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PREFACE

This thesis is the final project of my master’s degree in “Structures and Materials” at the University of Stavanger, written in the spring of 2011.

First of all I would like to thank my supervisors Jarle Daae and Øystein Bjaanes for giving me the opportunity to write my thesis for Aker Solutions in Bergen. I have sincerely appreciated their inputs and support throughout the process of this project. I would also like to thank my supervisor at UiS, Professor Jayantha P. Liyanage for his advice and inputs along the way.

Finally I would like to thank my girlfriend Gunhild and the rest of my family for supporting me throughout these five years of study.

Bergen, June 14th, 2011

Christian Erstad

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LIST OF ABBREVIATIONS AND TERMS

AI - Asset Integrity
AI-ESTATE - Artificial Intelligence Exchange and Service Tie to All Test Environments
AIM - Asset Integrity Management
ALARP - As Low As Reasonably Practicable
AM - Asset Management
AMST - Asset Management Software Tool
AS - Aker Solutions
CM - Condition Monitoring
CBM - Condition Based Maintenance
CMMS - Computerized Maintenance Management System
CRIS - Common Relational Information Schema
ENS - Engineering Numbering System
ERP - Enterprise Resource Planning
FMECA - Failure Mode, Effects and Criticality Analysis
HSE - Health, Safety and Environment
HTHP - High Temperature High Pressure
ICT - Information and Communications Technology
IEEE - Institute of Electrical and Electronics Engineers
IIC - Information Integration Core
I&CI - Information and Communication Infrastructure
IO - Integrated Operations
IMS - Information Management Systems
KPI - Key Performance Indicator
LAN - Local Area Network
MF - Main Function
MIMOSA - Machinery Information Management Open System Alliance
NCS - Norwegian Continental Shelf
NIST - National Institute of Standards and Technology
NPV - Net Present Value
O&G - Oil and Gas
O&M - Operations and Maintenance
OLF - The Norwegian Oil Industry Association
OOC - Onshore Operations Centre
OPEX - Operational Expenses
OSA-CBM - Open System Architecture for Condition Based Maintenance
PAM - Plant Asset Management
PDA - Personal Digital Assistant
PM - Preventive Maintenance
PSA - Petroleum Safety Authority (Petroleumstilsynet)

RAM	-	Reliability, Availability and Maintainability (Analysis)
RBI	-	Risk Based Inspection
RCM	-	Reliability Centered Maintenance
RUL	-	Remaining Useful Life
SF	-	Sub Function
SIL	-	Safety Integrity Level
SOA	-	Service Oriented Approach
TCI	-	Technical Condition Indicator
TIM	-	Technical Integrity Management
WI	-	Water Injection

ABSTRACT

The first part of this thesis will map the requirements and best practices for performing criticality classification, maintenance and inspection analyses leading to the establishment of preventive maintenance and inspection programs. Over the last decade or so the recognition of IO has brought increasing use of information and communication technology to the NCS making it possible to transfer vast amounts of real time data through high speed fiber cables between off- and onshore installations. This has led to increasing use of condition monitoring technology giving operators the possibility to detect degradations at an earlier stage. Emerging from this technology is the development of integrated information systems like the TIMS maintenance portal; a web-based decision support portal for managers, planners and decision makers giving access to a wide range of maintenance related information from multiple sources. The TIMS maintenance portal will be introduced and further exemplified in a case study of a water injection system, proposing a way to use real-time and offline technical condition data for visualizing the technical condition of the WI system in the TIMS maintenance portal interface.

1 INTRODUCTION AND BACKGROUND

This thesis was written during the spring of 2011, as the final project of the master education “Structures and Materials” at the University of Stavanger (UiS). The project’s objectives were given by Aker Solutions, and the thesis has been written in cooperation with them at their offices in Bergen.

1.1 Aker Solutions

Aker Solutions (denoted AS) has more than 40 years of experience for providing asset engineering, maintenance and modification solutions to the oil and gas industry. The company have executed major projects world-wide, and has developed oil and gas installations ranging from large complex installations in the deep and hostile North Sea environment, to facilities in arctic areas with small and marginal fields in shallow waters. By investing in research and development, AS has become one of the leading actors for using information technology, having continuously encouraged and developed new and cost-effective working relations with clients. Long-term design and maintenance experience is systematized into comprehensive maintenance and inspection services. The company aims to stay in the forefront of technology as one of the world's leading engineering organizations (AS Document 5, 2010).

1.1.1 The TIMS alliance

With the constant focus on performing safer, more reliable and environmental friendly oil and gas (O&G) activities developing new ways of operating and maintaining the assets is becoming ever more important. With the aim of developing more effective methods for managing the technical integrity of topside process equipment, AS have formed an alliance with SKF and IBM; offering Technical Integrity Management Services (TIMS). TIMS is a multidisciplinary service that unites multidiscipline knowledge from its participants; AS is specialist for inspection and condition monitoring of static process equipment, SKF is a leading provider of condition monitoring systems for rotating equipment and IBM contribute with their Integrated Information Core (IIC) technology, enabling information transfer between various databases, control systems and condition monitoring instruments. Through this multidisciplinary alliance TIMS aim to ensure the fit-for-purpose condition of assets, satisfy production targets while keeping a high focus on HSE. With this, the intention is to develop a decision support portal for managers, planners and decision makers, giving access to a wide range of maintenance related information from multiple sources.

1.2 Background

Today, the process for planning inspection and maintenance activities are extensively done separate, based on different criteria, measures and input data. The inspection and maintenance activities are relatively fixed based on risk-based inspection (RBI) and reliability centered maintenance (RCM) analyses respectively. With the implementation of Integrated Operations (IO) in this process, integrating inspection plans, maintenance plans, process and real-time data from condition monitoring sensors in the field, the intention is to improve the inspection and maintenance planning by utilizing right time monitoring of significant influence factors, increase the use of condition based maintenance (CBM) and enable more dynamic risk assessments. Through the IIC technology the TIMS portal is intended integrate multi-source maintenance-related information into one portal interface; with the intention of presenting the right information to the right people in a more effective manner. This integrated access to multiple information sources is believed to significantly reduce the time spent searching for relevant information and instead give more time for evaluation and making better informed decisions. In turn this will bring lowered maintenance costs and increased availability of the installation.

