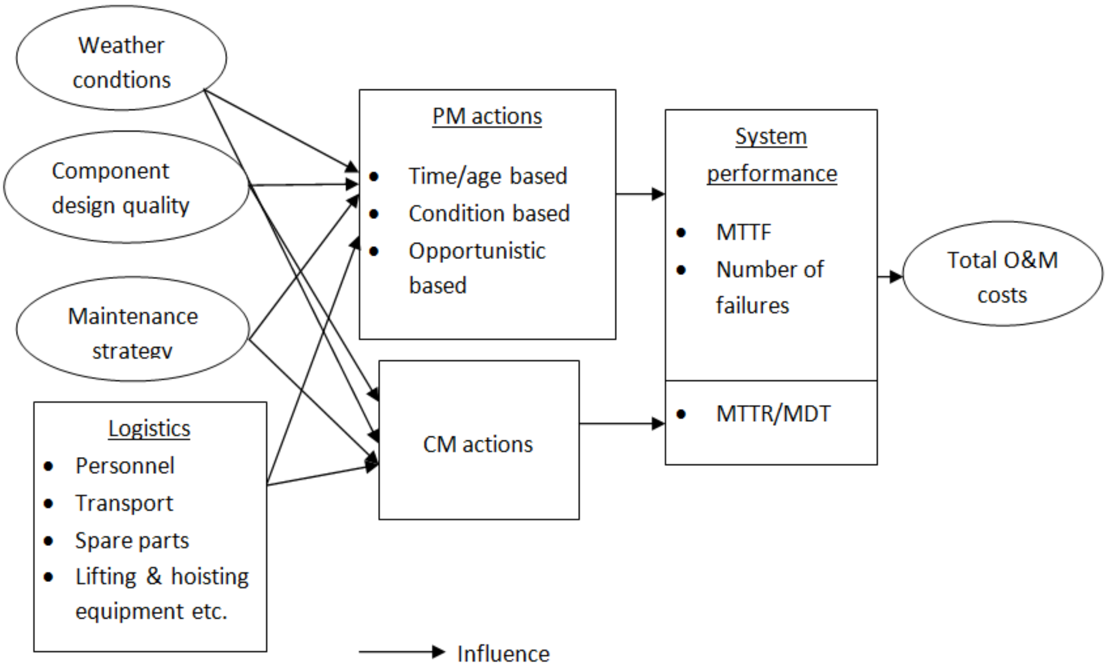

Figure 9: factors influencing system availability and O&M costs

Assuming that two types of maintenance can be carried out (PM and CM), and that the set up costs S, such as preparation and closure of the maintenance activities, a simple model of the total maintenance costs per time unit is $C_{tot}(\tau)$:

$$C_{tot}(\tau)=\frac{S}{\tau}+Cpm,i+(Ccm,i+P_i)\lambda(\tau)$$

P_i are costs due to production loss (related to the component's availability) and $\lambda(\tau)$ is the effective failure rate, depending on the maintenance interval, τ, for the component. Optimization would be to minimize $C_{tot}(\tau)$ by optimizing the interval. I have tried to indicate that the maintenance interval, τ, is a key factor in the maintenance cost optimization.

4.3.1 Offshore Production Facilities' Plant Equipment: impending failure detection

The consequence of component/sub-system failure on a system can be classified into three categories, critical, semi-critical and non-critical based on function criticality, operating context and complexity of the equipment/technology. The equipment's true degradation is estimated using condition indicators (or variables) like, vibration monitoring (e.g. belt, gear drive, or surfaces with components with relative motion), temperature (e.g. electrical components, bearing house, hydraulic pumps etc.), lubricant monitoring (transmission components like gears, cams, etc.).

The monitoring frequency could be periodic/ continuous. The operating context is important factor, which influences degradation. The adverse operating context in the offshore can also be classified into three operating regimes (Edwin and Chaturvedi, 2006), namely; normal, marginal and hostile operating contexts.

Under the influence of operating context, condition indicator levels are modulated, thereby true level of degradation cannot be inferred by the mere trending of condition indicator's level. Hence, operating context needs to be considered while using condition indicator level to understand the true state of equipment. On the other hand, the maintenance domain expert does not have a precise knowledge about the correlation of the operating context and level of degradation for a given level of condition indicator on specific equipment. Expert System theory (e.g. Artificial Intelligence) considers these vagueness and imprecise knowledge (i.e. by integrating quantitative and qualitative knowledge) to come up with possibilities of failure degradation modes and hence improving our decision making to improve maintenance performance.

4.3.2 Optimizing the Interval between Maintenance Activities (τ)

Traditional analytical techniques (mathematical and statistical models) needs large amount of data, which is difficult to obtain because of constraints i.e. rare events of components, human errors and economic considerations for estimation of the failure / repair characteristics of the system. Even if data is available, it is often inaccurate and thus, subjected to uncertainty, i.e. historical records can only represent the past behavior but may be unable to predict the future behavior of the equipment. Further, age, adverse operating conditions and the irregularities/imperfection of manufacturing/ production processes affects each unit of system differently (Sergaki and Kalaitzakis, 2002).

However, it may be difficult or even impossible to establish rational database to accommodate all operating and environmental conditions. In the absence of accurate data, rough (approximate) estimates of probabilities can be worked out. The estimates provided by experts are inherently subjective and to establish a rational method for reliability assessment, such subjective estimates should be merged with statistical randomness.

The uncertainty between initiation of degradation and reaching to unacceptable levels is shown in the Figure10 below. As shown in the figure, the performance decreases over a period of time and drops down to an unacceptable level (potential failure, t_p) and leads to a functional failure at a later time (t_f). The degradation of a component/system may vary widely due to above mentioned factors. Owing to this variation and associated randomness, the potential and functional failure times are also not precise. Hence, the frequency of monitoring decided on the basis of P-F interval (PF Interval = t_f - t_p) is also a variable. Some say PF interval itself is hard to define (Murray, 2007)

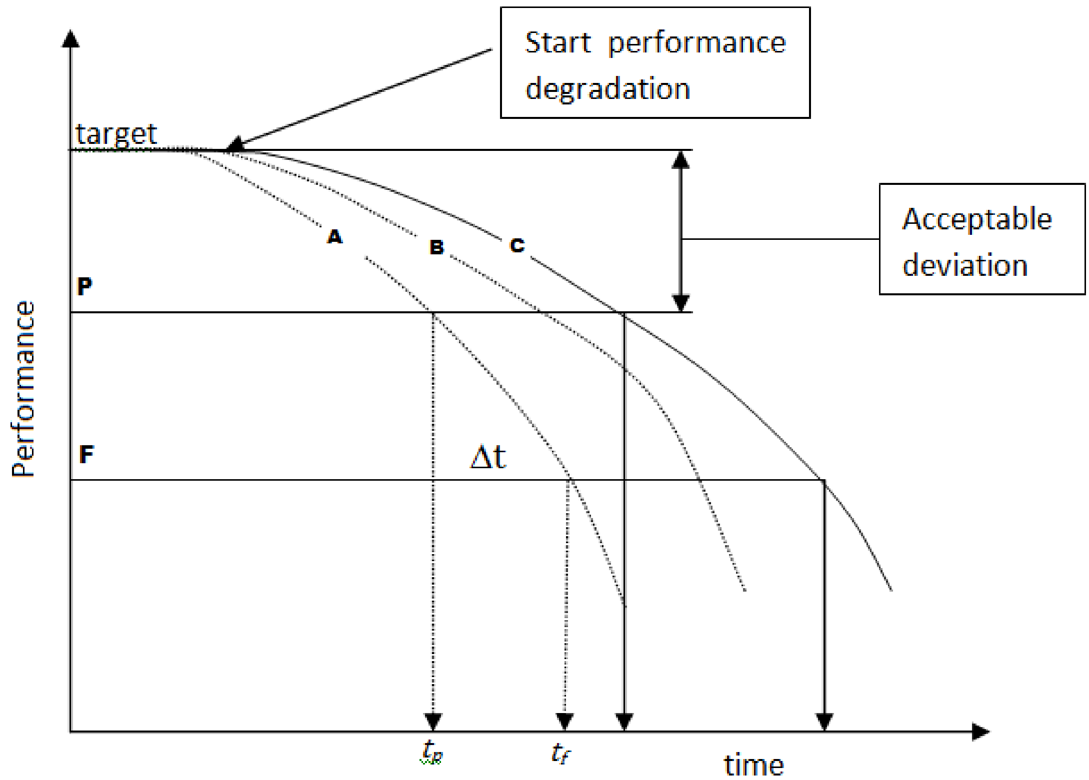

Figure 10: uncertainty in the PF interval (modified from Edwin and Chaturvedi, 2008)
(t_p =potential failure time, t_f =functional failure time)

Since this interval is uncertain and degradation is a random event (it could be pattern A, pattern B, pattern C. etc), predicting an impending failure is highly probabilistic. Therefore, the probability of detecting a failure in advance is not a crisp event and fuzziness (uncertainty) is associated with it. This uncertainty can be better handled with fuzzy logic using appropriate membership function to arrive at estimating appropriate possibility level. Fuzzy logic uses to reflect the dispersion of data adequately. The dispersion includes variation in human performance, vagueness in adverse operating/environmental conditions and vagueness in the system performance due to age.

