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**Developing Framework to Analyze
World-Class Maintenance (WCM) Indicators:
GAP Analysis to Highlight Challenges and Opportunities for
the Norwegian Petroleum Industry**

By

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This is submitted in partial fulfillment of the
requirements for the degree of MASTER DEGREE in Offshore Technology

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Abstract

World-class Maintenance (WCM) is a unique business process which actually does not cost, rather pays back. This study was an initial attempt to understand the extent of WCM concept being utilized in the Norwegian industry. The aim of the study was to develop a framework for analyzing the WCM indicators. For this purpose, the study was focused to: identify measurable WCM indicators, find the trends of WCM in the Norwegian sector, and find gap between current maintenance practices and world-class standard. The research study was conducted based on existing literature and experts' experiences which revealed that based on continuous developments within the maintenance paradigm, there is a great need for effective and broader maintenance concept like WCM. The study concluded with WCM indicators with measurable range which were based on industry best practices. The current maintenance practices in Norwegian industry were compared with aforementioned WCM standards. Based on these results, a framework was developed which forms the basis for gap analysis. Finally, some useful recommendations were also given to the Norwegian petroleum industry.

Key Words: World Class Maintenance, Key Performance indicator, Maintenance best practice.

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Abbreviations

KPI	Key Performance Indicators
WCM	World-class Maintenance
NCS	Norwegian Continental Shelf
RCM	Reliability Centered Maintenance
TPM	Total Productive Maintenance
RBI	Risk-based Inspection
CMMS	Computerized Maintenance Management Software
PM	Preventive Maintenance
CM	Corrective Maintenance
RCA	Root Cause Analysis
FMEA	Failure Modes and Effects Analysis
O & G	Oil and Gas
ROI	Return in Investment
FMECA	Failure Modes Effects and Criticality Analysis
PdM	Predictive Maintenance
BMP	Best Practiced Maintenance
MTBF	Mean Time Between Failures
RAV	Replacement Asset Value
OEE	Overall Equipment Efficiency
DNV	Det Norske Veritas

Chapter 1

Project Description and Formulation

1.1 Introduction

Since the beginning of industrial era, people have realized the need for the maintenance of equipment. But at earlier times people thought of maintenance as an added cost to the plant which did not increase the value of finished product and traditionally maintenance was only done when it was no longer possible to run it. Maintenance does not mean to eliminate the failure only, but to identify the cause and to understand the consequences.

Over the last few years, due to more competitive market and complex product, maintenance practices have significantly changed, from time and use based to reliability and condition based, as well as to find the root cause to eliminate failure and to monitor the condition of the equipment.

Maintenance plays an important role in success or failure of an industry. Maintenance function enables a company to increase their asset capacity by maintaining current fixed costs. Therefore, it is vital for maintenance management to be integrated with corporate strategy to ensure equipment availability, quality products, on-time deliveries and competitive pricing.

1.2 Understanding the importance of maintenance basics:

Most industries do not understand that, understanding the basics of maintenance is one of the core competencies of any type of business and also the first step before implementing any improvements initiatives. There is a repetitive tendency of failing to focus in the basics.

History shows that over the past few decades, maintenance did not receive the proper attention as it deserves. Insufficient resources were allocated to perform the maintenance activities. As a result, maintenance department has failed to preserve the asset in good working condition.

However, in last few years, this attitude of organizations has changed dramatically. Maintenance is now attending the peer attention together with operation. The corporate world has now realized the value adding essence of maintenance.

The new paradigm of maintenance is equipment capacity assurance i.e. run the equipment to its design capacity during most of its operating time. Ensuring the equipment reliability is the most vital responsibility of maintenance function (shown as in Fig 1).When the maintenance function is properly developed and managed, it can achieve world-class competitiveness and it is vital to understand the basics of maintenance to move towards new approaches.

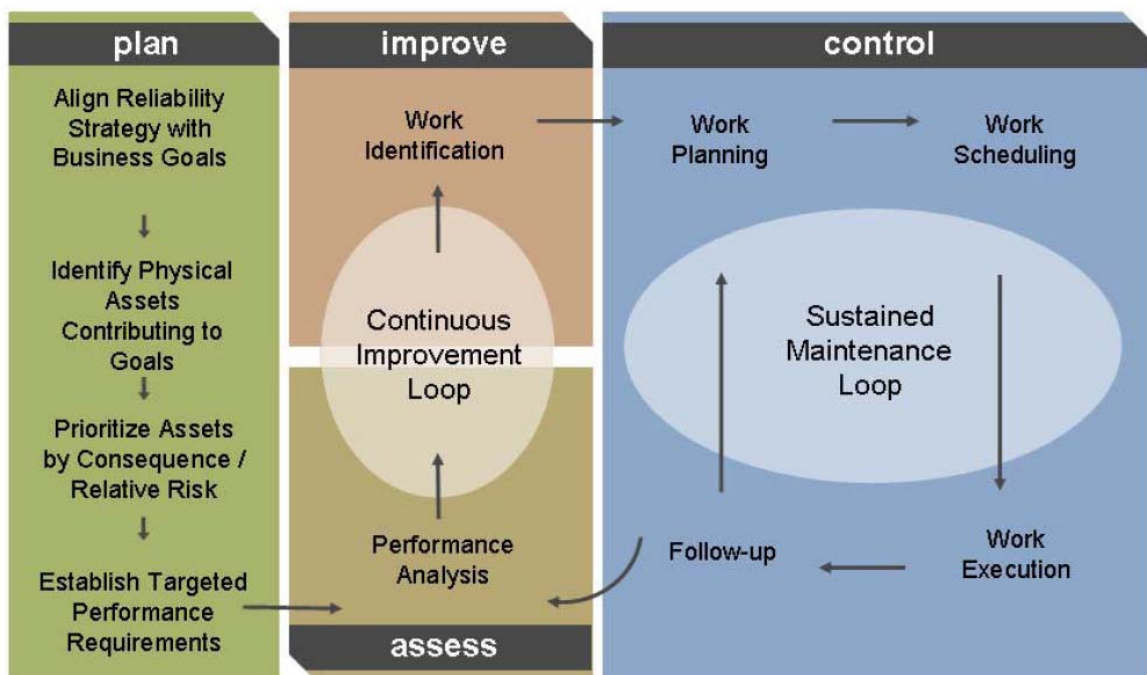


Figure 1: Managing the maintenance function (Weber 2005,p.5)

Companies must be more efficient and effective in utilizing assets and equipments. Maintenance department has the maximum contribution for asset management as maintenance impacts on condition of the equipment and thereby capacity.

The role of maintenance is to ensure that the equipment is performing its intended function at an optimal cost. The key to zero failures is to uncover and rectify hidden abnormalities which often go unnoticed. This is the fundamental concept of maintenance.

1.3 Maintenance Classifications:

Basically, there are two maintenance approaches. One is reactive and the other one is proactive. In a reactive approach (is shown in Figure 2), maintenance is concerned with how quickly equipment can be returned to operating condition after it has failed.

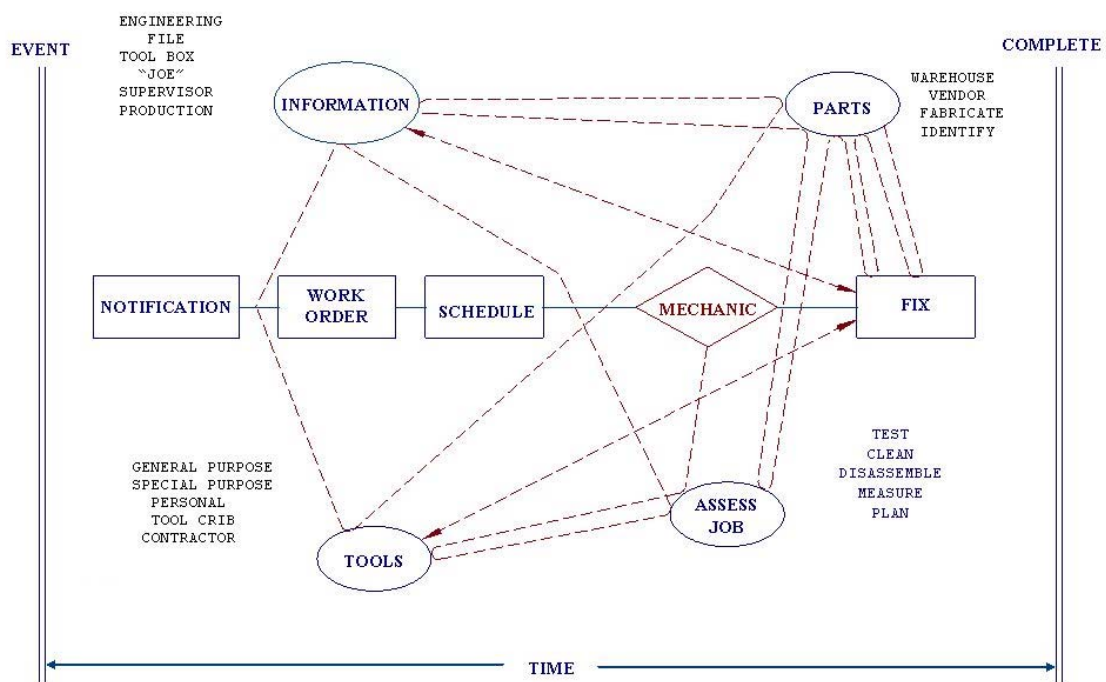


Figure 2 : Reactive maintenance Model (Smith and Mobley, 2008 p.4)

On the other hand, proactive approach (shown in Figure 3) is based on equipment assessment by preventive, predictive and condition monitoring methods. Preventive (proactive) maintenance is a planned maintenance activity that is designed to improve

equipment life and avoid any unplanned maintenance. Maintenance programs for offshore installations are developed based on preventive maintenance routines through the use of best practices recommended by the original equipment manufacturers. As suggested by Wireman, (1991) the results of preventive maintenance (PM) are:

- Increased automation
- Reduce business loss due to production delays
- Reduction of equipment redundancies
- Reduction of insurance inventories
- Longer Equipment life
- Produce higher quality product
- Creates more organized and planned environment
- Improved HSE