1.3 Thesis Objectives:

To create a basis for addressing future developments of maintenance and inspection practices, the first part of this thesis will map today’s requirements and best practices for maintenance and inspection engineering in accordance to supervisory authority requirements, industry standards and AS internal procedures.

Further, the thesis will present the structure and features of the TIMS maintenance portal, and examine what types of information are most relevant for effective visualization of higher level condition status to best enable planning and decision-making of maintenance and inspection activities. To limit the scope of this task, a case study will be performed to exemplify the TIMS portal with the basis of a topside water injection (WI) system. The focus of the case study will be on selected static and rotating equipment within the WI system, and how real-time and offline technical condition data can be used to visualize the system technical condition status in the TIMS maintenance portal.

1.4 Limitations

Data integration and interoperability between condition monitoring systems is a vital part of condition based maintenance systems, including the TIMS maintenance portal. However, this thesis will not focus on the technical details of this technology and will only provide an introductory presentation of the recognized standards and industry initiatives within this area. The TIMS maintenance portal is intended to cover a wide range of equipments and systems on an O&G platform with objective of increasing the total availability of the plant. As the relevant maintenance information will vary between the different systems and equipments, this thesis will only address the information relevant for the static and rotating equipment in a WI system. Performance indicators are only addressed according to the technical aspect; neither economic nor organizational considerations are addressed.

1.5 Methodology

To create a foundation for addressing the objectives of this thesis, relevant document, procedures and presentations was gathered from Aker Solutions' internal database. Technical literature from books and academic articles was collected from the UiS library and also relevant online websites. Meetings and discussions with my supervisors and other experienced personnel at Aker Solutions have provided important contributions to the writing and direction of the thesis. Visiting Statoil's condition monitoring (CM) centre and meeting with Mr. Gunnar Ølmheim (Head of Rotating Machinery and Condition Monitoring, Statoil) and Mr. Trygve Marken (Chief Engineer, Rotating Machinery, Statoil) (Appendix A) provided valuable insight to the current practice of CM and condition based maintenance within the O&G industry, and also some further inputs regarding their future thoughts and perceptions for implementing planning and decision support systems similar to the TIMS maintenance portal.

2 FIELD STUDY

2.1 Integrated Operations

Integrated Operations (IO) is a term for describing the new work processes emerging from the increasing use of information and communication technology (ICT) in the O&G industry. IO is a tool for improving the efficiency and interaction between disciplines and decision makers, regardless of their geographical location, through extensive use of real-time data and communication technology (Krokeide, 2008). Various O&G companies have developed their own definitions of IO, all giving roughly the same message through different formulations. OLF (2007) defines IO within these three points:

- Improve work-, decision- and implementation processes through use of modern ICT and real-time data, and thereby increase the level of HSE, increase added value and reduce financial costs.
- Integrate skills, tools and data in real time to achieve safer, faster and higher quality decision making through interaction.
- Improved utilization of skills – across disciplines, locations and organizations with the purpose of increasing the efficiency of exploration, development and operations through new ways of working.

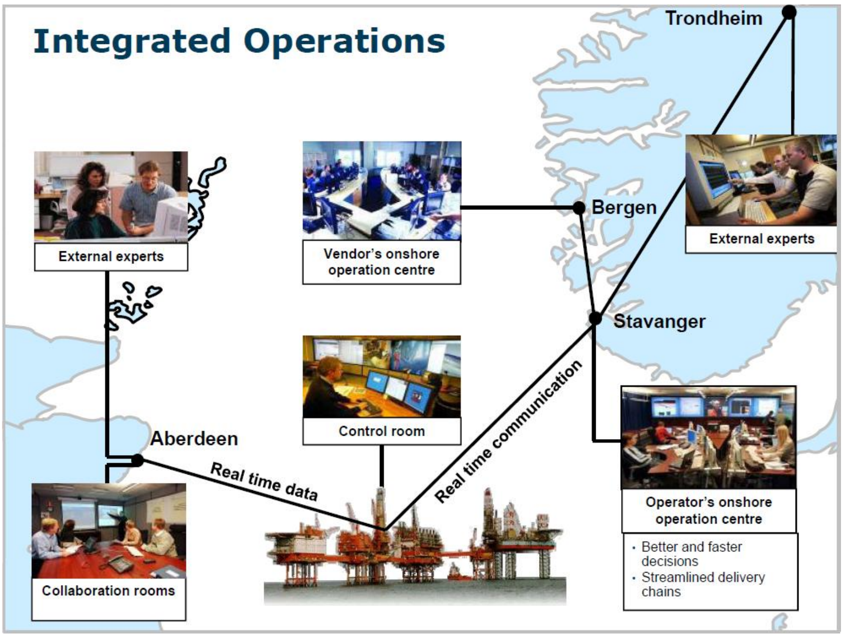


Figure 2.1, IO on the NCS, (Langeland, 2007)

Consequently, the continuous stream of real time data between offshore and onshore installations brings new possibilities for close cooperation between distant geographic locations. This means that a lot of activities previously performed offshore now are performed onshore. Expert consultations, problem evaluations, work planning and decision making can be done in Onshore Operation Center's (OOC) by multi-discipline expert teams with real time access to a wide range of information. This is believed to result in safer, faster and more informed decisions, in addition to lowering the risks and financial costs by reducing the manning on offshore installations. A report published by OLF (2007) estimated the added values from IO on the NCS to be in the range of 300 Billion NOK NPV. Needless to say these are huge numbers that somewhat illustrates the possible benefits of moving towards a more integrated approach, utilizing modern ICT and new work processes.