Rule-based fuzzy logic can be integrated into the maintenance program to determine the times for the periodic PM actions, considering maintenance imperfections. Indeed, considering human factors in maintenance programs is indispensable to assure more accurate results. However due to the difficulty to handle by their modeling, most theoretical maintenance models do not consider these factors.

Therefore, fuzzy logic can be an important tool to include them. We modify the maintenance program at every maintenance action according to the duration of maintenance actions and the technician's experience seeking to optimize the maintenance program ('just-in-time') so as to minimize the cost or maximize the availability of the system to compensate for high maintenance cost. Fuzzy Inference System (FIS) on a hardware platform can be developed for a real-time application.

Estimating the failure probability distribution with limited/un-organized maintenance data may be awkward and not rewarding. Possibility distribution of fuzzy sets (Zadeh, 1996) and transformation of probability distributions to possibility distributions and vice-versa offers a great flexibility and simplicity to compute possibility of events. The strength of the fuzzy logic, for examples in the field of reliability engineering, is well documented by Bowles (2003) and others. The efficiency of condition-based maintenance (CBM) program can be quantified by the ratio of failure modes detected in time to the total number of failure modes occurred in a specified interval of time on specified equipment.

Fuzzy Logic theory approach proposes to estimate the "Possibility of failure mode detection". For offshore, three fuzzy variables are important to be considered in the fuzzy inference System i.e.:

- level of condition indicator;
- frequency of monitoring; and
- operating context.

These variables can be expressed as fuzzy sets with linguistic descriptions. For instance, treating "condition indicator level" as fuzzy variable, it can be expressed the membership function using linguistic terms such as remote, low, moderate, high and very high. A schematic representation of fuzzy inference system (FIS) is shown in Figure 11.

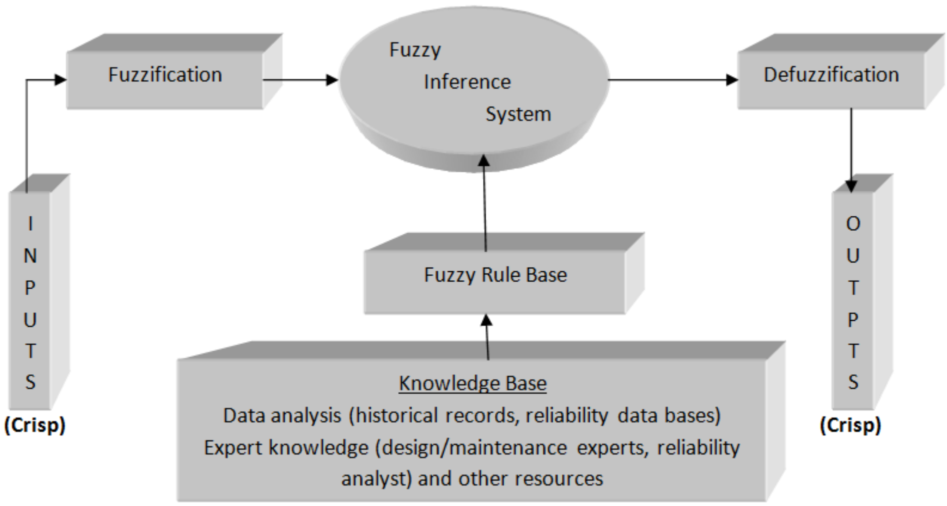

Figure 11: elements of fuzzy inference system (FIS)

Input variable is fuzzified using the fuzzy linguistic variable, like remote, low, medium and high, very high etc, with an appropriate membership functions. The selection of membership function is subjective and depends on the data type and its variability in the domain. Expert rule base is, a set of rules mapping the inputs to output under various input levels. There can be many rules, which are applicable simultaneously on the input variables and leading to many similar or dissimilar output situations. Aggregating these outputs can be done using a method commonly known as centroid method of aggregation (or Mamdani rule), which deals with max-min approach (Ross, 2000). For example, with the reliability perspective, when the possibility of failure mode detection is high, the reliability can be kept at higher levels as the required maintenance action to contain degradation level can be planned in advance, before an impending failure matures as a failure. With the risk perspective, risk can be minimized as risk mitigation can effectively be planned.

4.3 Brief Overview of Fuzzy Concepts

Fuzzy sets, membership function, alpha cuts, and linguistic variable, fuzzy logic

Fuzzy sets are sets whose elements have degrees of membership. Fuzzy sets were introduced by Lotfi A. Zadeh (1965) as an extension of the classical set. In classical set theory, the membership of elements in a set is assessed in binary terms (i.e. an element either belongs or does not belong to the set). By contrast, fuzzy set theory permits partial membership of elements in a set; this is described with the aid of a membership function valued in the real unit interval [0, 1]. Fuzzy sets generalize classical sets. In fuzzy set theory, classical sets are usually called crisp sets. The fuzzy set theory can be used in a wide range of domains in which information is incomplete or imprecise.

Fuzzy logic is a mathematical approach that analyzes analog input values in terms of logical variables that take on continuous values between 0 and 1, in contrast to classical logic, which operates on discrete values of either 0 or 1 (true or false).

The following equations are based on Rajiv et al., (2010)

$$NA/u = \{0,1\} \quad \text{……………………………………….……(1)}$$

A crisp set "A" can be represented by a characteristic function:

$$N_A(x) = \begin{cases} 1 \; if \; x \in \; A \\ 0 \; if \; x \notin \; A \end{cases} \quad \text{……………………………………(2)}$$

Where: U: universe of discourse, X: element of U, A: crisp set and N: characteristic

Function.

Differing to the classical sets, fuzzy sets accommodate various degree of membership on continuous interval [0, 1], where "0" conforms to no membership (i.e. 0%) and "1"conforms to full membership (i.e. 100% membership). Mathematically defined by equation:

$$\mu_{\tilde{A}}(x): U \longrightarrow [o,1] \quad \text{……………………………….………..(3)}$$

Where: $\mu_{\tilde{A}}(x)$: Degree of membership of element x in fuzzy set $\sim\tilde{A}$

Different types of membership functions such as triangular, trapezoidal, gamma and rectangular can be used for maintenance analysis. However triangular membership functions are widely used for calculating and interpreting maintenance data because of their simplicity and understandability (Yadav et al., 2003; Bai and Asgarpoor, 2004 cited in Rajiv et al., 210). For instance, imprecise/incomplete information such as low/high failure rate i.e. about 4 or between 5 and 7 is well represented by triangular membership function. In this thesis triangular membership function is used as it not only reflects the behavior of various system parameters but also reflects the dispersion of the data satisfactorily.

The dispersion takes care of inherent variation in human performance, vagueness in system performance due to age and adverse operating conditions. Thus, it becomes insightful for the maintenance experts to arrive at decisions. The a cut of a fuzzy set M, denoted as $\widetilde{M^{\alpha}}$ is the set of elements x of a universe of discourse X for which the membership function of M is greater than or equal to α i.e.

$$\tilde{M}^{\alpha} = \{x \in X, \mu_M(x) \geq \alpha, \alpha \in [0,1]\} \quad \ldots\ldots\ldots(4)$$

The alpha cut provides a convenient way of performing arithmetic operations on fuzzy sets and fuzzy numbers including in applying extension principle. Consider a triangular fuzzy number defined by triplets (m1, m2, m3) shown in Figure 12, with introduction of α cuts, $\widetilde{M^{\alpha}} = [m_1^{(\alpha)}, m_3^{(\alpha)}]$. The cut is used to define the interval of confidence of triangular membership function and is written as equation 5 (for details refer to Kokso, 1999 and Ross, 2000).

$$\tilde{M}^{\alpha} = \left[\, (m_2 - m_1^{(\alpha)})\alpha + m_1^{(\alpha)}, -(m_3^{(\alpha)} - m_2)\alpha + m_3^{(\alpha)} \right] \quad \ldots\ldots\ldots(5)$$

Moreover, when an event is imprecisely or vaguely defined, the experts would simply say that the possibility of occurrence of a given event is “low”, “high”, and “comparatively high”. To calculate approximately such subjective events, linguistic expressions are used. The analyst can use linguistic variables to assess and compute the events using well-defined fuzzy membership functions (Tanaka, 2001 cited in Rajiv et al., 2010). For instance, we can use linguistic terms such as “Remote”, “Low”, “Moderate”, “High”, and “Very high” to represent probability of occurrence, severity and non-detectability in FMEA.