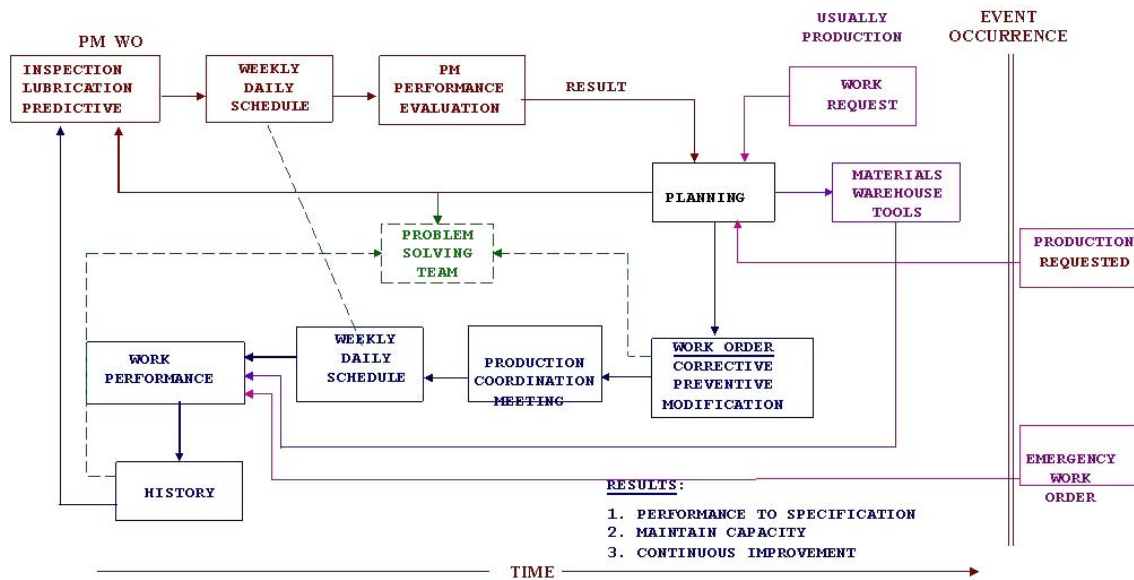


Figure 3 : Mt. Holly's proactive maintenance model (Smith and Mobley, 2008 p.5)

Combinations of these two approaches include a range of maintenance techniques currently used by the industries. According to a research by Wireman (2010), some examples of these techniques and tools are:

- Preventive maintenance
- Stores and procurement
- Work Flow Systems
- Computerized Maintenance Management Systems (CMMS) and EAM
- Interpersonal Training

- Operational Involvement
- Predictive Maintenance (PdM)
- Reliability-Centered Maintenance (RCM)
- Total Productive Maintenance (TPM)
- Statistical Financial Optimization
- Continuous Improvement.

1.4 Problem Formulation

The present thesis provides insights into the recent development of maintenance technologies and current practices in the petroleum industry. In this context, a combined maintenance concept World Class maintenance (WCM) has been addressed with following questionnaires:

- What is the meaning of WCM concept?
- How can an organization achieve world-class status?
- How feasible it is to apply WCM concept in the Norwegian Petroleum industry?

The purpose of this thesis is to formulate a framework based on the WCM indicators. To establish the framework it is necessary to define the WCM indicators first. Key questions to address such challenges are:

- Is the current maintenance practice capable of delivering the required function?
- What can be gained by adopting the WCM concept?
- What are the WCM indicators?
- Are the WCM KPIs capable of highlighting the opportunity for improvement?

This thesis also focuses to addresses the need for quantifiable indicators which will be used to find the gap in the current practices against the world class standards.

1.5 Thesis Objectives:

1.5.1 Main Objective:

Developing framework to analyze World Class Maintenance (WCM) indicators.

1.5.2 Sub Objectives:

- To identify existing WCM standards.
- Develop a framework for measurable indicator for WCM (for the petroleum industry).
- Identify trends of WCM in the Norwegian sector.
- Recommendations/suggestions to the petroleum industry.

1.6 Project Activities:

This study focuses on the evolution of WCM concept in the petroleum industry. For this purpose the following activities were required to perform:

- Perform a detailed literature survey on current maintenance practices and on the facts that bring about the WCM concept.
- Discussion with experts in this field to assess the validity of the practical implication of the WCM indicators for the Norwegian industry.
- Recommendations are given based on the challenges faced by the industry,

1.7 Research Methodology:

Various plant maintenance sites, seminar papers, presentations, internet search engines and articles from internationally renowned maintenance authors were put into effective use in developing this thesis. The main source of information was internet. Some books related to the topic of interest have also reviewed. Furthermore, applicable standards and regulatory requirements were reviewed to obtain detailed insights into specific rules and regulations of maintenance in Norway. Experts' experiences from the industry plays a key role to find the reasonable logics for the implementation of the indicators.

1.8 Research Limitation:

The framework developed in this thesis is mainly based on theory and knowledge gained through discussion with experts in the field. As the primary implication is the complex offshore oil and gas production facilities, implementations might be limited. For gap analysis purpose, it was required to perform a survey by interviewing responsible maintenance personnel from the industry. But due to time constraints interview was not carried out and for that it is out of scope at this stage.

Chapter 2

World-class Maintenance

2.1 Introduction

World-class process means to be able to compete anywhere in the world and to be able to meet and beat any competitor by product- price, quality and on-time delivery. World Class Maintenance (WCM) is the best model of the maintenance process, which presupposes that it is comprehensible for all participants in the process, which is easy to apply and requires minimal implementation costs as well as that it is universally applicable and increases overall efficiency of technical systems, which ultimately leads to a greater profit for the company.

2.2 Definition of World-class maintenance

Different industry has adopted different initiatives to be a world-class organization. Many of them have referred to world-class maintenance as transition from a Preventive to Predictive Maintenance while others have argued about having the CMMS (Computerized Maintenance Management Software) in place. Some of the prevailing definitions of world-class maintenance are given below:

Mishra, et al., (2009) have given a very simple definition. WCM is the collection of best practices in maintenance that are followed and adopted by various organizations to transform themselves to be a world-class manufacturer.

Angeles, R. (2009) has stated “World-class means the art and science of managing maintenance resources performed by best in class industries from around the world”.

Ingalls (2002, 2003) mentioned that the concept of maintenance optimization is called maintenance excellence or world-class maintenance.

Kodali, *et.al.*,(2009) stated that the function of maintenance with the optics of world-class is interpreted like a strategic capacity that a company has and allows it to compete through a good integral management of equipment throughout the service life.

Norman, (2001) stated that World-class maintenance is a holistic system which is created when organizations combine coherent, visionary leadership with robust processes and supportive culture to ensure that the vision and ownership of appropriate maintenance methods permeate the organization.

Here, visionary leadership means the capacity to speculate the future related to market demand, global competition, ability to cope with modern technology. Robust process means combination of PM, PdM, Condition Monitoring etc. which will fit with the management process. And supportive culture means industry practice to adapt with the changes.

2.3 Criteria/Characteristics of WCM

Levitt, (1996) and Peterson, (2002) has indicated few characteristics of WCM which are given below:

- Clear Vision and Mission for Maintenance
- Well Defined Equipment Strategies
- Top Management Support
- A Proactive NOT Reactive Approach
- Accurately Managed Costs
- Total Facility Understanding & Participation in Maintenance.
- Effective Maintenance Planning
- Use benchmarking
- Make continuous improvements
- Provide continual training
- Share information
- Make people, rather than technology or computer systems, the priority

2.4 How a company can achieve World-class status:

It is a real challenge to become world-class and required to implement best practices in maintenance. There are a lot of ingredients to establish a WCM program. Among them five important ingredients of WCM are:

- Considering maintenance as a profit center.
- WCM focus on resources for best ROI
- WCM avoid intrusive maintenance
- WCM measure results
- WCM employ an effective manage system. (Smith, 2009)

WCM requires integration of maintenance management function with total organizational function. The concept does not mean merely that by following some world-class maintenance indicators an organization will eventually become world-class. In reality, the organization needs to reach some levels. It is shown in the following figure:

- **First level:**

This is the very first attempt of the organization to be world-class. At this level, the basic maintenance work process should be maintained. After the basic functions are in place, areas to be improved should be identified. Most of the maintenance expenses are found at this step.

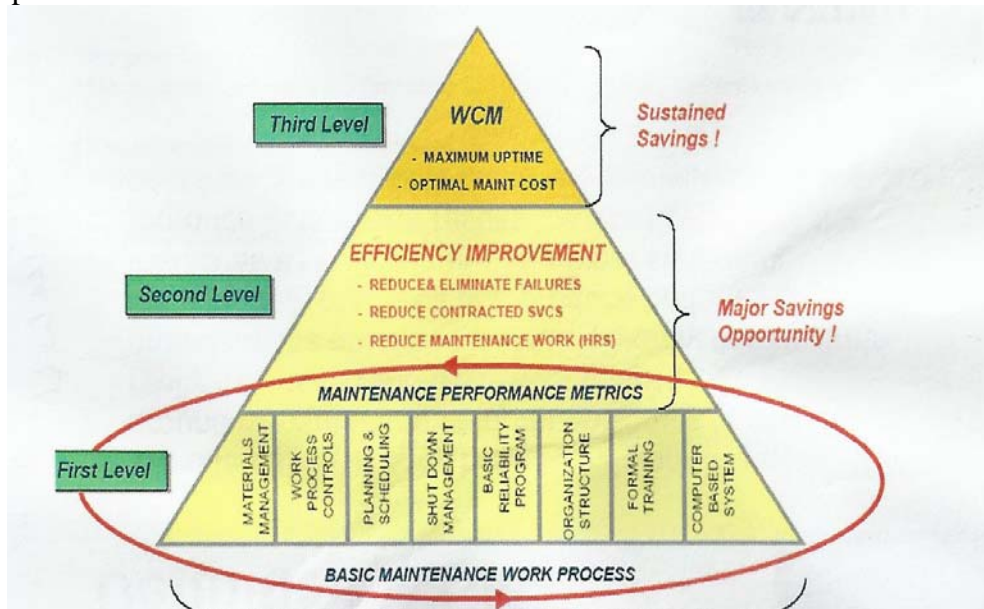


Figure 4 : Levels to achieve world-class standard

- **Second level:**

At this level, the efficiency of the maintenance program should be improved by reducing and eliminating failures. Maximum saving opportunities are possible here.

- **Third level :**

At this level, the equipment uptime should be maximum. Therefore, maintenance cost reaches to an optimal level reflecting sustained savings. When the organization reaches at this level, it can be regarded as World-class Maintenance organization.