Consequently IO brings new ways of operating and offer potentials for significant operational cost reductions. This is becoming increasingly important as the maturing fields on the NCS are reaching their tail end production phases; making the reduction of operational expenses (OPEX) vital for extending the economical lifetime. As tail end O&G production is approaching the maintenance activities will form bigger and bigger parts of the total cost needed to keep the production facilities operational (Kumar, Panesar, & Markeset, 2009). This has induced the need for O&G companies to streamline and modernize their operations and maintenance concepts in order to lower the OPEX and thereby extending the production periods of the installations (Figure 2.2).

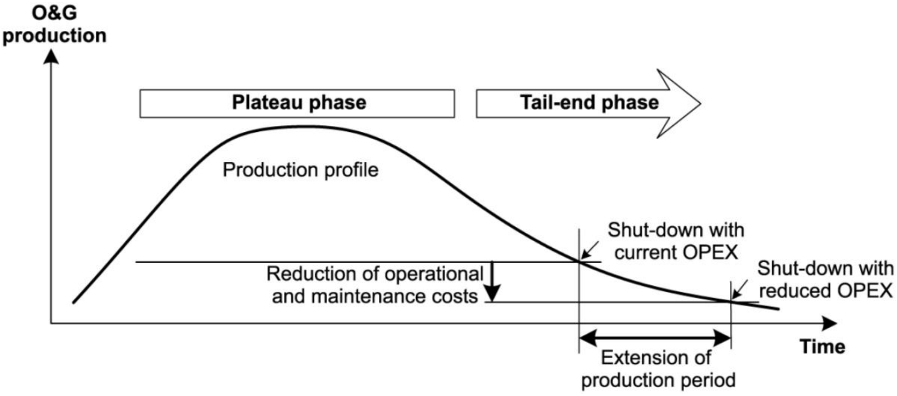


Figure 2.2, Extending the production period by lowering OPEX'es, (Kumar, Panesar, & Markeset, 2009).

In addition to declining O&G production, many of the aging installations on the NCS are approaching the end of their intended design life. As a result of this, many installations will experience increasing failure rates (bathtub curve phenomenon), resulting in higher risks to health, safety, environment (HSE) and economy (Ratnayake and Toreset, 2010). As a result from this, O&M activities must be performed at even higher levels of quality to assure that the technical integrity of the installations is in compliance with ever more stringent HSE requirements, while at the same time consequently be performed at lowered costs for extended production periods.

2.2 Asset Integrity (AI)

The term “integrity” means being in a state of undiminished, unimpaired or perfect condition (Ratnayake and Toreset, 2010). Asset integrity (AI) is defined as “*the inherent ability of an asset to perform its duty at specified technical, operational and business requirements in spite of any internal and/or external intentional or unintentional influence or action*” (CIAM, 2008). Asset Integrity Management (AIM) seeks to ensure a consistent performance throughout the assets lifetime in order to deliver the business objectives profitably and without major accidents (Risktec, 2010). The concept tries to optimize labour, tools, equipment, materials and information by integrating financial and human resources together with production, materials and enterprise resource planning (ERP) systems (Dilger, 1997). However, having well developed procedures and work processes does not guarantee for the successful implementation of AIM. It is also critically dependant of top-level management support, common understanding of risk across the organization, access to high quality information for making informed decisions and also regular reviews/analyses for continuous improvement. All stages of the assets life cycle must focus on integrity, from the design stage to maintenance management to decommissioning. Figure 2.3 illustrates the integral parts of Asset Integrity.

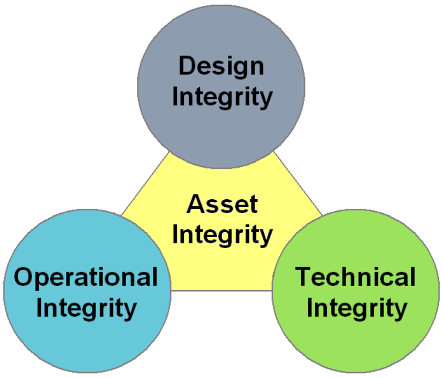


Figure 2.3, Components of Asset Integrity (Erstad, 2011)

- Design Integrity;
  Design is based on calculations, simulations and analyses that confirm the assets ability to fulfill the required levels of safety and functionality throughout the intended lifetime.
- Operational Integrity;
  Assets are operated through defined operational envelopes without compromising the assets acceptable limits.
- Technical Integrity;
  Sustaining an acceptable condition of assets through maintenance, inspection and testing activities.

The technical integrity (TI) of facilities, systems or equipment is consequently the condition that allows them (when properly operated, assured, maintained, monitored and modified) to perform their intended function within design limits, whilst keeping risks to personnel, assets or the environment as low as reasonably practicable (ALARP) (AS Document 6, 2011). High-level TI can be ensured by assigning the most optimal maintenance strategies to the different systems and components in an O&G facility. However, ensuring and managing TI over time is dependent on the organization's management and its ability to implement and execute the operational and maintenance strategies.

2.2.1 Technical Integrity Management

Ratnayake and Toreset (2010) define Technical Integrity Management (TIM) as "*the management of physical assets with well trained (competent) personnel in accordance with sound recognized practices and procedures whilst predefined threshold limits are unimpaired through protecting societal health and safety, and natural environment whilst optimizing the return on investment*". Reaching the highest possible level of HSE is one of the main targets of TIM. This means that O&G production facilities is operated and maintained in ways that HSE risks are identified, analyzed and eliminated or mitigated down to acceptable levels (Kumar, Panesar, & Markeset, 2009). TIM is performed by multi-discipline personnel covering the expertise needed for assuring the company goals defined in the operational and maintenance strategies. TI assurance is also vitally dependant on access to quality data and information, as well as models, tools and methods for analyses and assistance in decision-making processes. From this the intention is to maximize the assets availability and efficiency by ensuring the condition and controlling the rate of deterioration in order to execute safe and environmental friendly operations with minimized financial costs (Ratnayake and Toreset, 2010). Such objectives are also concurrent with the main objectives for IO; ensuring the safest ways of conducting O&G activities while minimizing operational expenses and maximizing added values.