Fuzzy rule base and inference system

The rule base explains the criticality level of the system for each combination of input variables. Normally it is expressed in “If-Then” style (where, ‘If’ is an antecedent which is compared to the inputs and ‘Then’ is a consequent, which is the result/output). The input variables are formulated in linguistic terms using approaches like Expert Knowledge and expertise.

By using the inference mechanism an output fuzzy set is obtained from the rules and the input variables. There are two most common types of inference systems frequently used:

- The max-min inference and

- The max-prod inference method (Zimmermann, 1996; Ross, 2000 cited in Rajiv et al., 2010).

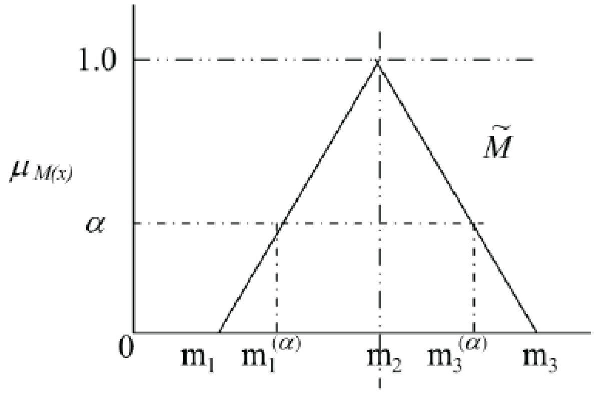

Figure 12: A triangular membership function with a cut (modified from Rajiv et al., 2010)

Defuzzification

In order to obtain a crisp result from fuzzy output, deffuzification is carried out. Different techniques for deffuzification such as centroid, bisector, weighted average, etc. exist. The centroid method is the most common use for deffuzification as it gives mean value of the parameters, besides its simplicity.

For example to analyze the behavior of system in quantitative terms various parameters of interest such as availability, reliability, expected number of failures, and meantime between failures(MTBF) are computed at different alpha cuts. Depending on the value, the analyst predicts performance measures for the system. If ,for example, the uncertainty in input data is described by means of triangular fuzzy numbers, then the possibility distribution of failure rate and repair time is a distorted triangle because after applying the fuzzy mathematics, the linear sides of triangle changes to parabolic one (Sittithumwat et al., 2004 cited in Rajiv et al., 2010). In order to make decisions with respect to maintenance actions it is necessary to convert fuzzy output into a crisp value i.e. deffuzification, using centroid method, for example.

4.4 Fuzzy Logic Application to Improve Maintenance

Gearbox as an Example

Gearbox is taken as an example to discuss the failure behavior both in quantitative and qualitative terms. Gearboxes are used in diverse range of applications within oil and gas production facilities. The effective maintenance activities, at relevant frequencies, are designed to maintain functionality and prevent catastrophic failure of gearboxes thus ensuring that the risk associated with asset business goals covering safety, environment, production and cost are limited.

The main drivers for maintenance that are incorporated in asset typical performance standards will typically include the following:

- Fluid containment: the maintenance strategy objective is to ensure that process fluids are contained under all normal operating circumstances

- Control of ignition Sources: the maintenance strategy objective is to ensure that no sources of ignition are created by gearboxes situated in hazardous areas during normal operation.

FMECA analysis: Qualitative framework

To diagnose the unreliable aspects of the machine, root cause failure analysis (RCFA) of the gearbox, as a system is carried out by listing all the possible causes related to the machine units(see Figure 15). Further, to quantify the sources of unreliability related to process problems and identify potential system failure modes, their causes and effect on performance of the system, it is decided to conduct failure mode and effect and criticality analysis (FMECA) of one of the components. In brief the methodology used to compute the scores related to failure of occurrence (P_f), likelihood of detection of failure (P_d), and consequence/severity (S) of failure of various components are discussed as follows (Sharma et al. 2005a).

The main objective of FMECA is to discover and prioritize the potential failure modes (by analyzing the respective RPN), which pose threats on the system performance. The approach involves statistical data collection especially related with the frequency of component failures and their likelihood of detectability and severity it imposes on system performance. The results of the analysis help maintenance personnel to identify the failure modes, their causes and correct them during the stages of design and production.

The critically debated disadvantages of FMEA based on RPN analysis are:

- Various sets of failure occurrence probability [P_f,], severity [S] and detectability [P_d] may produce an identical value, however, the risk implication may be totally different which may result in high-risk events may go unnoticed.
- The RPN ranking method neglects the relative importance among P_f, S and P_d. The three factors are assumed to have the same importance. In real practical applications there is a relative importance among these factors.

To address these disadvantages related to traditional FMEA, a fuzzy logic application, with gearbox as an example, is presented in this thesis to prioritize the failure causes in a better way.

FMECA attempts to predict possible sequences of events that lead to system failure, determine their consequences or reoccurrence. Often criticality level of a failure mode is expressed using risk priority number (RPN) and is given by:

RPN=Probability of failure X Severity X Probability of detection= $P_f X S X P_d$

Probability of occurrence of failure [P_f]: Probability of occurrence of failure is evaluated as a function of mean time between failures (MTBFs). The data related to mean time between failures of components is obtained from previous historical records, maintenance log-books and is then integrated with the experience of maintenance personnel. For instance, if MTBF of component is between two to four months then probability of occurrence of failure is high (occurrence rate 0.5-1 percent) with the score ranging between 7&8. Table 9 presents the linguistic assessment of probability of failure occurrence with corresponding MTBF and scores assigned.

*Probability of detection of failures [P_d]:*The chance of detecting a failure cause or mechanism depends on a variety of factors such as ability of operator or maintenance experts to detect failure through naked eye or by periodical inspection or with the help of machine diagnostic aids such as automatic controls, alarms and digital sensors. For instance, probability of detection of failure of a component through naked eye is say, 0-5% is ranked 1 with non-detectability 'Remote'. The values of P_d for various failure causes reported in this thesis are evaluated according to the score reported in Table 9.

Consequence (severity) of failure (S): Severity of failure is assessed by the possible outcome of failure effect on the system performance. The severity of effect may be regarded as remote, low, moderate, high or very high. In this paper the data related to mean time to repair (MTTR), affect on the quality of the product are used to obtain score for severity. For instance, if MTTR of facility/component is less, say lies between 12-15 minutes, then effect may be regarded as remote. If external intervention is required for repairs, or MTTR exceeds 1/2 days and there is appreciable deterioration in the quality of production then effect may be regarded as high and if system degrades resulting in line shut down /production stoppage then the severity may be regarded as very high. Table 10 presents the traditional FMEA analysis for the gearbox.

The numerical values of FMEA parameters i.e. P_f, S and P_d are obtained by using the discussed methodology. Failure with larger RPN number indicates a high level of consequence (HSE, production and economics) compared to the failure mode that has lower RPN. In practice many times, it is not possible to quantify the three parameters of RPN due to lack of statistics. In such cases subjective judgments can be used. For example if an event Y has high rate of occurrences and if X event has low rate of occurrence, then allocate number 10 to event Y and 1(or so) to event X on a scale of 1-10, where 10 indicates high rate of occurrence and 1 indicate a rare rate of occurrence. Similarly severity(S) and detection probability (P_d) can also be quantified using similar scale and allocating numbers according to our judgments to describe the degree of severity or possibility of their detection of failures. (Markeset, 2010)

From Table 10 it is observed that causes F13 and F15 produce an identical RPN i.e. 280, however, the failure occurrence rate and failure detectability for both the causes are totally different. Also, F4 and F11 though represented by different sets of linguistic terms produce identical RPN i.e. 180, which could be misleading.