2.5 Major offshore accidents due to negligence in

Maintenance:

History shows that due to negligence in maintenance, devastating disasters like Sea Gem, Alexander Kielland, Ocean Ranger, Piper Alpha, Petrobras P-36, West Atlas, Deepwater Horizon and many more had occurred. It is a matter of sorrow that these incidents keep recurring in the offshore industry. Similarities between the blowout in Montara field, West Atlas and the Deepwater Horizon tragedy are quite striking.

Findings of these incidents have pointed fingers at operators as well as maintenance department, that these incidents occurred due to common mistakes and negligence in terms of maintenance, inspection and pre-planning.

The lesson learned from all these incidents will definitely help to make the path of the evolution of WCM. Two of these major incidents have been discussed here.

2.5.1 Deep water Horizon:

Deepwater Horizon is regarded as the largest accidental oil spill in history into the Gulf of Mexico. The incident made a tragic headline around the world which kills 11 people and unleashing oil spill up to 4.9 million barrels. Here we will not focus in details about the incidents rather will try to reveal the hidden causes of failure which are related to maintenance.



Figure 5 : Explosion at offshore oil rig Deepwater Horizon

- Study report shows that there were Lack of training in well control
- Lack of proper maintenance of BOPs.
- Late and continual changes of design and plan in an atmosphere of urgency and the need to save money or cost cutting. (Park, 2012)
- Lack of safety culture. (The Coast Guard report, April 2011)
- Inadequate maintenance, staff and inspection. (At nine years old, Deepwater Horizon has never been in dry dock.)

2.5.2 Piper Alpha:

The piper Alpha disaster in 1988 was a defining moment for the regulation of offshore operations. It has been said that at the time of the disaster, piper was one of the heaviest platforms operating in the North sea. After several investigations, it has been found that the lack of maintenance played a major role for this accident. The findings for maintenance are:

- The initial condensate leak was the result of maintenance work being carried out simultaneously on a pump and related safety valve.

- The operator of Piper Alpha was found guilty of having inadequate maintenance and safety procedures.
- There was a late change of plan, and a plant isolated for maintenance was brought back on line at short notice.



Figure 6 : Destroyed Piper Alpha oil rig in North sea

2.6 Lesson learned from history triggers evolution of WCM:

The reasons to mention the above two incidents are to emphasize that how important maintenance is for offshore industries and how time demanding the concept of WCM is. These are only two examples but there are many more. Lesson learned from those major accidents made management to think about a more robust and effective maintenance system.

All those lackings found in above two examples are basic characteristics of WCM. These lackings lead to the development of WCM indicators which are discussed in the next chapter. The lesson learned from these accidents actually the initial step of the evolution of WCM concept.

The above problems faced by the offshore industry could have been addressed by establishing a culture where each person is allowed to do the right things. If they would

have concentrated about finding the root cause, then the repetition of the same incidents had not been happened.

Chapter 3

Current Maintenance Practice in Norwegian Petroleum Industry

3.1 Introduction

Norwegian petroleum industry is more than 40 years old. So, the maintenance history is also quite old. The last major accident was in 1982 when the living quarter installation of Alexander Kielland capsized. Since then, there have been no major accidents in last 30 years. Most Norwegians are viewing the oil and gas industry as safe. But, after the Deepwater Horizon rig disaster in 2010, Norway's Petroleum Safety Authority, Ptil has been put under pressure to review the safety and maintenance implications for the NCS. Questions have aroused whether or not a similar rig blowout and fire is possible on the NCS. Although the Ptil is responsible for the safety only on the NCS, it is very much concerned about learning from incidents all over the world. It believes that transferring the experiences into lessons will help the Norwegian Petroleum industry to plan for a better future. Maintenance history of Norway is shown in the Figure: 7

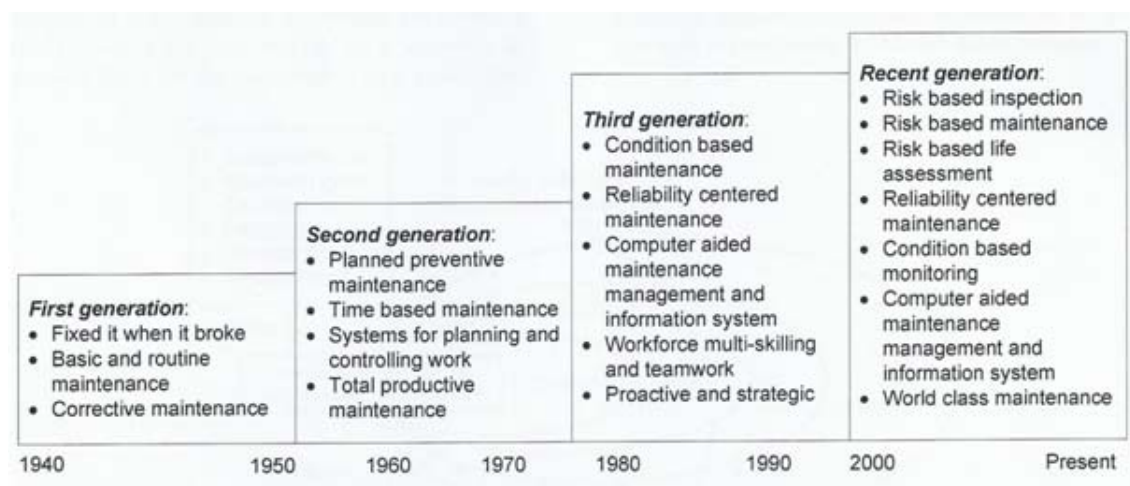


Figure 7 : Evolution of maintenance philosophies (Ratnayake, 2012)

3.2 Norwegian Offshore industry towards world-class

operation and maintenance:

The leading energy company in oil and gas production in Norway, is developing operations and Maintenance towards a world-class organization. As a first step, the leading company hired DNV to benchmark the performance of operation and maintenance for its installations in NCS. The analysis revealed a number of shortcomings of current maintenance practice which are:

- Reduced equipment availability
- Need for better prioritization of safety critical failures
- Inefficient operation and maintenance management practices
- Poor utilization of availability and maintenance opportunities.

These shortcomings necessitate a revised system for maintenance. The goals for implementing the revised maintenance management system are:

- Continuous improvement
- Enhanced production availability
- Improved management for safety and production critical equipments
- Value based performance culture.

These objectives are in summary, a contribution towards the leading company's objective in achieving world-class performance in the field of operation and maintenance.

3.3 Facts that bring about WCM concept in Norwegian

Petroleum industry:

The Petroleum Safety Authority, Ptil set standards and follow up to ensure that the Petroleum activities maintain high standards of health, safety and environment. During March 2007, Ptil conducted an audit of maintenance management of several companies in the Norwegian Petroleum industries. The audit shows that these industries do not meet the regulatory requirements for maintenance management.

The observations found in the audit were characterized as non-conformities and are grouped under the following main areas:

- Classification of systems and equipment.
- Use of classification as a basis for selecting and prioritizing maintenance.
- Managing cost-effective maintenance
- Handling and documentation of non-conformities.
- Spare part management.
- Competence of performing maintenance task.

With the current status of classification, it is difficult to make decisions for maintenance purposes. Prevailing system also does not allow to formulating maintenance needs and resource requirements. These facts trigger a new system which is capable of meeting the shortcomings found in the audit. The concept WCM comes into picture to eliminate the challenges faced by the petroleum industries now-a-days.

By comparing the characteristics of WCM with prevailing maintenance practice, it is possible to find how WCM concept can help to solve the existing challenges:

- While establishing a PM program, current standard neglects the fact that PM activities influence the failure rates. In WCM, failure rate plays a major role and has been included in different WCM standards (Chapter 4). For example failure rate is used to define the correct PM to CM ratio.
- DNV report has found extensive lack of competence of the worker. In WCM, strong emphasis has been given to training of employees to make them skilled.
- The audit report reveals that most of the companies have imbalance between resources and maintenance expenses. In WCM, maintenance program is designed according to the resources by choosing cost-effective maintenance strategies.

Chapter 4

World-class Maintenance indicators/standards

4.1 Introduction

According to NORSOK Z-008, standards are developed to ensure adequate safety, value adding and cost-effectiveness for future developments. The purpose of standard is to provide a guideline to establish an optimized maintenance program.

Maintenance performance is an outcome of complex activities which can be evaluated by appropriate indicators to measure both actual and expected result. Measurements allow us to determine if our equipment is performing well or not to achieve the organization's goal. In case of maintenance, these measurements are done in the form of some Key Performance Indicators or KPIs. These KPIs provide the organizations with some sort of benchmarks which is the starting point to improve in the required area. According to Drucker, P. (2008), "What gets measured, gets managed." So, if the areas need to be managed can be identified, selection of the KPIs can be done accordingly (what to be measured). Data from CMMS or any other kind of system will show the equipment performance based on the targets.

Key performance indicators are used to evaluate and improve efficiency and effectiveness to achieve excellence in maintenance. European Committee for Standardization provides Maintenance Key Performance indicators to support management in achieving maintenance excellence or World-class standard. Indicators can be evaluated as a ratio between factors measuring activities, resources or events, according to a given formula .These indicators should be used to:

- Measure the status
- Compare (internal and external benchmarks)
- Diagnose (analysis of strengths and weaknesses)
- Identify objectives and define targets to be reached
- Plan corporate actions
- Continuously measure changes over time. (Norsk Standard, NS-EN 15341:2007)

Organizations are focused on reducing maintenance cost. But this cannot be done at once. First, the existing process should be improved by applying best practices. Best practices are mainly practiced by the leading organizations in the industry producing quality products at a minimum cost. The management should support the journey to excellence in implementing best practices. Then it is determined which strategies, programs, or activities are required to do the improvements.

It is not easy or feasible to recommend a set of KPIs and indices suited for an organization since the KPI varies from business to business. There is no single and perfect KPI that can measure the performance of one particular industry. So, there will be different sets of KPIs and organizations need to decide which KPIs will fulfill their target using their existing resources. Both maintenance and operations should decide on what indices they want to measure and what they can control. For maintenance, it is possible to measure the rate or number of breakdowns, downtime, availability, utilization, mean time between failures, Overall Equipment Efficiency (OEE), set-up-time, repair time, maintenance costs, spare costs and so on.

4.2 Benchmarking Best Practices:

Benchmarking is the process of continuously comparing and measuring an organization with business leaders anywhere in the world to gain information that will help the organization take action to improve its performance. Benchmarking provides an effective means to identify and quantify reliability and maintenance improvement opportunities.