All systems and equipments will inevitably be exposed to degrading mechanisms during their operational lifetime. In order to manage and maintain an acceptable level of TI, competent personnel working to defined standards within a management framework is consequently required. The TI of a plant echoes from how management and strategies are implemented and executed by the organization, and is therefore dependant on effective methods and quality work processes. Figure 2.4 illustrates the maintenance management process and its components, a model well known within the O&G industry for managing and continuously improving the maintenance activities on O&G installations.

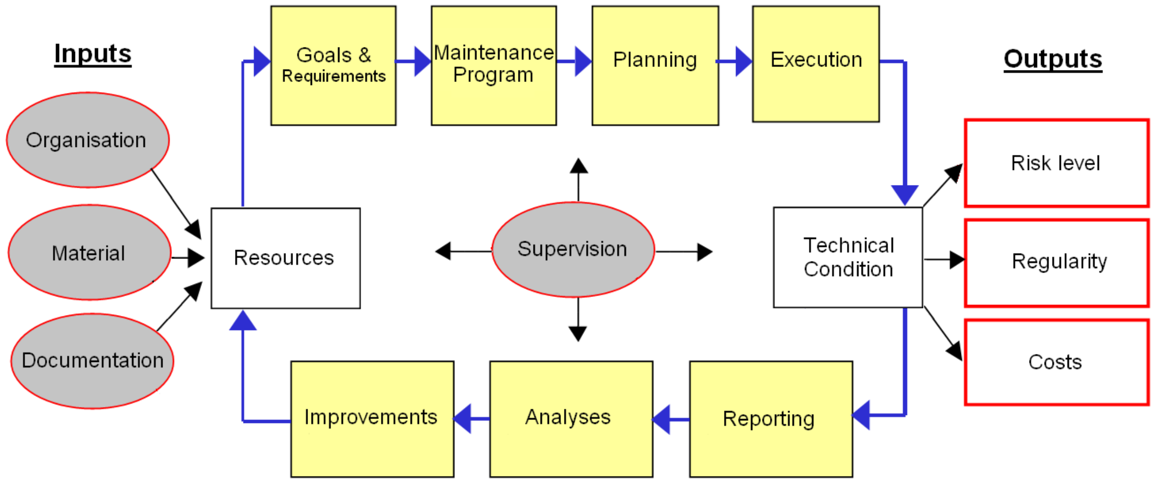


Figure 2.4, Maintenance Management Loop, AS Document 4 (2003)

Resources in form of the maintenance organization/personnel, materials and support documentation are the enterprise input factors to the work processes in the management loop (Øien & Schjølberg, 2007). The input resources are managed with the objective of producing the desired outputs that is measured by the plant's technical integrity and the corresponding level of risk, regularity and costs. This will imply that the facilities are "*capable of carrying out their intended functions in all phases of their lifetime*" cf. the Norwegian Petroleum Safety Authority (denoted PSA) regulations relating to conducting petroleum activities (the Activities Regulations) section 45 on maintenance.

Goals and requirements to the maintenance processes should be defined in accordance to the superior strategies for HSE, regularity and costs. Maintenance programs are developed in accordance to regulations (cf. the Activities Regulations section 47 on Maintenance programs and section 46 on Classification) with the objective of ensuring safe, efficient and cost effective operations. The maintenance activities are planned and executed according the specified programs, and after execution reports based on the maintenance results, the achieved technical condition, costs, regularity and risk is analyzed. Any identified improvements are implemented into the process (cf. the Activities Regulations Section 49; Maintenance effectiveness), and then the loop is closed. All the elements must be present and the management loop must be closed for ensuring the most effective maintenance function. It is important that the entire process is supervised and documented to ensure sufficient quality and continuous improvement of the work processes.

Following section will present an overview and short description of the different maintenance policies and practices for maintaining industrial plants and offshore installations today.

2.3 Maintenance Strategies Overview

Offshore O&G installations are complex facilities where resources are limited; specific maintenance personnel, tools or spare parts are not always readily available. The installations are often geographically remote, which means that a critical unforeseen or unplanned failure event can cause considerable production downtime. The events that bring production reduction or shutdown can turn very expensive in a short amount of time. With the mindset of operating in accordance to regulations, standards and internal company policies, while at the same time maximizing production; the assets must be maintained to the specified level of performance for ensuring the highest level of HSE. To achieve this, different maintenance strategies are applied for different types of systems, equipments and components based on their criticality, reliability, and cost efficiency. Figure 2.5 presents an overview of different maintenance policies and categories, and will be further explained below.