Table 9: Scale used for P_f (probability of failure of occurrence), S (severity) and P_d (likelihood of detection of failure)

Linguistic terms	rank	MTBF(years)	Occurrence (%)	severity effect	Likelihood of detection (%)
remote	1	Less than 3	<0.01	Not noticed	0-5
low	2	1-3	0.01-0.1	Slightly noticed	6-15
	3				16-25
moderate	4	0.4-1	0.1-0.5	Slight deterioration in system performance	26-35
	5				36-45
	6				46-55
high	7	2-4months	0.5-1	Significant deterioration	56-65
	8				66-75
Very high	9	<2months	1	Production loss and non-conforming products	76-85
	10				86-100

Table 10: generic modes of effect analysis (FMEA)

function	Functional failure	Failure modes		Failure effects	Failure characteristic	Pf S Pd	RPN
To transmit rotary power & contain oil and gas vapors	A. Fails to transmit rotary power	F1	Gearbox bearing failure- Radial or thrust.	Collapse of bearing seizure, loss of sealing and internal damage	Random failure resulting in bearing wear, increased vibration, noise, increased bearing temperature, reduced oil pressure, shaft damage and bearing seizure	5 6 8	320
		F2	Input shaft misalignment	Loss of unit output to system, loss of redundancy or reduced production output.	Random failure	7 7 6	276
		F3	Gear teeth wear	Increase in noise, temperature and vibration. If a tooth falls off there will be loss of functional gearbox and significant damage to the gearbox.	Loss of drive, damage to driving and driven machine	4 6 7	168
		F4	Coupling from driver failure	Loss of unit output to system, loss of redundancy or reduced production output.	Loss of drive transmission	4 9 5	180
		F5	Loss of lubricant function	Oil discolored, increased bearing wear	Time related wear out resulting in an increase in vibration	6 6 6	216
		F6	Failure of lubrication circulation	Eventually gearbox seizes	Random failure indicated by loss of lube oil pressure	5 8 6	320
		F7	Gearbox failure for any reason whilst shutdown	Loss of unit output to system, loss of redundancy or reduced production output. Failure will not be apparent during normal operation	On start up, unable to provide prestart lubrication, pump start permissive do not operate unable to start main pump	3 6 8	144
		F8	Drive cones wear	Drive belt slippage resulting in an increase in noise, temperature, and vibration	Random failure resulting loss of oil to surrounding area	8 8 8	512
		F9	Failure of variable speed adjustment device	Loss of unit output to system, loss of redundancy or reduced production output.	Eventual loss of lubrication	7 9 7	441
	B.fail to contain oil and vapors	F10	Shaft oil seal leakage	Loss of unit output to system, loss of redundancy or reduced production output.	Random failure	6 5 5	150
		F11	Gear casing joints external leakage. All other leaks than shaft leaks	Loss of unit output to system, loss of redundancy or reduced production output.	Random failure resulting loss of oil to surrounding area	5 6 6	180
		F12	Over feeling of gearbox with oil	Over pressurization of the gearbox resulting in leakage of oil from shafts	Time related	8 9 9	648
		F13	Gearbox failure for any reason whilst shutdown	Loss of unit output to system, loss of redundancy or reduced production output.	Loss of drive transmission when required	5 8 7	280
		F14	Oil supply pipe works fittings leak externally	Loss of unit output to system, loss of redundancy or reduced production output. Atomized oil leak possible	Random failure resulting in loss of lubrication oil to surrounding area, pressurized oil leak possible, fire danger	5 9 6	270
		F15	Pinion oil supply nozzle blocked	Loss of unit output to system, loss of redundancy or reduced production output.	Random failure resulting in loss of lubrication oil. Increase heating effect, pinion failure	8 7 5	280
		F16	Gearbox breath choked	Over pressurization of the gearbox resulting in leakage of oil from shafts	random	5 6 8	240
		F17	Failure of hydraulic/lubrication system	Loss of lubrication & cooling increased bearing wear eventually seizes.	Time related	8 7 9	504

Fuzzy Approach: Qualitative Framework

The above listed limitations of traditional FMEA are addressed by using fuzzy logic developed using MATLAB based on fuzzy set principles as discussed above. The basic system architecture of fuzzy logic consists of three main modules i.e. knowledge base module and user input/output interface module as shown in Figure 12.

The input parameters i.e. P_f, S and P_d, used in FMEA, were fuzzified using appropriate membership functions to determine degree of membership in each input class. For the output variable, to rank riskiness level, both triangular and trapezoidal membership functions were used (Figure 13(a) and 13 (b)). Multiple experts with different degree of competencies (skill, knowledge) were used to construct the membership function.

The resulting fuzzy inputs were evaluated in fuzzy inference system, which makes use of well-defined rule base based on the membership functions of the three input variables P_f, S, P_d with, five fuzzy sets (remote, low, moderate, high and v. high). Finally to express the riskiness/criticality level of the failure so that corrective or remedial actions can be prioritized accordingly, deffuzification is done using centroid method to obtain crisp value from the fuzzy conclusion set.

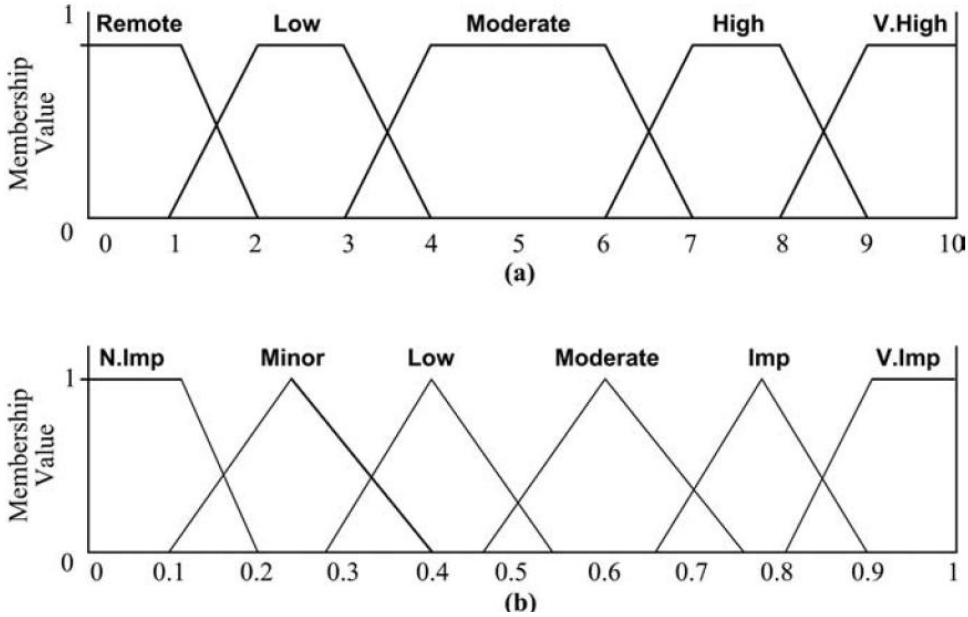

Figure 13: membership functions for: (a) input (P_f, S and P_d); (b) the output (RPN) (modified from Rajiv, et al., and 2010)

Table 11: FMECA and Fuzzy Logic

Failure modes	FEMCA RPN output	FEMCA ranking	Fuzzy RPN	Fuzzy ranking
F1	320	4	0.664	3
F2	294	4	0.660	4
F3	168	9	0.617	6
F4	180	8	0.655	5
F5	216	7	0.511	9
F6	320	4	0.664	3
F7	144	10	0.521	8
F8	512	1	0.667	2
F9	441	3	0.679	1
F10	150	10	0.511	9
F11	180	8	0.511	9
F12	648	1	0.699	1
F13	280	5	0.664	3
F14	270	5	0.657	5
F15	280	5	0.660	4
F16	240	7	0.617	6
F17	504	2	0.621	3

The summary of the results obtained through traditional and fuzzy method is presented in Table 11. From Table , it is observed that for events F13 and F14 where P_f, S and P_d are described by "Moderate, High" and "High", and "High, High, Moderate" respectively, the traditional FMEA output is 280 for both, this means that both the events are prioritized at same rank i.e. 5th . But the defuzzified outputs for F13 and F15 are 0.664 and 0.660 respectively which shows that F13 should be ranked higher (i.e. 3rd) than F15 (i.e. 4th). Also, for causes F4 & F5 which are represented by different sets of linguistic terms, (i.e. 'Moderate', 'Very high' and 'Moderate'; 'Moderate', 'Moderate' and 'Moderate') produce identical RPN i.e. 180.(i.e. 8th) . But fuzzy logic output so obtained is different for both of them (i.e. 5th and 9th, respectively).

4.5 Failure Analysis and Improvements: Root Cause Failure Analysis (RCFA) Strategies

The effectiveness of the maintenance is evaluated systematically on the basis of recorded data for performance and technical condition in respect of facilities or parts thereof. The party responsible continually improves health, environment and safety by identifying the processes, activities and products that need improvements, and implement necessary improvement measures. The measures must be followed up and their effect must be evaluated. The personnel have to be stimulated to take part in identifying weaknesses and suggest solutions. Therefore it is critical to choose the KPIs that support the overall goal and strategy the company has for the operational phase the asset. Setting targets, measuring performance and acting on the results are the key to the success of a company's maintenance management.

When it comes to developing useful KPIs, it is easier to measure what was done in the past to generate lagging indicators. It is more difficult to identify and measure reliable leading indicators which predict future performance (for more details about KPIs see section. 2.1.2). For practical reasons some trigger levels are applied above which a more detailed investigation is done aiming at finding the root cause for the failure.

The triggers can be, for example, related to:

- HSE related equipment failure
- Production losses
- Cos of single failure events in terms of time, repair cost or spare cost
- Number of repeated failures over a given time period for key components
- Technical condition assessments, etc.