Best maintenance practices (BMP) are established standards for the measurement of industrial performance (Smith and Bruce, 2004). Generally, best practices are good practices that have worked well elsewhere. They are proven and have produced successful results. In maintenance, best practices are defined as the maintenance practices that enable a company to achieve competitive advantages over its competitors. The tool for getting measurable indicator is benchmarking with best practices.

The reliability and maintenance management consulting firm Idcon has shown the results about what will happen after applying best practices. This is given in the following figure:

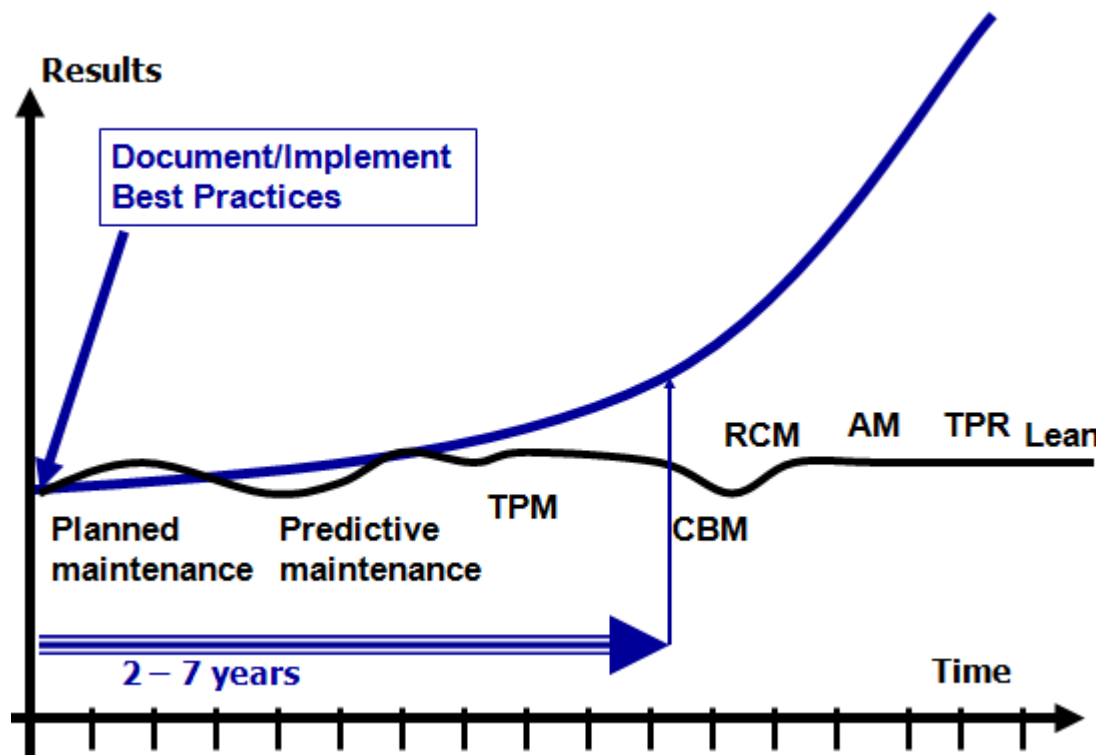


Figure 8 : Results after applying best practices (IdconInc, 2009)

4.3 Measurable WCM Indicators/ Standards:

WCM indicators indicate if the performance of maintenance is world-class. Here, measurable indicators mean that the indicators are capable of measuring the current status of the organization as the indicators are attributed with some numbers. The numbers are based on industry experiences and benchmarking with best practices. During literature

survey of this thesis project, a number of measurable indicators have been revealed. The most relevant indicators related to maintenance are discussed in following sections.

4.3.1 Preventive maintenance to Corrective Maintenance ratio:

This is called '6 to 1 Rule'. This is a ratio of Preventive maintenance work orders to Corrective maintenance work orders. The rule says that there will be a corrective maintenance work every after 6 preventive maintenance works.

The "6 to 1 Rule", is proven by John Day, JR., Manager of Engineering and Maintenance at Alumax of South Carolina. At that time (1989) Alumax of South Carolina was certified as the first "World-Class" maintenance organization. Therefore, the rule is based on industry best practices.

Call, (2007) stated that it is a proven theory is that the Preventive Maintenance to Corrective Maintenance work order ratio should be 6 to 1. The theory assumes that the Preventive maintenance inspections should reveal some type of corrective work. The objective is to identify deficiencies and correct them before they become emergencies with the best possible use of available maintenance resources. If the ratio is greater than 6:1, the preventive maintenance is being performed too often. The result will be that there is little time allowed for emergency work and no time left for solid corrective work to prevent emergencies or perform other unplanned work.

If the ratio is less, the PM is not often enough. At the same time, if the PM program is not finding any problems, the program is not effective. The important fact here is to set up the right frequency of PM program. Frequency of performing a PM should be based on asset failure rate or Mean Time Between Failure (MTBF). MTBF is defined as the average time between two consecutive failures ; and is a measure of time the equipment is operating until the time it encounters a failure (which means run an equipment to failure, fix it, and then run it to failure again). By knowing the MTBF, routine checks and preventive measures should be done within this time frame. The result will be an extended MTBF. To establish the right PM program, it is required to keep adjusting the frequency until having the effective one.

Ratio of PM to CM depends on many variables:

- Asset Criticality, age, history & technology
- Percentage of maintenance expense
- Analyzing past performance.

When applying a proactive Preventive Maintenance program for the first time, the frequency should be established in a conservative manner. Here manufacture suggested PM frequencies can be a good starting point. It is not fixed that all PM work order should be within this ratio. This is a best practiced benchmark and benchmarks differ from organization to organization. But if the correct procedure is followed, the ratio will be close to 6:1.

Industry experts from Norwegian petroleum industry have recommended this ratio to 5:1. Since the Offshore installations are complex in operation, safety issues are priority here. It is quite common that the emergency situation occurs frequently compared to other industries. So, more time is required for emergency corrective works. Therefore, every after 5 Preventive work orders, there might be 1 corrective work order.

4.3.2 Annual Maintenance Cost as a Percent of Replacement Asset Value (RAV):

$$\text{Annual Maintenance Cost per RAV (\%)} = \left(\frac{\text{Annual Maintenance Cost}}{\text{Replacement Asset value}} \right) \times 100$$

The Maintenance cost can be calculated= Equipment repair cost + lost of production due to downtime

Where, Equipment repair cost = (Number of men X hours used in maintenance work) + material cost

This indicator has been standardized by the Society of Maintenance & Reliability Professionals (SMRP) based on the experience and consensus of its Best Practices

committee. This standard will allow comparing expenditures for maintenance with other plants of varying size and value, as well as to benchmark.

The indicator is the amount of money spent annually maintaining assets, divided by the Replacement Asset Value (RAV) of assets being maintained, expressed as a percentage.

To be World-class in maintenance, the annual maintenance cost should be in between 1.5% to 2.5% of the Replacement Asset Value. Recent research (Schjøberg, 2012) shows that the maintenance cost is 1.8% of the replacement asset value for the Norwegian industry. In Norwegian petroleum industry, it may be difficult to evaluate exact maintenance cost practically due to many factors. Therefore, it is recommended that the maintenance cost can be regarded as work “man-hours”.

In most of the cases loss of production is not added for calculating maintenance cost which is 2 to 15 times of the repair cost.

So, annual maintenance cost are labor (including maintenance performed by operators, e.g., TPM), materials, contractors, services, and resources. Also included all maintenance expenses for outages/ shutdowns/ turnovers as well as normal operating times. Here, capital expenditures for plant expansions, or improvements will not be included.

Replacement Asset Value is the money/dollar value that is needed to replace the production capability of the present assets in the plant. It includes production or process equipment as well as utilities, support and related assets.

4.3.3 Maintenance Schedule Compliance:

The schedule is the coordination between operations and maintenance. Maintenance schedule compliance indicator is related to maintenance performance. Schedule compliance is defined as the percentage of work orders completed during the schedule period before the required date. It is calculated either as a ratio of maintenance labor hour consumed for jobs or tasks completed (approved) divided by the total available labor hours during that period. Another way to calculate schedule compliance is as a ratio of the number of jobs/tasks completed (approved) divided by the total jobs/tasks on a schedule.

By planning and scheduling maintenance activities, we can save a lot of money in the long run. The objective of scheduling is to coordinate between the assets to be maintained with the available resources for example: labor, material and services by creating a schedule to execute ‘the right work at the right time’. This means that the work must be done within the specified time period to achieve the desired level of performance. Otherwise, the result is not meeting the schedule and indicates the reactive attitude towards maintenance.

Schedule compliance indicator ranges from 35% to 95% from organization to organization. As it is quite impractical to achieve 100 % schedule compliance due to reactive work appeared during weekly schedule, an organization with more than 90% schedule compliance is regarded as the best practiced or World-class organization. High schedule compliance means high uptime and high asset utilization rate.

Based on industry experience, it is recommended for the Norwegian industry that there should be zero overdue (no overdue). Some experts suggests a flexible range of schedule compliance from 90% to 95% for the Norwegian Petroleum industry to achieve world-class status.

4.3.4 Equipment Availability:

Maintenance plays an important role to keep the equipment in an operable condition. Availability is defined as the time a machine is available for work less all the downtimes (both planned and unplanned downtime) divided by the total available time. So, availability is calculated by the following formula:

$$\text{Availability} = \left(\frac{\text{Available Time} - \text{All Downtime}}{\text{Available Time}} \right) \times 100$$

One rule of thumb is that the improvement in Availability by 1% will reduce the maintenance cost by 10%. The main difference of World-class maintenance with prevailing maintenance concept is that WCM has the right amount of equipment available at the right time to achieve its function. Thus it is required to implement different methods of maintenance to improve availability. The cost of applying maintenance

techniques is quite small in comparison to the cost of equipment unavailability (loss of output). From this, it can be easily understood how important equipment availability is for achieving a world-class standard. The developing countries are becoming much more competitive because they are focusing on equipment failure elimination through the use of existing technologies to ensure equipment availability.

Equipment availability is taken as a maintenance indicator because the performance of an equipment is influenced by the maintenance. This indicator ranges from 65% to 99%. World-class organizations exceed 97% of equipment Availability.

For Norwegian petroleum industry, equipment availability is also recommended to be more than 97% to achieve world-class status based on industry expert's experiences.