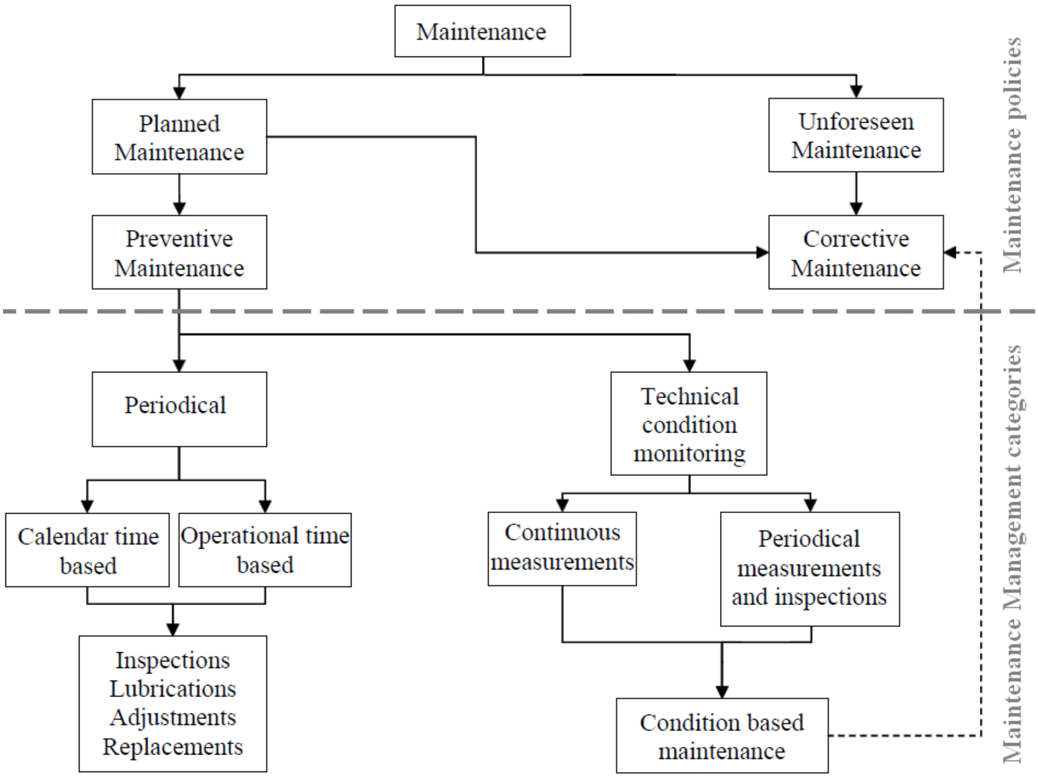


Figure 2.5, Classification of Maintenance Policies (adapted from Nystad, 2008)

Generally, there are two main types of policies; **planned** and **unforeseen** maintenance (Nystad, 2008):

1) **Unforeseen Maintenance** will always be corrective maintenance, since the failures occur unexpectedly. The maintenance action is performed after the part/system has failed. The purpose is putting the part/system back to function as soon as possible, either by repairing or replacing the failed item.

2) **Planned Maintenance** can be further classified as corrective maintenance or preventive maintenance.

   a) **Planned corrective maintenance** is when parts/systems are deliberately run-to-failure. This strategy is applied for non critical components where failures represent no threat to HSE, availability or economy. It does however assume continuous follow-up of costs and availability for assuring necessary changes and adjustments.

   b) **Planned preventive maintenance** is the maintenance activities performed while the parts/systems are in operation. This includes all actions for retaining the part/system to a specified condition, by performing systematic inspection, detection and prevention of incipient failures.

      Planned preventive maintenance can be further classified into two categories:

      i) **Periodical maintenance** interventions consist of inspecting and overhauling/replacing parts or systems at time scheduled intervals. The interventions can either be scheduled at specific pre-defined calendar times or based on concepts like operational hours, number of system activations, etc.

      ii) **Technical condition monitoring** is a way of gaining continuous knowledge about the technical condition of equipments and systems, providing possibilities for monitoring degradation and discovering incipient failures at an early stage. This will give the maintenance personnel time to plan, decide and perform maintenance interventions before failures and breakdown occur. Avoiding unforeseen breakdowns can minimize the extent of damage on equipment, reduce repair costs and reduce the total system downtime. It is important to note that condition monitoring is a preventive process with the purpose of justifying the maintenance actions to be performed; a kind of “if not broken, don’t fix it” policy.

The best overall maintenance strategies will normally be a combination of the categories mentioned above, exploiting the strengths and weaknesses of each category by using them where best appropriate. Some maintenance categories are substantially more expensive than others and will therefore not be cost effective for all types of equipment.

2.3.1 Maintenance regulations, standards and best practices

All O&G installations on the NCS must be operated and maintained in compliance with the rules and regulations issued by the Norwegian government and the PSA. To assure the highest level of safety, while providing a high working environment standard with the lowest possible emissions to the environment; the following hierarchy of governing regulations, requirements and standards apply (Figure 2.6).

Figure 2.6, Hierarchy of steering documents (Erstad, 2011)

The following sections of this chapter will map today's requirements and best practices for maintenance and inspection analyses leading to the formation of maintenance and inspection programs for O&G process equipment. The study is based on the following authority regulations and requirements, industry standards, recommended practices and AS internal best practice procedures;

1) Authority Regulations

PSA is the governmental supervisory authority of the Norwegian petroleum industry. Its responsibility regards the technical and operational safety, emergency preparedness and working environment in the Norwegian O&G industry (Ptil.no). According to AS Document 1 (2010), the following PSA regulations are applicable for doing maintenance and inspection analyses:

- *The Activities Regulations, Chapter IX: Maintenance (section 42 – 47)*
- *The Management Regulations, Chapter VI: Follow-up and Improvement*
- *The Facilities Regulations: Regulations related to design and outfitting*

2) Industry Standards

- Norsok Z-008: Criticality Analysis for Maintenance Purposes

This standard serves as a guideline for establishing a basis for preparation and optimization of maintenance programs, based on the criticality of systems and equipment. The intention is to provide requirements and guidelines to a foundation for preparing and optimizing maintenance programs for static and rotating equipment. It is applicable for equipment placed on offshore or onshore, topside or subsea, new or in-service facilities.

3) Recommended Practices

- DNV RP-G101: Risk Based Inspection of Offshore Topsides Static Mech. Equipment

This recommended practice describes a method for establishing and maintaining a RBI plan for offshore static mechanical process equipment. It provides guidelines and recommendations used for customizing methods and working procedures that support the inspection planning process.

4) AS Internal Procedures

- AS Document 1 (2008): P132 – Maintenance Analyses

Document for ensuring that maintenance analyses performed in connection with modifications/new buildings are prepared in a systematic way, at a qualitative acceptable standard, and in accordance with authority requirements, customer requirements and AS best practices.