The aim of RCFA is to:

- avoid reoccurrence of the same event by finding the root cause
- institute remedial actions accordingly, and
- organizational learning from the event for continuous improvements

Learning from failure and events is a key to continuous improvement of performance of a plant and an organization. The following Figure 14 shows in general the work flow for continuous improvement.

The root cause failure analysis is a structured process aiming to reveal underlying physical, human, organizational or latent causes for unwanted event/incident. By learning from these underlying/root causes, proper actions can be taken at the 'right time' and the right measures implemented in order to prevent future unwanted related events.

As a result from the root cause and failure analysis, typical factors that could be subjected to attention and/or improvement are:

- Design
- External factors having negative impact on expected lifetime of equipment/component
- Condition monitoring indicators
- Operational conditions and/or procedures

- Competence(skill, knowledge and attributes)
- Procedures related to installations, repairs, modifications or reinstallations

By using root because failure analysis on a regular basis, one enables continuous improvements of existing equipment, related work processes and routines in operation and maintenance. In order for the work to be predictive, it is also of great importance that suggested measures are not just locally implemented out but also across relevant plants, organizations and regions in an integrated operational setting.

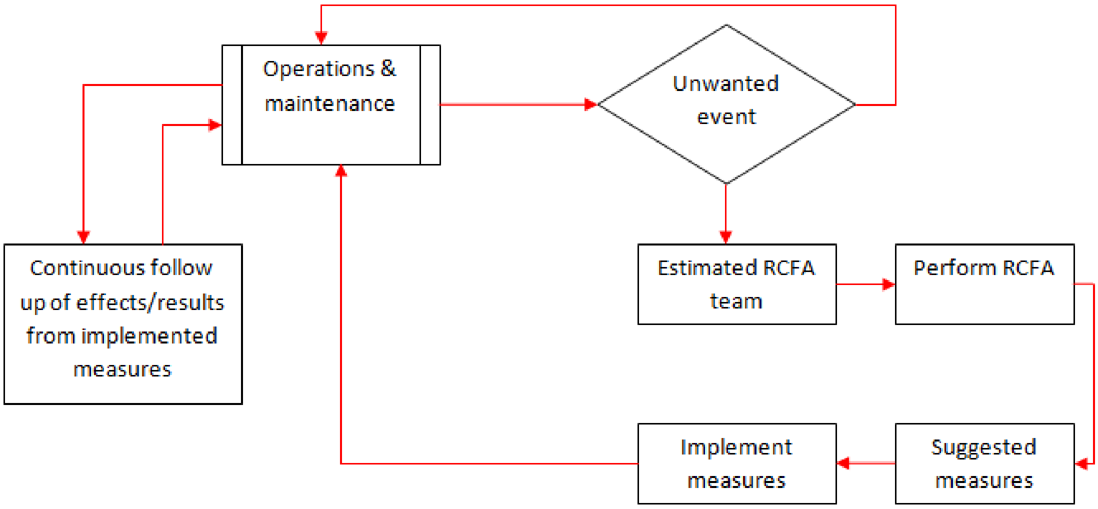

Figure 14: Root Cause and Failure Analysis improvement loop (adapted from DNV, 2009)

It is important to be unbiased towards the cause of failure in the initial stage of an assessment as the real cause can be quite different from what we observed as the trigger for the event. In order to narrow the search for the root cause, as shown in Figure 16 below, a set of tools and methods are available, such as: STEP (sequential time event plotting); FMECA (failure mode effect and criticality analysis); FTA (fault tree analysis) etc.

The RCFA process is an elimination of causes via collecting of evidence and logical reasoning in order to narrow the search for the root cause (see Figure 15).

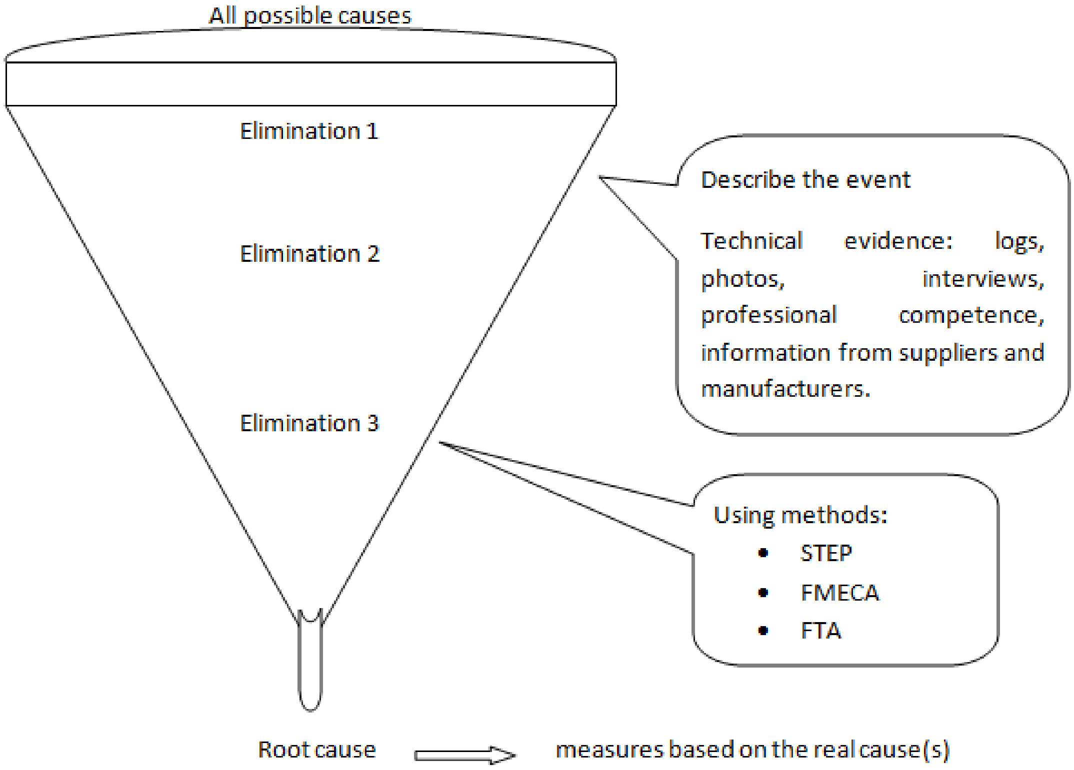

Figure 15: RCFA elimination process (adapted from NDV, 2009)

Root cause might mean different things depending on where in an organization the question is asked. For example, a failed bearing can be:

- simply lack of lubrication or installation misalignment for a technical person
- lack of training of maintenance and operation personnel for the manager
- employment policy for an operator
- And the case can be approval of license to operate for authorities

An integrated operational approach solves the above problems. The 'loss causation' model (Appendix D), for example, is a model aiming to align these different 'causes'. The model is reactive in the sense that it explains events, and proactive in the sense that preventive efforts can be instituted to avoid reoccurrence. The model also is a mean of avoiding blaming technical causes only put points to the organization, its handling of people/organization, procedure/standards and capacity. The model was developed connected to safety management, but it is also relevant in connection to operation and maintenance management and hence can be taken as a generic model.

For complex and advanced industrial assets he following three things must be considered to improve RCFA methods;

- New tools for conducting root cause analysis
- Increase monitoring and control of the physical asset
- Reporting of incidents/events in a more comprehensive way

CHAPTER 5

Summary and Conclusion

5.1 Work Summary and Results

New technologies are becoming advanced and complex for offshore Oil & Gas production facilities. However, this advancement and complexity in technology creates a more complicated and time consuming forensic processes for finding causes of failure, or diagnostic processes to identify events that reduce performance. As a result, micro-sensors, efficient signaling and communication technologies for collecting data efficiently, expert software (such as fuzzy logic, neural networks, and simulation based optimization) have been developed, in parallel, to manage such complex assets.

Given the nature and scale of ongoing changes on complexities, there are emerging concerns that increasing complexities, ill-defined interfaces, unforeseen events can easily lead to serious performance failures and major risks. To avoid such undesirable circumstances, 'just-in-time' measures of performance to ensure fully functional is absolutely necessary

This paper highlighted improvement mechanisms to establish 'just-in-time' maintenance by developing an integrated maintenance management framework to optimize maintenance program and to ensure continuous improvements in maintenance strategies based on maintenance domain experts as well as operational and historic data. Figure16 shows the overall vision of the integrated maintenance management can contribute to improving overall performance of the asset. As shown in the Figure 16 the repairable asset needs 'just-in-time' maintenance intervention in order to perform full functional. The system performance curve then follows the same path until it reaches the next failure point. Potential cost benefits can be gained by saving the system from unnecessary down time.