4.3.5 Percentage of Preventive Maintenance or Predictive Maintenance Hours to total Hours:

Preventive maintenance is the strategy based on inspection, component replacement and overhauling at a fixed interval regardless of its condition at that time. It is a scheduled inspection which includes replacing filters, oils, belt or lubricating. PM inspection may require another work order to repair other discrepancies found during the PM in a scheduled outage. Optimized Preventive maintenance (PM) plan is developed by using reliability principles and techniques such as Failure Mode and Effects Analysis (FMEA) and reliability Centered maintenance (RCM) as well as wise use of Condition Based Maintenance (CBM) and predictive maintenance (PdM) technologies.

In Predictive Maintenance, equipment condition is measured after observing signs of degradation or impending failure based on either continuous monitoring or statistical data of the equipment and initiatives are taken accordingly. These conditions can be measured in several ways. For example by

- Condition Monitoring
- Statistical process control
- Equipment performance
- Use of the human senses.

PM/ PdM can save as much as 1.2% of the total plant output. PM allows the organizations to plan better and thus reducing the maintenance cost. Based on a survey on USA's manufacturing industry, it is found that only 22% of the organizations are practicing Preventive maintenance. To be effective in implementing PM, there should be a coordination between operation and maintenance. Almost $\frac{3}{4}$ of all organizations experience problems in coordinating preventive maintenance with the operation group.

But the results of implementing PM/PdM cannot be consumed at once. It can take three to five years to feel the improvements by best practices. The percentage of hours spent on preventive and predictive maintenance activities ranges from 20% to 50% compared to the total hours spent. The World-class requirement is 50% of total hours will be spent for PM/PdM activities.

Schjøberg, (2011) stated that in Norwegian petroleum industry, it has been found that the percent of preventive or predictive maintenance is 30.9% of the total maintenance hours. Recommendation for world-class status is more than 40% of the total time.

4.3.6 Stores Service Level:

Store service level means the percentage of the time, a part or material is found in the right location and that the quantity of them in the store matches with the system inventory number.

In many companies, inventories may be 20% to 30% higher than necessary because of lack of management attention. Many companies overstock the store room to solve maintenance material problem. With successful maintenance inventory management service, material cost can be reduced upto 19% compared to the company who does not pay attention in this area. The savings from reduction of insurance inventories can actually finance the entire preventive maintenance program. It should be kept in mind that storing parts costs are over 30% of the items per year.

The store service level ranges from 80% to 99%. World-class maintenance organization service level will be more than 95%. A service level below 95% will result in unnecessary downtime due to parts outages. A service level above 97% indicates too many spare parts

are being carried. There should be a balance between financial considerations for downtime and insurance cost for holding the spare parts.

Based on experts' advice, in Norwegian petroleum industry, the stores service level should be 80-90% for world-class standard.

4.3.7 Maintenance planning:

Maintenance planning is important for effective maintenance organization. Planned maintenance organization is ready to compete with any other organizations. Maintenance planning will result in:

- Improved quality
- Improved utilization and uptime
- Reduced maintenance labor and material cost.

Only one-third of the maintenance organizations have a tendency to plan maintenance activities. It has been estimated that the cost ratio is 1:5 for planned and unplanned work. To reduce the time for planning, computer technologies like CMMS should be used so that more time is available for other activities.

Percent of planned work means what percentage of work orders (Parts, materials, specifications, procedures, tools, etc) have been defined prior to scheduling the work. Planned maintenance indicates that the maintenance is proactive rather than reactive. This indicator ranges from 35% to 95%. The best practice range is over 80%. The range also depends on the type of business. But as long as less than 20% of the work is reactive , which means 80% or more is planned and scheduled, the organization is considered to be world-class.

Schjøberg, (2011) stated that, the percent of planned maintenance work in Norwegian industry has been found to be 58.3%. But recommendation for world-class status is more than 90%.

4.3.8 Reactive Hours as a percentage of Total Hours:

To be world-class, it is required to focus on maintenance basics to achieve world-class status. One third of the maintenance expenditures are wasted through inefficient and

ineffective utilization of maintenance resources. This waste can be saved by implementing a proper maintenance program. An effective PM activities can enable a company to achieve a ratio of 80% proactive maintenance and 20% (or less) reactive maintenance. Once the ratio is at this level, other practices (such as planning and scheduling) in the maintenance program become more effective.

The percentage of reactive hours compared to total hours spent in maintenance work varies from organization to organization. Generally, this indicator ranges from 5% to 50% or more. But to be a world-class organization, the reactive hour should be less than 10% even though this is not the limit. It is always possible to have some reactive works is beneficial for a cost-effective maintenance program.

Statistics from manufacturing industry in USA shows that 14.1% of the total maintenance work time is overtime indicating the reactive attitude towards maintenance. For WCM, it should be about 4.7%. This overtime cost is to meet the schedule compliance and productions not made on time. As a rule of thumb, if the corrective maintenance costs rise upto 80% of total cost of the equipment, a detailed Cost Benefit Analysis (CBA) is recommended to evaluate possibilities for modification and/or replacement of the equipment. To control reactive hours, detailed Root Cause Analysis (RCA) is recommended to identify failure causes and to initiate mitigating actions accordingly.

Schjølberg, (2011) found that in Norwegian industry, percent of reactive work is 23.7% whereas recommended range is less than 5%.

4.3.9 Work order coverage:

Work order coverage is one of the most critical indicators of the status of a maintenance organization. Without work order system, it is impossible to control maintenance activities. Work order coverage means the amount of maintenance work that are reported to maintenance work order system. In a world-class organization, All the maintenance activities are tracked through the work order system. Without this system, it is very easy that the data are lost and true analysis can never be performed.

A work order can be defined as a request that has been screened by a planner who has decided that the work request is necessary and has determined what resources are required to perform the work.(Wireman, T., 1991) .

Computerized system can help performing and follow-up work-order. Work-order system assists to plan the maintenance activities by identifying emergency work patterns of equipment. So, work order systems are used to initiate, track and report all maintenance activities. To be effective, work order information is used and coordinated by different departments which are maintenance, Operations, engineering, Inventory, Accounting and Upper Management.

Work order coverage indicator ranges from 60% to 100% with 95% as world-class standard. Ruud and Nguyen (2011) stated that for a world-class maintenance organization, following are the attributes for work orders:

- 80% of all work orders are planned completely within 5 days and 90% of them are man-hour estimated within an accuracy of +/- 10%.
- 80% of all work orders are either canceled, executed or validated for planning within 3 days.
- 95% of all planned and scheduled work orders are completed in accordance with plan.
- 98% of all work orders are executed in accordance with required quality and precision.

For Norwegian petroleum industry, work order coverage is recommended to be more than 95% to 100% to achieve world-class status based on industry expert's experiences.

4.3.10 Maintenance Training and Competency:

There is a repetitive tendency of maintenance rework due to lack of proper knowledge and skills. The importance of maintenance training can be easily understood if developing skilled people is considered as an investment. When there is lack of training in an organization, then the employees will not have enough competence to perform the job

well. The result will be devastating for example work delays, equipment damage, low quality products and customer dissatisfaction.

The training program within the organization should be a continuous process. According to Wireman, (2009) 80% of the skills of those now working in technical areas, will be obsolete in three to five years because of rapid technological advances.

One organization may have great plans, best processes and outstanding technologies, but if it does not have skilled and competent employee, everything is a waste. The cost of training is very small compared to the cost of savings through skilled people. Intensive training and education encourage self improvement for everyone. Gulati (2009, pp.274) stated that developing people – the workforce- and empowering them to give their best is the key to defining the difference between an ordinary organization and a world-class organization

Unfortunately, the skill level of employees in most of the organization is below the accepted level. Studies have shown that 70-80% of the equipment failures are self induced and most of them are a result of human error. Maintenance training can increase product quality and productivity, improve employee morale and ultimately can save a huge amount of money,

A recent survey by the American Society of training and development (ASTD) showed that 2.20 to 2.97% of the payroll should be expended for maintenance training. So, for the world –class standard,

$$\frac{\text{Total Training Dollars}}{\text{Total Plant Payroll}} \times 100$$

This ratio should be more than 3%. Recommendation for Norwegian industry is also more than 3%.

4.3.11 Overall Equipment Efficiency (OEE)

Overall Equipment Efficiency (OEE) measures how well the equipment performs compared to the designed specification. The fact is that while in operation, the equipment faces many influencing factors which affect its performance. OEE can be improved by

collecting the performance history, converting it into information and then interpreting into necessary steps to improve effectiveness.

OEE is calculated by the following formula:

$$\text{OEE} = \frac{\text{Availability (A)} \times \text{Performance efficiency (P)} \times \text{Rate of Quality (Q)}}{\text{Rate of Quality (Q)}}$$

Where, Availability (A) = $\frac{\text{Loading Time} - \text{Downtime}}{\text{Loading Time}} \times 100$

Performance Efficiency (P) = $\frac{\text{Processed Amount}}{\text{Operating Time}} \times 100$

Rate of Quality (Q) = $\frac{\text{Processed Amount} - \text{Defect Amount}}{\text{Processed Amount}} \times 100$

It is difficult to attribute any fixed number to this indicator to be world-class as it is strictly dependent on the type of business. In general, it has been observed that the OEE indicator varies from less than 20% to more than 85%. Willmott, (2011) stated that even though Japanese has mentioned 85% as World-class for typical mining industry, in offshore industry the business will be collapsed soon if OEE is not more than 90%. So, the concluding remark will be that the world-class range will be decided by the type of business.

OEE measures the Operational improvements. For WCM, OEE should be 85 percent. As OEE increases, the number of safety incidents decreases. Schjølborg, (2011) found that in Norwegian petroleum industry, the Overall Equipment Efficiency is 72.7% based on

industry experience. But Willmott (2011) recommended that world-class status should be more than 90%.

4.4 Comparison of maintenance practices:

Table 3.1 shows a comparison of current maintenance practices with world-class standards. All the information here are based on experts' opinion and benchmarking with best maintenance practices. There are four columns. Column 1 is about typical range of maintenance practice (based on industries all over the world), Column 2 is about world-class standards (all industries), column 3 is based on current maintenance practice in Norwegian industry and column 4 is about recommended world-class range for Norwegian industry.