- AS Document 2 (2006): A132-K01 - Method description for Maintenance Analyses

This document describes AS methodology and work processes for performing maintenance analyses and maintenance program establishment. The methodology is based on general requirements from authorities, typical customer requirements, acknowledged standards and company best practices.

- AS Document 3 (2006): A132-K02 - Method description for Inspection Analyses

Provides a brief description of working processes, methods and criteria for analysis of static equipment to identify risk and prepare inspection programs for monitoring the condition of plant during operation.

2.4 Maintenance Engineering Process

High level, cost efficient TI can be achieved by assigning the correct maintenance strategies to the different systems and components of an O&G facility. Thus it is important to evaluate the criticality of components before deciding on their respective maintenance strategies. The maintenance activities are planned, prioritized and executed based on equipment criticality with respect to HSE and production acceptance criteria. Figure 2.7 shows the main elements involved for today's practice of maintenance engineering, and the following sections will describe the main activities in this process.

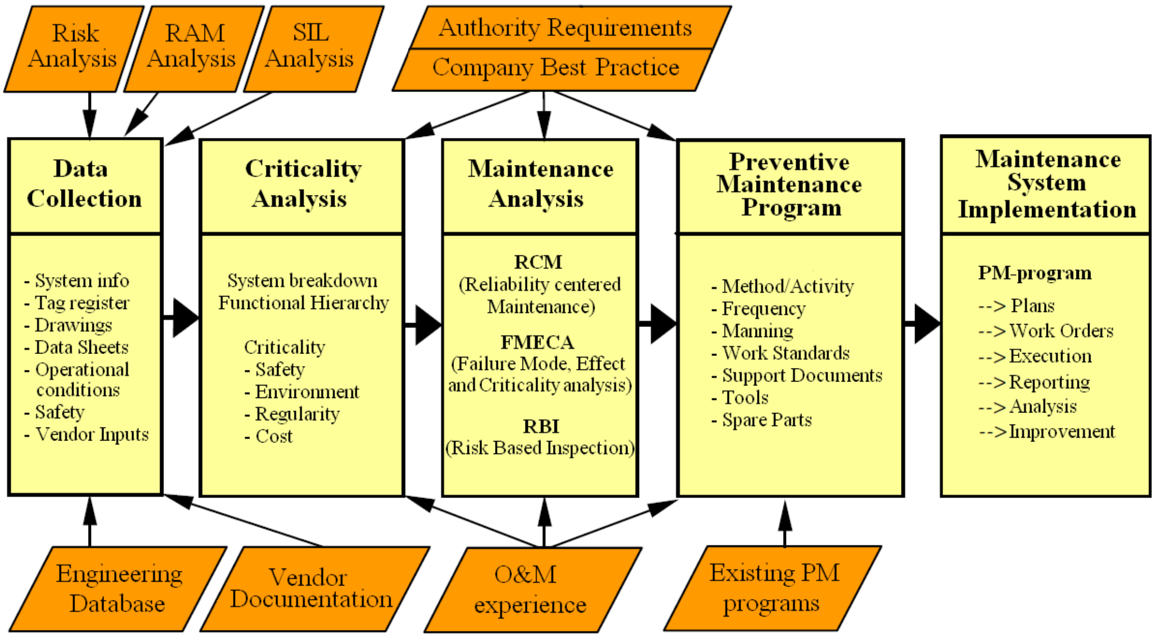


Figure 2.7, Maintenance Engineering Process, AS Document 4 (2003)

2.5 Data Collection

First step of the process is gathering technical data and information on all relevant components and systems for creating a sufficient basis to the criticality and maintenance analyses. Reliability, Availability and Maintainability (RAM) analyses, Safety Integrity Level (SIL) analyses and design phase risk analyses are important inputs in this process. Also, data is collected from company internal or common industry engineering databases. Vendors will also provide valuable technical and operational information regarding the systems and equipment they deliver.

2.6 Criticality Classification

Performing criticality classification will give an assessment of the consequence for loss of function with regards to safety, environmental and financial aspects of all tagged functions and equipment. The analysis provides valuable information that forms an important foundation for establishing maintenance and inspection programs. According to the PSA's Activities Regulations, Section 46:

"Facilities' systems and equipment shall be classified as regards the health, safety and environment consequences of potential functional failures.
For functional failures that can lead to serious consequences, the responsible party shall identify the various fault modes with associated failure causes and failure mechanisms, and predict the probability of failure for the individual fault mode.
The classification shall be used as a basis in choosing maintenance activities and maintenance frequencies, in prioritizing between different maintenance activities and in evaluating the need for spare parts."

Consequently there are legal requirements for the responsible parties to perform system criticality classification and equipment ranking with regards to consequences of function failure, and analyzing severe failure modes and mechanisms with predicted probability of failure (PoF). To perform the classification in accordance with regulations, the PSA advise the Norsok Z-008 standard to be used.

2.6.1 The Classification Process

Criticality analyses consist of performing a system breakdown into main- and sub-functions, and then ranking the equipment with respect to the consequences of function failure. This calls for good knowledge and experience regarding equipment, systems and their operational functions. To assure a high quality analysis, it is vital that a group of multidiscipline representatives participate in the consequence assessments and functional breakdown. The methodology will be further addressed in the following subchapters, with the basis of the Norsok Z-008 and AS internal procedures.

2.6.1.1 Establish decision criteria

Classification of the consequence of failures must be defined before initiating criticality analyses. This should be done in compliance with the company’s HSE policies, and the financial losses shall be defined in accordance with the specific facility subject for analysis.