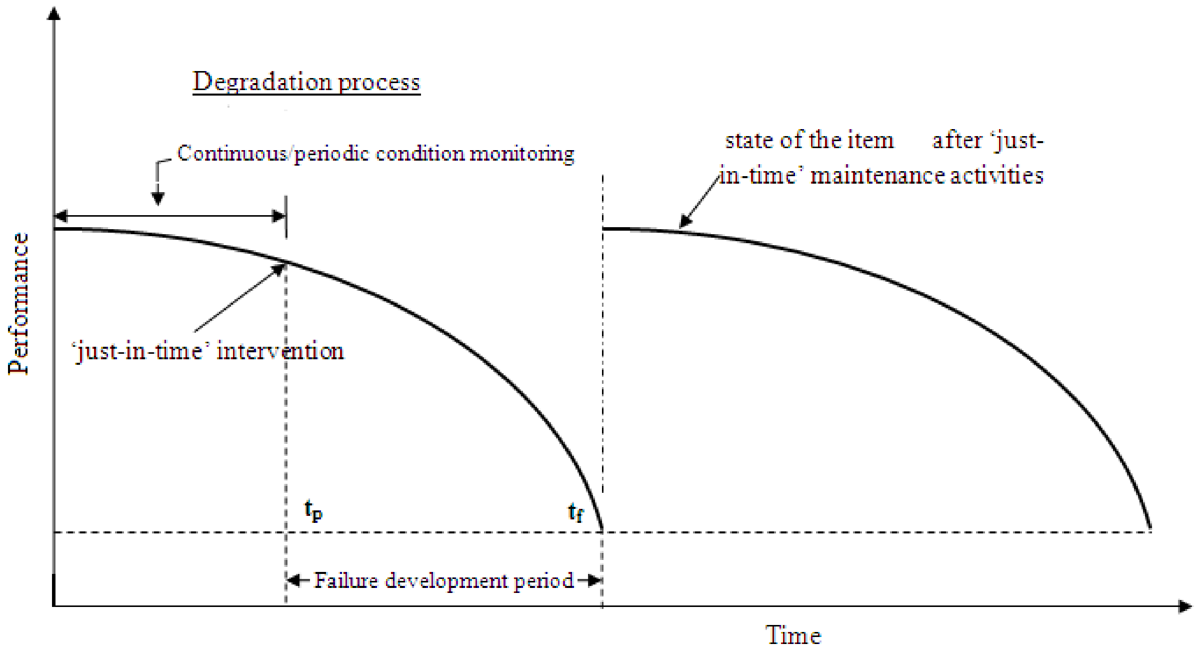

Figure 16: Optimized performance curve for repairable equipment

In the above optimized performance curve for repairable equipment, we can argue that by establishing 'just-in-time' maintenance intervention, maintenance related costs can be improved for the system. This is the concept that maintenance experts must consider while implementing new techniques (e.g. intelligent techniques) for performance optimization.

To put it in nut shell, the output of the thesis, as a result of this integrated maintenance management framework, optimized maintenance performance helps to improve HSE risk levels, production regularity and cost related to maintenance as depicted in the Figure 17 below.

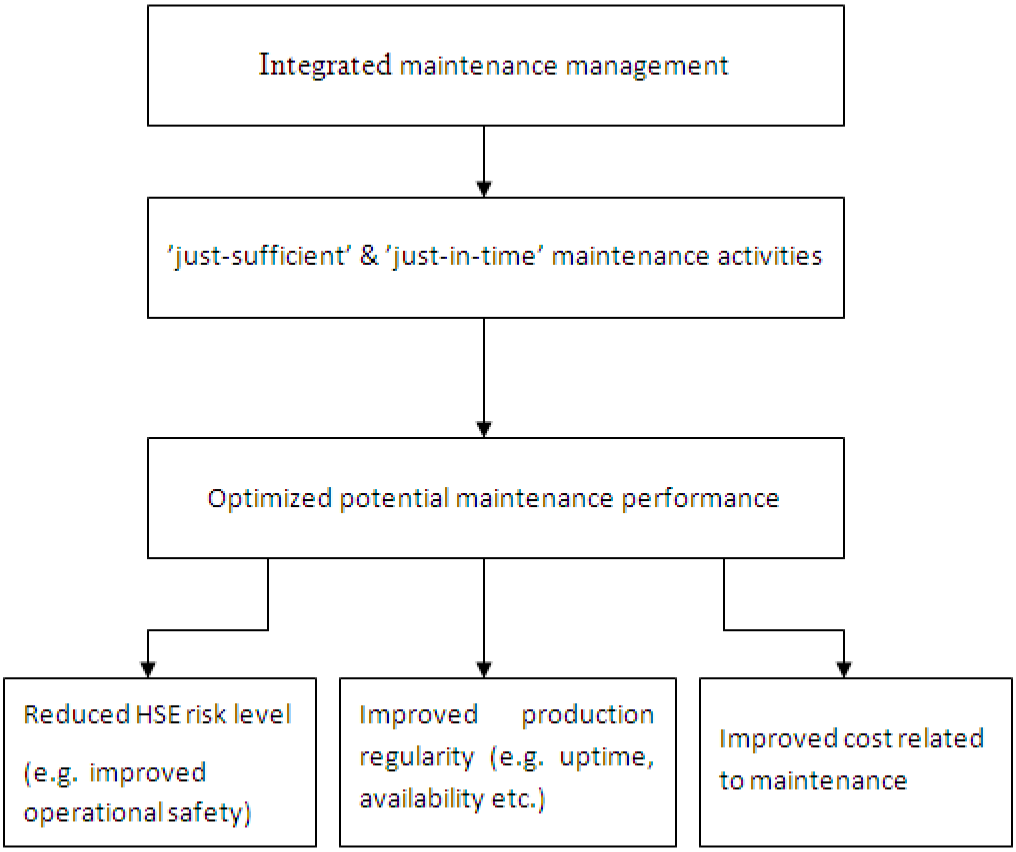

Figure 17: Integrated maintenance management to improve maintenance performance

5.2 Conclusion and Future Research Directions

Integrated maintenance management framework in the Oil and Gas Industries helps to explore the use of sophisticated technical solutions. The application of such sophisticated technologies in maintenance and operations of complex production facilities can bring huge benefits in terms of reducing risk. To utilize such sophisticated technologies, it is important to understand the interconnected issues and challenges. Some of the potential benefits of the use of such integrated maintenance management include:

- Enhancement in terms of better and effective control of potential events and incidents that may lead to functional failures.
- Model, analyze and predict the behavior of systems in more realistic manner (removes vagueness in maintenance planning).
- Manage the dilemma of direct (quantitative) evaluation of intangible (qualitative) criterions used in traditional analytical methods with the help of well defined membership functions to synthesize fuzzy information.

- Helps in a quick review of ranking of numerous maintenance tasks to plan suitable maintenance practices /strategies for improving system performance (Jardine, 1991; Sherwin, 2000; Sharma et al. 2005b, c; Pintelon et al., 2006).
- Helps to eliminate “over/under maintenance”
- Helps to find out hidden failure causes.

Successful applications of various maintenance optimization models are rare. The major problems in applying the models are: computational difficulties; difficulties of collection of data and modeling of failure distribution. It is vital to carry out an in-depth investigation to:

- develop an effective methodology for modeling equipment’s failure distribution or degradation process, which considers what information is required for modeling, how such information is obtained, how the model parameters are estimated, and how the model is updated when new information becomes available(Albert et. al. , 2006);
- I believe that extensive data collected from asset maintenance logs and historic records can be analyzed to justify the cost-benefit analysis of the ‘just-in-time’ maintenance interventions and is therefore recommended as a topic for further research.

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Appendix

A-Maintenance Management model

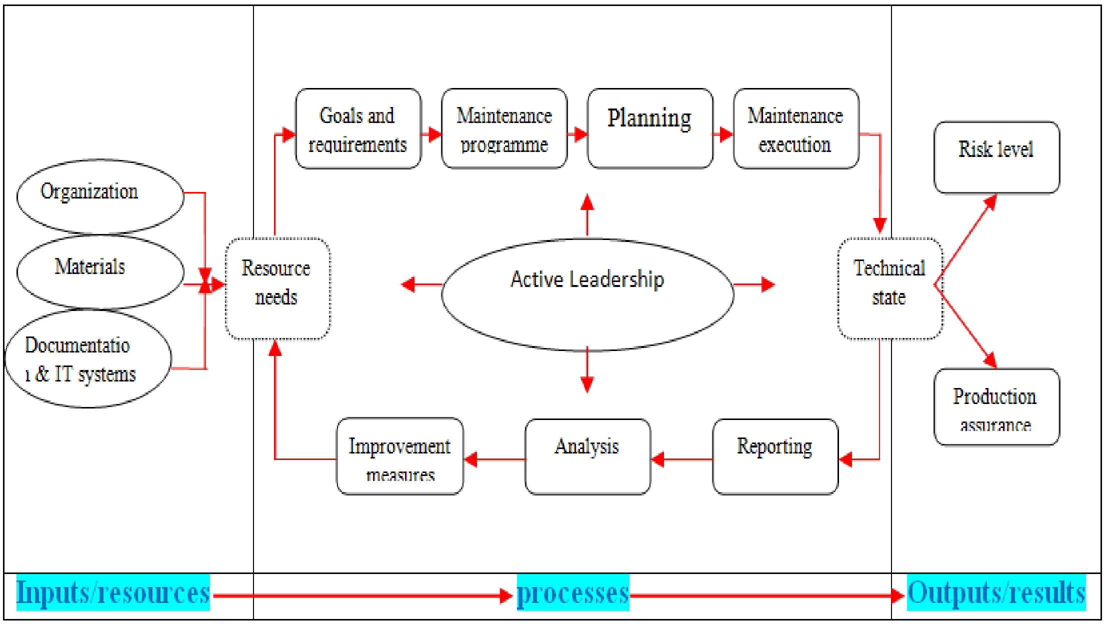

Figure A-1 Maintenance management model (PSA, 1998)