WCM Indicators	Typical Range	World-class Range	Norwegian industry practice	Recommended for Norwegian industry for WC
PM to CM ratio	3:1 to 5:1	6:1	3:1	5:1
Annual Maintenance cost as a percent of RAV	3% to 9%	2.5% to 3.5%	1.3	Less than 1.8%
Maintenance Schedule Compliance	35% to 95%	More than 90%	Not found	90% to 95%
Equipment Availability	65% to 99%	More than 97%	89.8	More than 90% to 95 %
% of PM or PdM hours to Total Hours	20% to 50%	50%	30.9 %	More than 40%
Store Service level	80% to 99%	95%	Not found	90% to 95%
Maintenance Planning	35% to 95%	80% or more than 80%	58.3%	More than 90%
Reactive Hours as a % of Total hours	5% to 50%	Less than 10%	23.7%	<5%
Work-Order Coverage	60% to 100%	95%	Not found	95% to 100%
Overall Equipment efficiency	20% to 85%	More than 85%	72.7%	More than 90%
Maintenance Training and Competence	1% to 3%	More than 3%	Not found	More than 3%

Table 1: Comparison of WCM indicators

Chapter 5

Framework for measurable WCM indicators

5.1 Introduction

Framework is a structure that supports the theory of a research and shows the relationship among the variables of the theory. Developing framework for WCM indicators is a challenging task as there are no specific rules and regulations for selecting the right indicators suitable for the organization. Therefore, the framework should be flexible enough to be modified according to the requirements and easy to use. This will ensure continuous improvements. The framework is focused on the role of maintenance performance indicators to achieve world-class status. So, it is a systematic, disciplined roadmap to get best possible results. The framework shown here (Figure : 11) serves as a basis for conducting this research project.

The conceptual WCM indicator framework (Figure:11) which has been developed is guided by the following improvement model (Figure: 9)



Figure 9 : Maintenance Improvement Model (Compliant with BSI; PAS – 55: 2008)

In the book “Rules of thumb for Maintenance and Reliability Engineers”, Smith and Mobley, (2009) have proposed a framework for maintenance process key performance indicators. The proposed framework has been presented in this section (Figure :10). The framework shows how the maintenance key performance indicators work in a maintenance program. This framework has also provides insights into formulating the WCM indicator framework.

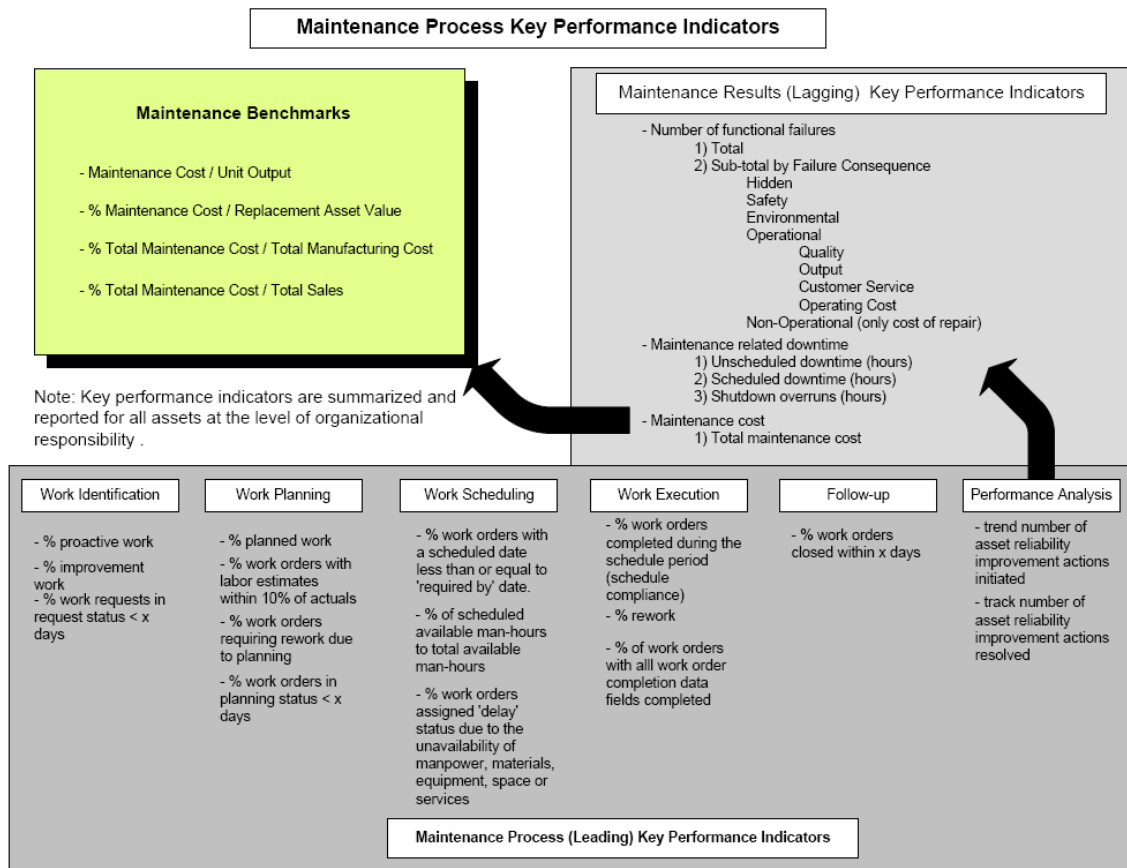


Figure 10 : Example of how maintenance KPIs are implemented

5.2 Explanation of the developed WCM indicators framework:

framework:

This framework (Figure:11) specifies that performance measurement by WCM indicators is a continuous loop of the following steps: indicator selection, implementation, follow-up and reassessment. The framework is developed based on the basic assumptions and concept of WCM indicators found in chapter 4. In order to implement the framework in an organization, it is vital to understand it properly. The main features of the framework are:

There are some influencing factors that affect the vision of the organization. If the vision is to have a reliable and robust approach for establishing WCM, it is important to combine practical knowledge with current technology and available resources. Then the first step to set up goals and objectives which must be proactive. This is the most

challenging fact because goals are never constant. To be competitive, goals should be changed over time and thereby ensures continuous improvements. Before formulating the performance indicators for maintenance, it is vital to ensure that the maintenance strategies are clearly defined. After the strategies are defined, the WCM indicators are selected. The selection can be done in three ways which are marked by 1, 2, and 3 in the framework. For ease of understanding, the remaining framework is explained in three sections separately with three diagrams which are actually retrieved from the main framework.

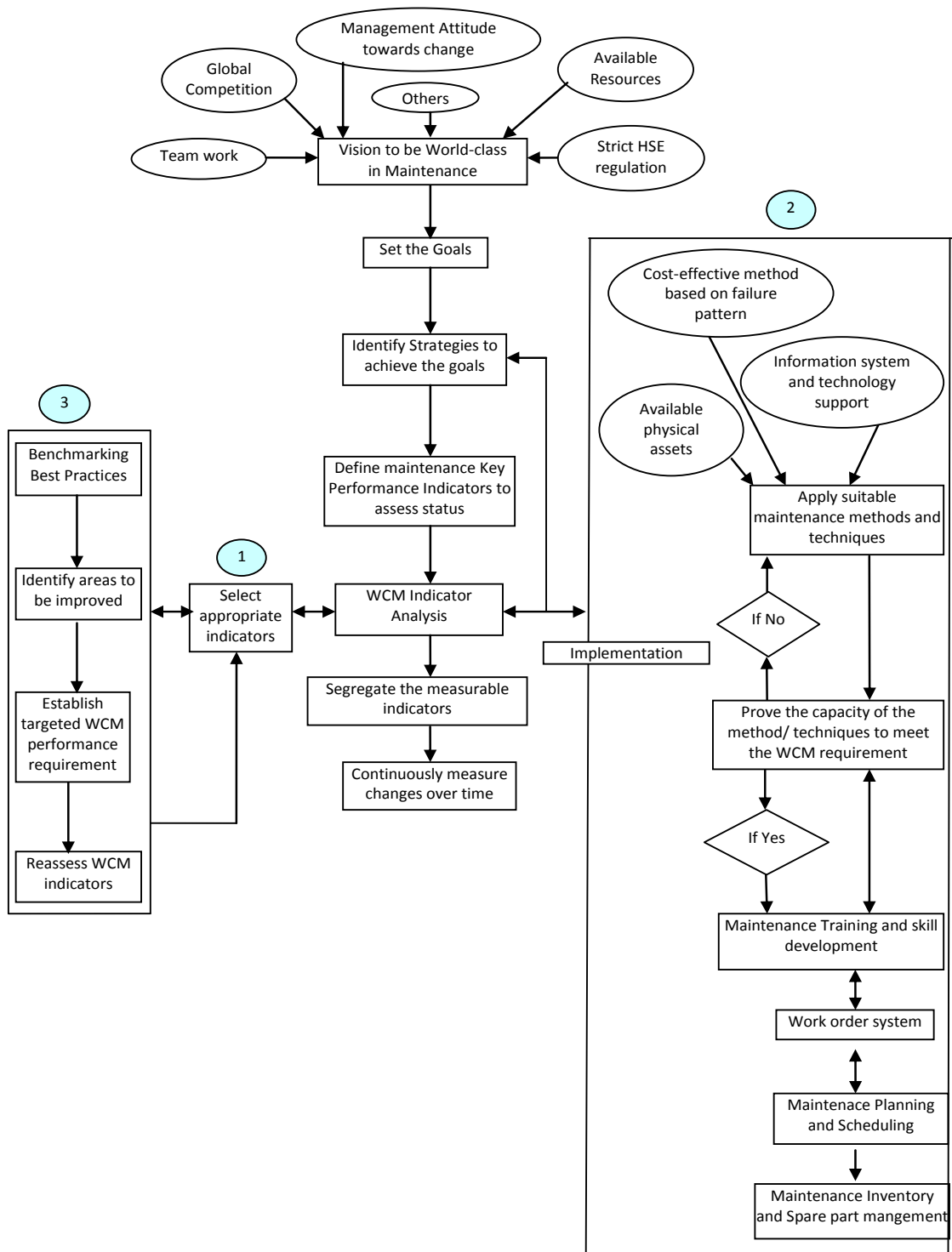


Figure 11 : Framework to Analyze WCM Indicator

5.3 Description of main three parts of the Framework

WCM indicator framework is divided based on the selection procedure of indicators.