Consequence Classification

AS Document 2 (2006) recommend using a matrix like Table 1 for classifying the most serious effects for loss of functionality. Consequence is divided into five degrees of criticality. Values for regularity (lost production) and cost limits must be specified according to the production rates and repair costs of the particular facility or system. If a failure causes “loss of containment” there is need for separate evaluations regarding the consequences for HSE, as leakage to the environment will have varying effects depending on the chemical composition of the medium, the volume and location of the leakage (open sea, shore, earth or atmosphere). The consequence classification related to containment is intended as a prioritization of static mechanical equipment for establishing an inspection program, and will be further presented in Chapter 2.8. In addition to oil, three different chemical groupings have been included to give more precise estimations of the seriousness of leakage, according to the toxicity and reactivity of the chemicals.

Category / Consequence:		**1**	**2**	**3**	**4**	**5**
Safety:		First aid	Medical treatment	Serious personal injury	Permanent injury	Death
Environment	*Oil*	< 200 l	0.2 – 2 m3	2 – 20 m3	20 – 200 m3	> 200 m3
	Chem. Deg. 1	< 25 l	25 – 200 l	0.2 – 1 m3	1 – 10 m3	> 10 m3
	Chem. Deg. 2	< 200 l	0.2 – 1 m3	1 – 10 m3	10 – 100 m3	> 100 m3
	Chem. Deg. 3	< 1 m3	1 – 10 m3	10 – 100 m3	100 – 1000 m3	> 1000 m3
Regularity:		< 250k	250k – 1 mill	1 – 10 mill.	10 – 50 mill.	> 50 mill.
Costs:		< 50k	50k – 250k	250k – 1 mill	1 – 10 mill.	> 10 mill.

Table 1, Consequence Criteria, AS Document 2 (2006).

Frequency Classes

Classifying the estimated function failure frequency (Mean Time to Failure). The frequency classification is not included in the Norsok Z-008, but is part of AS' procedure for criticality classification (AS Document 2, 2006). The frequency values are usually based on company/vendor/customers historical and reliability data.

Frequency class	Frequency (f) (expected failures per year)	MTBF (Mean Time Between Failure)
a	f < 0.03	MTBF > 30 years
b	0.03 < f < 0.2	30 years > MTBF > 5 years
c	0.2 < f < 1	5 years > MTBF > 1 year
d	1 < f < 2	1 years > MTBF > 6 months
e	f > 2	MTBF < 6 months

Table 2, Frequency Classes, AS Document 2 (2006).

Criticality classes

Criticality is the combination of stated likelihood and the consequence of potential function failure. Criticality classifications are performed with the use of five grades, shown in Table 3. Criticality will indicate risk-ranking for equipment and give basic indication for which maintenance priorities or strategies to be used for establishing maintenance programs.

Criticality		**Maintenance Strategy**
VH	**Very High**	Equipment/system should not be operated under specific conditions
H	**High**	PM/Condition Monitoring
M	**Medium**	PM if appropriate/cost-efficiency requirements
L	**Low**	Corrective Maintenance or 1st line mainenance
VL	**Very Low**	Corrective Maintenance

Table 3, Criticality Classification, AS Document 2 (2006).

2.6.1.2 Defining Main and Sub-functions

O&G facilities consist of numerous components and systems to perform the different tasks required for production and processing. Prior to criticality analysis, the plant should be divided into systems covering the whole facility's functions (e.g. gas export, gas conditioning, gas compression etc). The boundaries between these systems must be clearly defined, and each of the systems shall be given a unique id with the use of engineering numbering system (ENS). Systems relevant for further criticality analysis must be identified. Selection of equipment should be based on maintenance cost, main contributors to production loss/unavailability and safety related incidents.

Main function (MF) definition

MFs are the principal tasks performed on the facility (e.g. pumping, compression, separation etc). All MFs must be identified, assigned unique numbered descriptions and named according to the task/process performed. The name should aim to describe the active function (i.e. compression instead of compressor). The MF boundaries should be clearly defined and documented in P&IDs, flow diagrams and other relevant documentation.

MF consequence assessment

To get sufficient assessments for the consequences of severe MF faults, there is a need for personnel with experience from risk and reliability evaluations in cooperation with experienced operations and maintenance personnel. The total MF is assessed in terms of the most critical effects of a fault, with the level of redundancy disregarded. Redundancy will be treated independently. The most critical, but still realistic, effects from a fault shall be identified, and the impact they have on the total performance of the MF shall be quantified in accordance with Table 1. For some cases, it will be important to also describe compensating operational actions in the consequence assessment, and estimate the time from failure occurring till it actually affects the system. If a failure is likely to affect more than one of the categories (HSE, production and cost), this shall be assessed and the probable course of events described.

Sub function (SF) definition

The MFs shall then be further divided into sub functions. As for MFs, the SFs shall describe the active function performed. SFs for typical process equipment can be standardized to cover all requirements. Some SFs (e.g. lubricating or containment) will often be repetitive in a system. The most important thing is that all equipment in each instrument loop is connected to **one** SF. In cases where a SF performs several tasks, the equipment shall be connected to the most critical SF.

SF consequence assessment

The same principles apply for consequence assessment of SFs as already outlined for MFs. The impacts of failure on SFs are assessed with respects to HSE, production and costs (excluding production loss). If a failure on the SF can occur without affecting the MF under normal operating conditions, this shall be identified and labeled a hidden failure. For the SFs that are safety critical, the failure modes and rates must be identified and expressed in detail in order to select the optimal maintenance activities when assessing the consequences of function failure (Norsok Z-008).

Redundancy of MFs and SFs

All MFs and SFs shall be defined by the number of units, the unit capacity (%) and the level of redundancy. If there is redundancy within a SF, the number of parallel units and capacity per unit shall be stipulated. The redundancy shall be classified using the codes in Table 4.