B-Main Function and Sub Function Classification

For example, the sub functions of typical process equipment can be classified as follows to cover all requirements. These sub functions are:

- Main task (term describing the task).
- Pressure relief.
- Shutdown, process.
- Shutdown, equipment.
- Controlling
- Monitoring
- Local indication.
- Manual shut-off.
- Containment
- Other functions.

A comprehensive assessment of the standard list of sub functions has to be completed with other sub functions relevant for the particular operation to easily identify functional failures. All equipment (identified by its tag number) in each instrument loop be assigned to one sub function. If a sub function performs multiple tasks, the equipment will be assigned to the most critical sub function. The standard sub functions are only to be used if relevant. When appropriate, other repetitive sub functions (i.e. lubricating, containment of different services, etc.) may be used.

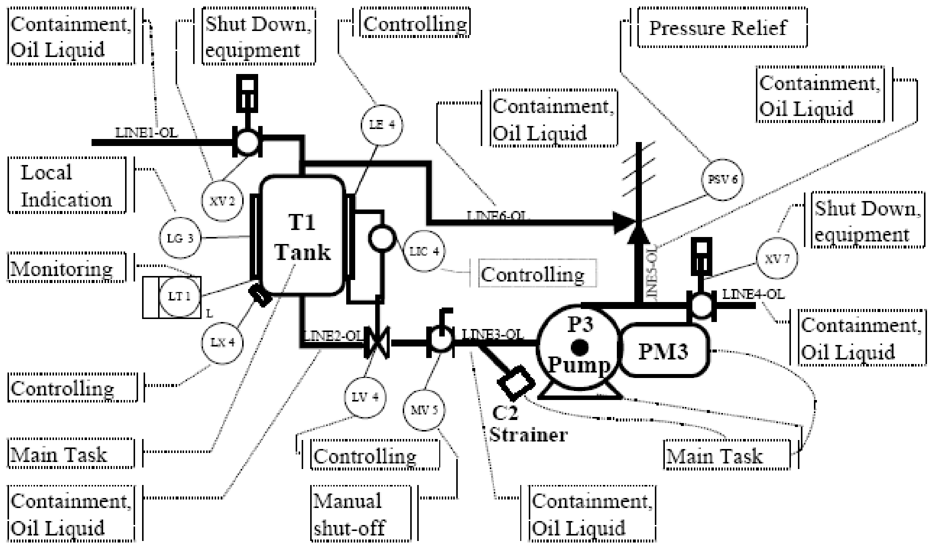

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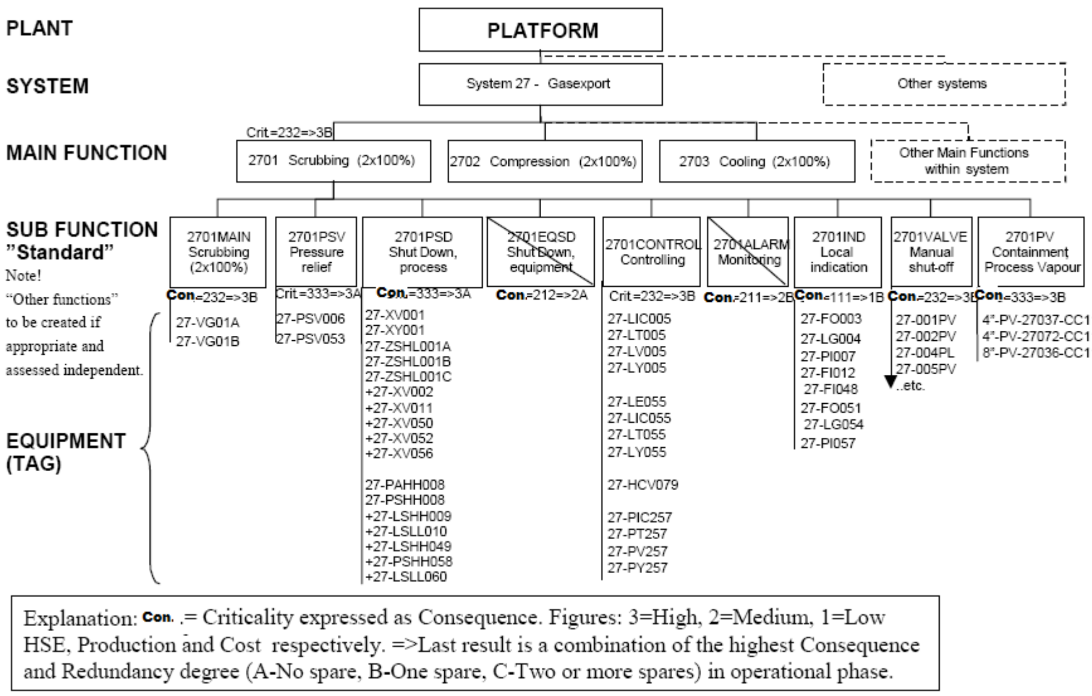
Figure B-1: Illustrates how equipment in a MF is assigned to standard sub functions (adopted from, NORSOK Z008 rev. 2)



FigureB-2: Functional Hierarchy, example with standard sub function and classification (modified from NORSOK Z008 rev. 2)

C- Maintenance program and Planning (as recommended by NORSOK-Z008)

As an example a work flow for establishment of maintenance programme for a new plant is describe below and illustrated in Figure C-1. The figure is based on NORSOK Z008.