5.3.1 Selection of Indicators:

Selection of indicators is a never ending process. There are many ways to select the maintenance performance indicators suitable for the organization. The main approaches which are used in formulating the main framework are shown in Figure:12

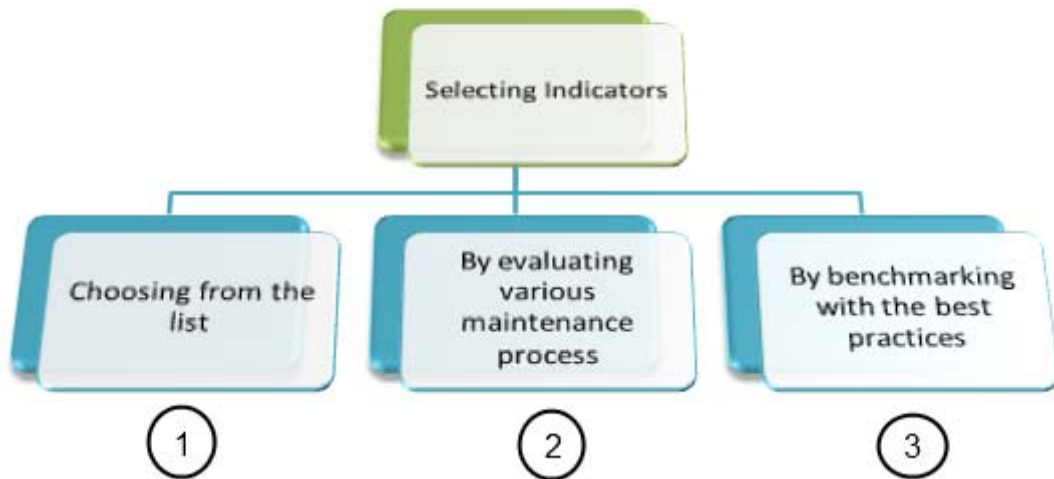


Figure 12 : Selection of KPIs

Each part is explained separately in this section.

5.3.2 Selection of KPIs by evaluating various maintenance processes:

Defining maintenance goals and formulating strategies is an important aspect WCM indicator framework. There are many strategies available for maintenance. To achieve world-class status, the framework suggests to keeping all of them in place and recommends to selecting from them according to the requirements. Applying suitable maintenance methods and techniques will help to reach the targeted ranges of indicators. Target should be to achieve the level of percentage mentioned in the WCM indicators chapter (Chapter 4). For example, corrective maintenance should be less than 10% of total hours, schedule compliance should be more than 90% etc.

Suitable methods and techniques are selected from

- Corrective Maintenance (CM)
- Preventive maintenance (PM)
- Predictive Maintenance (PdM)
- Reliability Centered Maintenance (RCM)
- Condition Monitoring
- Risk-based Maintenance (RBI)
- Total Productive Maintenance (TPM)
- Lean Maintenance
- Others

There are also many technologies available for example:

- Root Cause Analysis (RCA)
- Failure, Modes, Effects and Criticality Analysis (FMECA)
- P-F interval
- 5S
- Six sigma
- Pareto Analysis or 80/20 Rules
- Others.

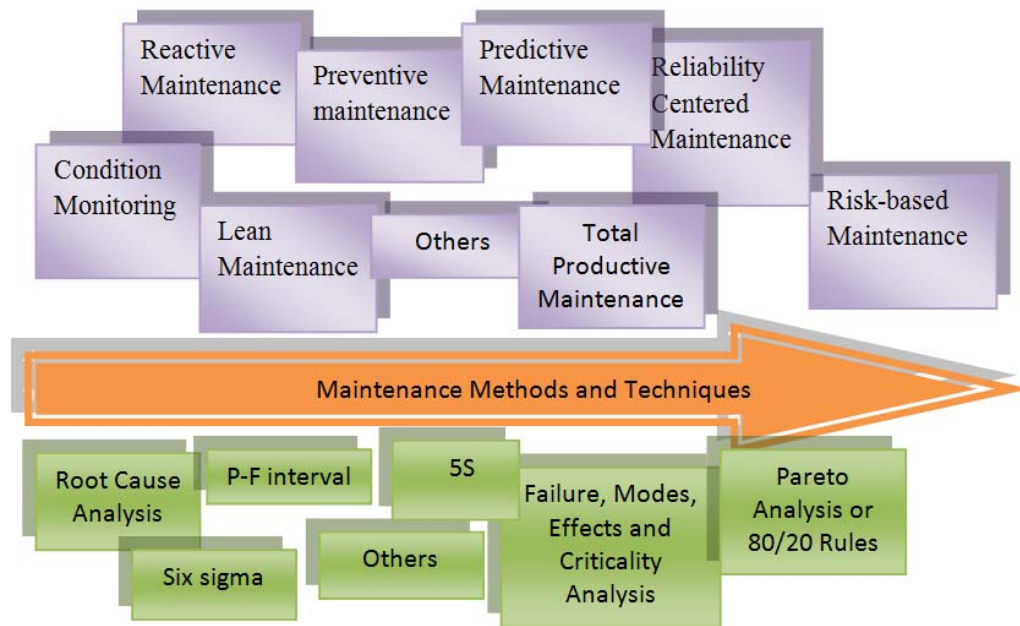


Figure 13 : Apply suitable methods and techniques

5.3.3 Selecting KPIs by benchmarking with Best Practices:

Benchmarking best practices examines specific process in maintenance. Then, it compares the process to companies that have master those processes and finally maps the changes to improve the specific process. According to the American Productivity and Quality Center, the three main barriers in adoption of a best practice are lack of:

- Knowledge about current best practices.
- Motivation to make changes.
- Knowledge and skills required for best practices.

The following steps mentioned in the figure:14 should be followed for selecting the KPIs by benchmarking with best practices,:

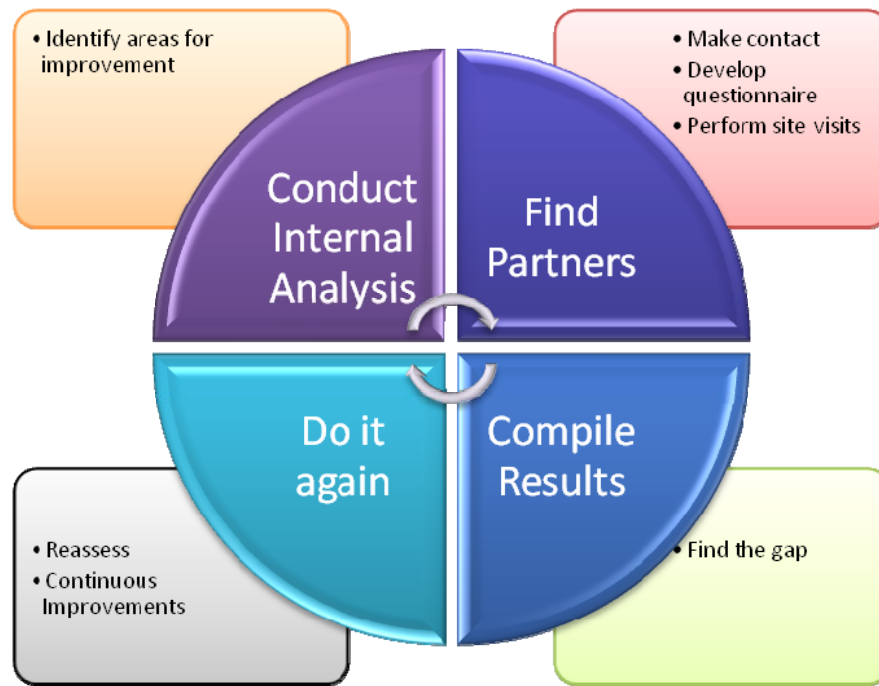


Figure 14 : Benchmarking best practice

5.3.4 Selection of KPIs from a list

The maintenance performance indicators can also be selected from a list. For Norwegian industry, the maintenance key performance indicators are listed in Norsk Standard NS-EN15341:2007. The technique of selection is to understand the need of the organization, then select the indicators accordingly and thus measure the performance. The leading and lagging indicators are defined by Society for Maintenance and Reliability Professionals (SMRP). Leading indicators lead to results while lagging indicators are actually the results. The process is shown in Figure: 15

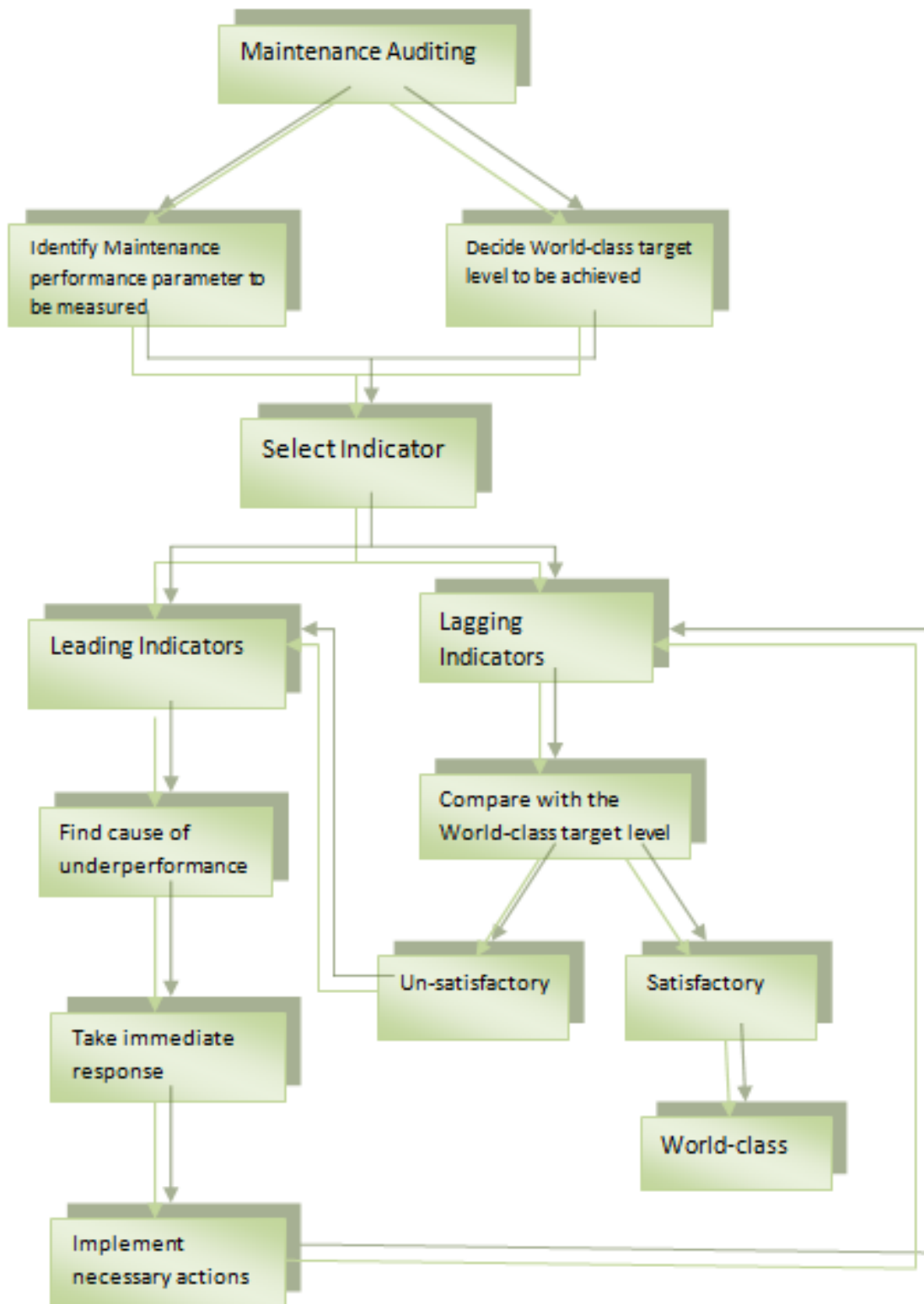


Figure 15 : Selection of indicators from a list

5.4 Gap Analysis:

Gap Analysis is the analysis to find the differences/gaps between where the company is now and where it wants to be. Gap analysis is the key component of any improvement initiatives. The first step of gap analysis is to compare company's current performance with the expected performance. Benchmarking is one of the tools to perform the analysis. If a company wants to effectively use gap analysis, all the parameters in terms of indicators must be quantifiable and time framed. If not, gap analysis will be meaningless.

The purpose of maintenance gap analysis is to respond three key goals:

- i. To obtain an objective and independent assessment of the maintenance function
- ii. To use the results to develop a road map for future operational and maintenance performance improvement; and
- iii. To identify opportunities for maintenance to increase the value and reduce the cost of the services.(Omdec Inc, 2009)

Gap analysis is divided into three steps:

1. Baseline – The present status of the company. It includes listing of characteristic factors for example, performance indicators, competencies of the present situation.
2. Entitlement – The best the company can achieve by using current resources. It includes identifying the factors that are required to achieve the desired goals.
3. Benchmark – The best practice performance of a truly optimized process. It highlights the gaps exist in the current process. (Wireman, T., 2009)

Results followed by a gap analysis are:

- i. A detail findings and recommendations
- ii. An assessment of priorities
- iii. Cost-effective maintenance improvements.
- iv. Finally, a reliable and well-functioning maintenance management system.

A systematic approach should be selected for performing the gap analysis. For example, for an equipment, all the available historical data should be in place. With all the available information, each performance indicator is reviewed and compared with the WCM

standards. The findings are reported on a Gap Analysis Matrix. The gaps reported are ranked according to the priority of safety, in terms of low, medium and high criticality. The gap analysis matrix is shown in figure: 16.

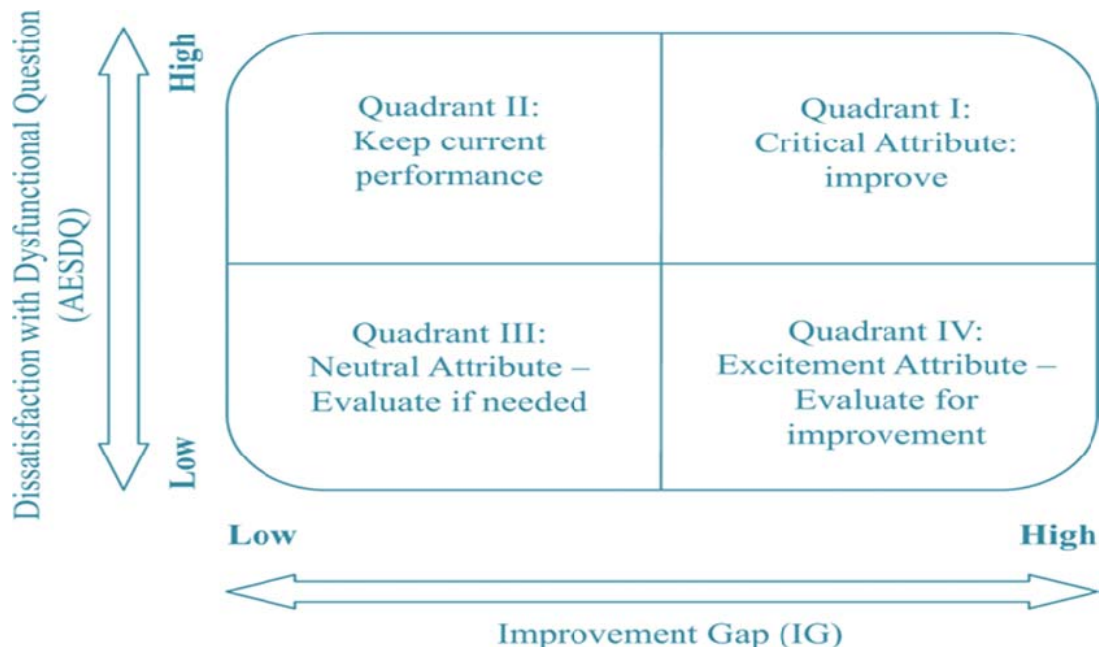


Figure 16 : Gap analysis Matrix (Picolo and Tontini, 2010)

In this thesis project, a number of maintenance key performance indicators have been identified to achieve world-class maintenance status (chapter 4). The measurable indicators have a range to achieve world-class status. An organization with a vision to be world-class, can measure its current performance against these ranges. If the current performance is not up to the mark, there will be a gap. So, necessary improvement initiatives should be taken. It is possible to assign some scores to the performance indicators. During benchmarking, survey questions regarding the indicators can be asked to the best practiced organization and attained scores are assessed. Then the gap against the best practices can be identified.

Gap Analysis

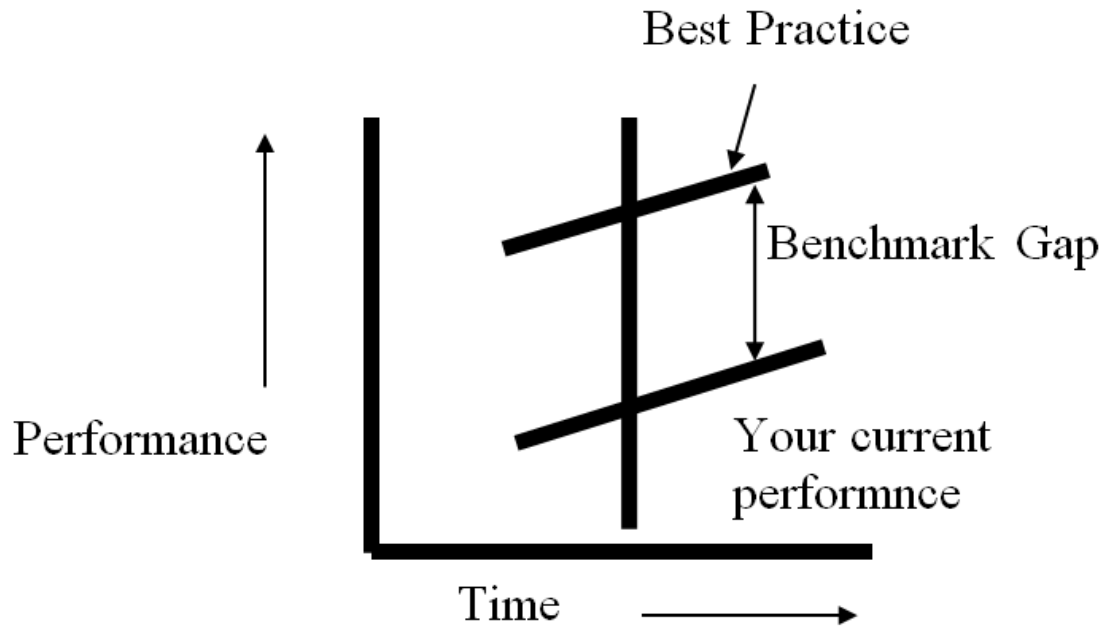


Figure 17 : Gap Analysis

The gap between the observed best practice and the organization's current performance is plotted on the vertical axis of the graph. Time is shown on the horizontal axis. The graph clearly indicates that the performance measures must be quantifiable to find any result.

Chapter 6

Challenges and Recommendations to the Petroleum industry

The application of WCM concept in maintenance and operations of complex facilities can bring great opportunities for the petroleum industry. WCM indicators have the great potential to eliminate the shortcomings of current maintenance practices. But to get the full benefits of the framework and the WCM indicators, it is necessary to comprehend the related challenges and issues. Some of the potential challenges regarding implementation of WCM indicators and recommendations to overcome the challenges are discussed here.

6.1 Challenges and Recommendations:

- In WCM, it is possible that the organization is trying to implement a handful of new process (If it was not practiced previously) as well as some improvement initiatives. As it is expected to implement additional processes, strategies should be developed for prioritizing the additional work load.
- Management must create the atmosphere that motivates successful implementation to world-class Maintenance efforts. So, the managerial leadership required to transform reactive operating environment to proactive environment through
 - Change of culture
 - Universal commitment
 - Perseverance
- The common challenge that keeps many organizations from achieving the world-class maintenance status, is the lack of understanding of the basic maintenance functions. There is a repetitive tendency of failing to focus on the basics. Strong

maintenance basics create the path of successful implementation of WCM indicators.

- Skills of many maintenance personnel fall short of levels required to maintain advanced equipment technology. So, it is highly recommended to focus on training and continuous education.
- Coordination between operation and maintenance is also a challenge. If the maintenance and operation are not working together, none of the benefits of WCM indicators can be achieved.
- Management faces problems to put into place the new performance indicators that will contribute for the business success. This is a real challenge to apply the WCM indicators. To overcome this challenge, recommendation to the petroleum industry is to create awareness of the necessity of WCM indicators by explaining the benefits gained from this.
- Generally, organizations emphasize on cost reduction rather than maintenance excellence. This attitude should be changed first. It is challenging to create a culture where often undisciplined (reactive) people work in a disciplined (proactive) system. The management should support this journey to change the attitude.

6.2 Future Research Direction

The purpose of this thesis was to identify the measurable world-class maintenance indicators and to make a framework to analyze the indicators. The indicators have been selected based on the literature and expert's experiences in this project. Practical implementation of these indicators is capable of finding the maintenance performance gap in the Norwegian industry against the standards. Thus, This thesis recommends a mathematical modeling of the found indicators with the help of pairwise matrices for further research.

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