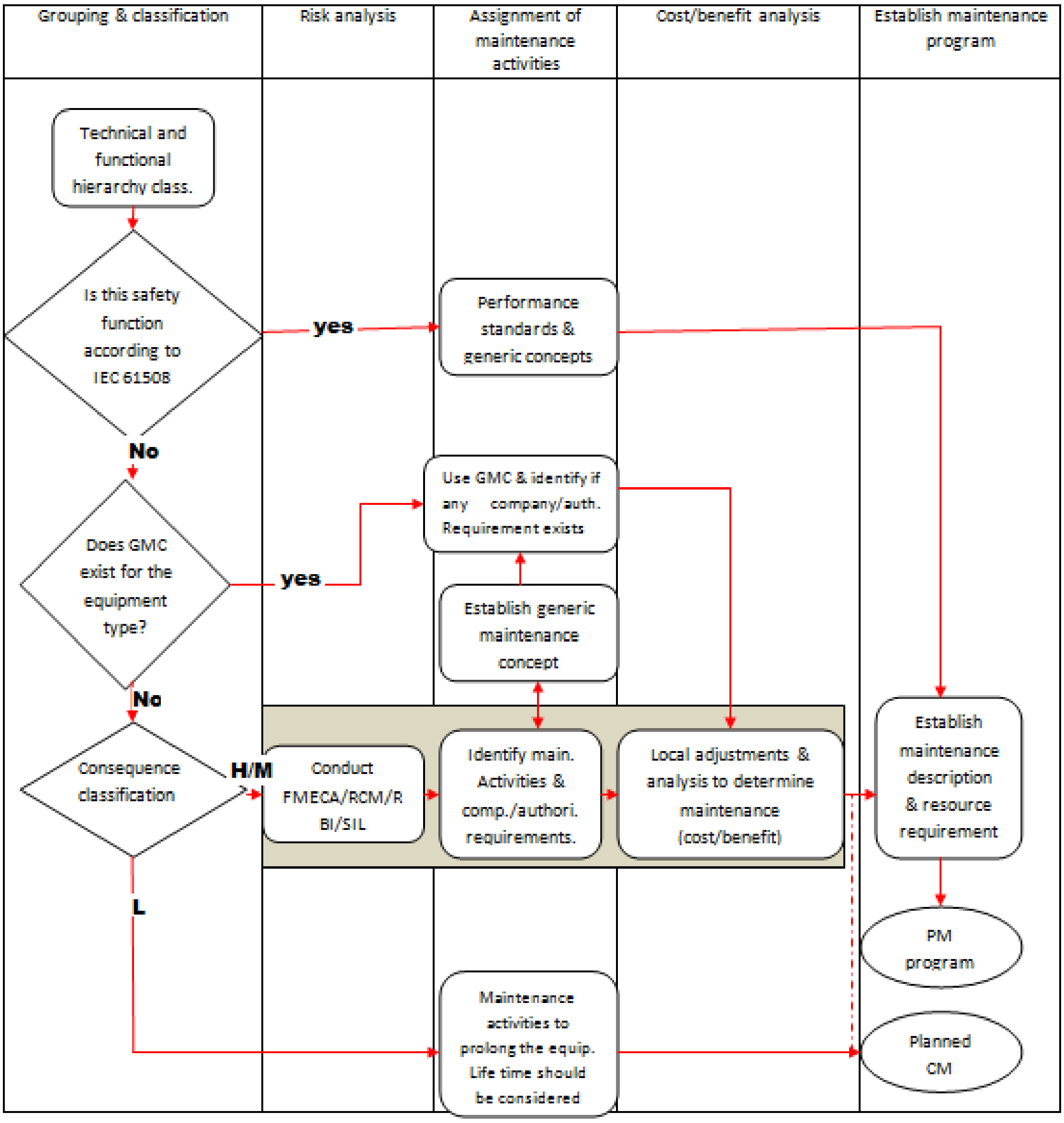


Figure C-1: work process for the establishment of maintenance programme (NORSOK Z008 rev. 3)

The process is based on the following principles:

- Input to the process is the technical hierarchy and a functional grouping. The classification acts as a screening process in the sense that equipment groups related to safety barriers are handled directly as such equipment shall have set performance standards with reliability requirements and associated test intervals. Furthermore, for many safety systems there will exist additional maintenance tasks to be done like cleaning, lubrication, etc. which should be described in generic maintenance concepts for this equipment group. These data and tasks are then input to the maintenance programme.

- Formal FMECA/RBI/RCM to determine failure mode, failure mechanisms and cause tasks is done for new equipment representing high risk and where no GMC are available.

- For equipment where maintenance has been done for some time and where maintenance task lists are available, the optimization process is mainly to challenge the existing regime regarding content and frequency of the existing activities as well adding new once based on experienced failure degradations. This implies that maintenance and operation personnel familiar with the installation is closely involved with this work.

- FMECA/RBI/RCM analysis can be transformed to a generic maintenance concept for later use on similar equipment

- For equipments classified with low consequence of failure, a planned corrective maintenance strategy may be selected (run to failure). However, a minimum set of activities to prolong a lifetime may also be considered.

- Cost/benefit analysis is used to determine maintenance strategy for the offshore production facilities and intervals based on consequence of failure, cost of maintenance and how this maintenance will affect future probability of the identified failure modes.

- Finally, all the maintenance tasks should be packed and scheduled considering plant production plans, resources requirements, turnaround schedule, etc. to derive to the final maintenance plan.

The following Figure C-2 is such as example showing selection of work orders to prioritize (maintenance planning as recommended by NORSOK-Z008)

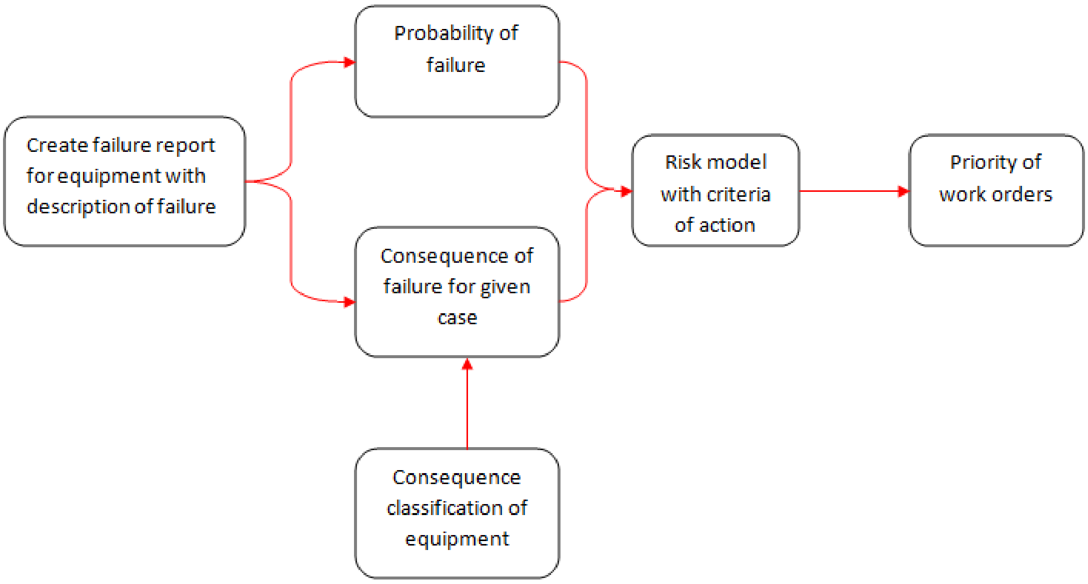


Figure C-2: priority of corrective work orders based on risk of failure (based on NORSOK-Z008 rev. 3)

The traditional process involves the following points:

- Assigning the consequence of failures to the case. It can be done via criticality classification of the component. This consequence always be supplied by information regarding the actual failure modes, the actual operational condition of the plant, possibilities for re-routing the process, etc. as such the process cannot be automatic, but requires involvement from personnel knowing the production facilitates and the actual case.

- Assigning the failure impact. The failure impact is a coarse probability scale. (Critical, degraded and incipient failure), see Table 6 below.

- The risk associated with the consequence and probabilities as well as actions from this risk must be defined in given criteria, for example by means of risk matrix. Table 8 shows an example of a risk matrix model described as a risk matrix used to determine precedence of work orders.

D-The 'Loss Causation' Model

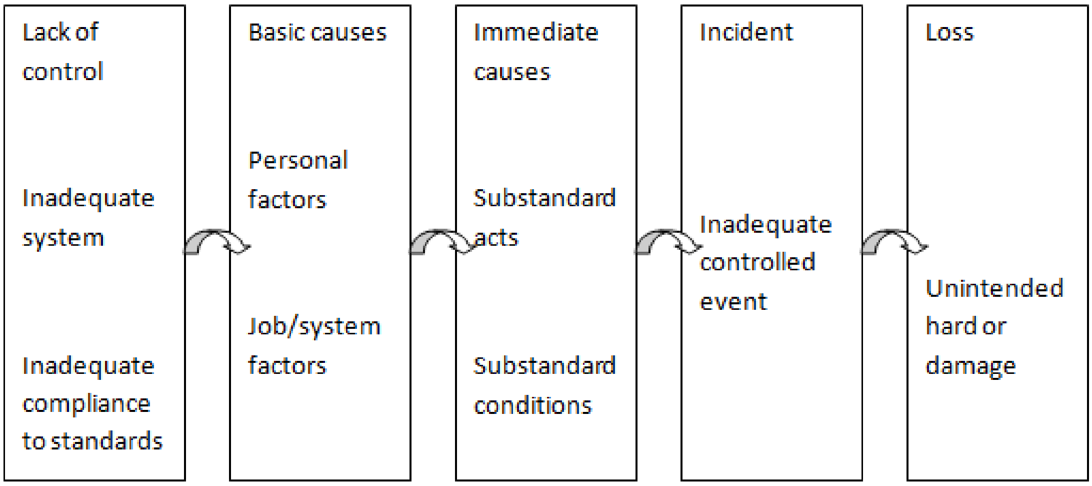


Figure D-1: the 'loss causation' model (adopted from DNV)

E- Reporting

The ISO 14224 standard gives recommendations for reporting of data related to maintenance. The results from the maintenance activities should be logged on the work order. Typical issues to be reported are:

> Equipment/tag
> Failure mode
> Failure cause and mechanism
> Start and end date
> Spare parts consumption
> Man-hour activities
> Equipment down time and etc.

Below are lists necessary information to be registered in order to comply with ISO 14224.

- Maintenance data
    - Maintenance record identification
    - Equipment identification/location
    - Failure record identification(relevant for CM only)
    - Date of maintenance
    - Maintenance category(CM, PM)
    - Active maintenance time
    - Downtime and etc.
- Failure data
    - Failure record identification
    - Equipment identification/location
    - Failure date
    - Failure mode

- Failure impact on equipment(critical degraded or incipient failure)
- Failure mechanism
- Failure cause
- Sub unit failed maintainable item failed, etc.

For safety systems, the results should be reported in a way that enables back tracking to individual units, i.e. individual PSVs, gas detectors, etc. as opposed to reporting performance for a group of equipment.