Redundancy	Redundancy Degree Definition
A	No unit can suffer a fault without influencing the function
B	One unit can suffer a fault without influencing the function.
C	Two or more parallel units can fail at the same time without influencing the function

Table 4, Redundancy Classification, adapted from NORSOK Z-008 (2001)

Functional hierarchy

The facility has been broken down to a functional hierarchy consisting of plant systems, main-functions and sub-functions. Figure 2.8 illustrates the breakdown of a gas export system, with the defined MFs covering the principal tasks of the system, and the standardized sub functions covering the MF.

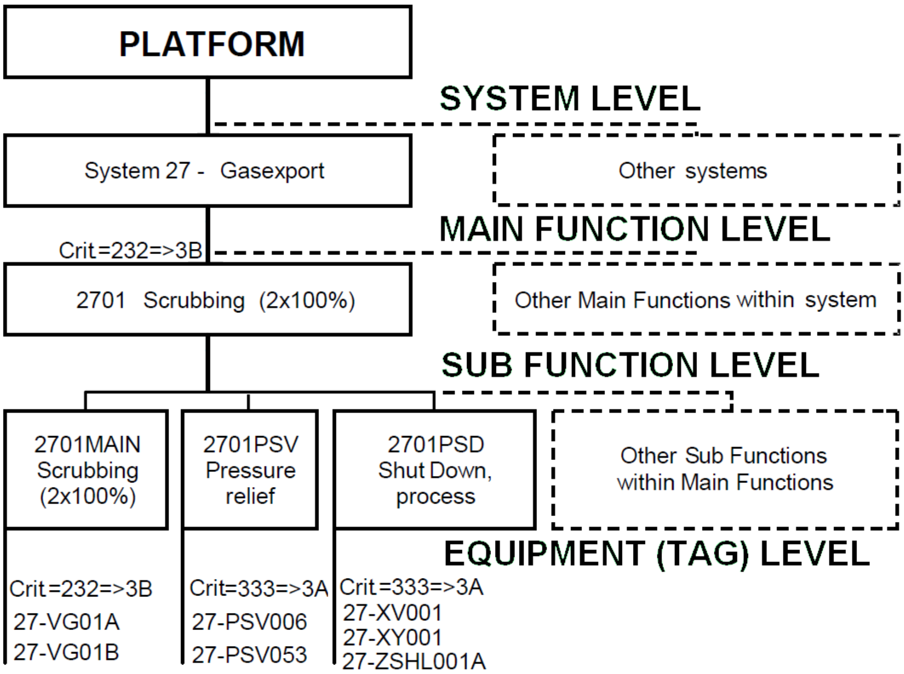
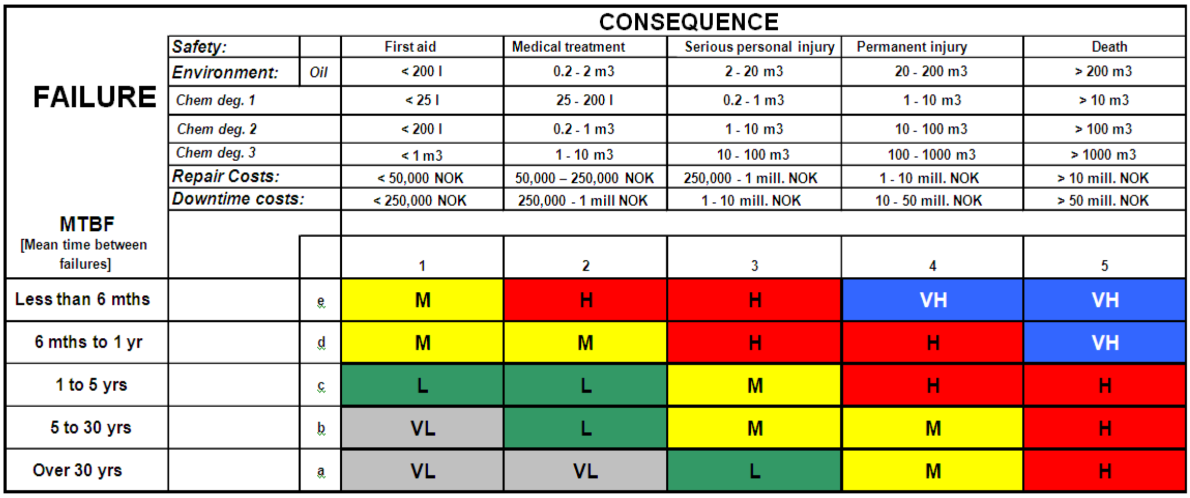


Figure 2.8, Example of Functional Hierarchy, adapted from Norsok Z-008 Appendix C (2001)

2.6.2 Equipment Criticality Classification

To summarize; the whole facility has been divided into MFs and respective SFs, and all tagged equipment has been assigned to one SF. The decision criteria are defined; consequently the foundation for equipment criticality classification is set. Table 2 for failure frequency and Table 1 for consequence are combined into one decision-making matrix for criticality (Table 5). This matrix shows criticality levels in accordance with the pre-defined criticality classes (Table 3) for the various combinations of frequency and consequence. All tags within one SF must be given the same description, consequence classification and redundancy as the SF they are part of, because failure on any of this equipment will cause the same consequence on the MF.



			CONSEQUENCE				
FAILURE	***Safety:***		First aid	Medical treatment	Serious personal injury	Permanent injury	Death
	Environment:	*Oil*	< 200 l	0.2 - 2 m3	2 - 20 m3	20 - 200 m3	> 200 m3
	Chem deg. 1		< 25 l	25 - 200 l	0.2 - 1 m3	1 - 10 m3	> 10 m3
	Chem deg. 2		< 200 l	0.2 - 1 m3	1 - 10 m3	10 - 100 m3	> 100 m3
	Chem deg. 3		< 1 m3	1 - 10 m3	10 - 100 m3	100 - 1000 m3	> 1000 m3
	Repair Costs:		< 50,000 NOK	50,000 – 250,000 NOK	250,000 - 1 mill. NOK	1 - 10 mill. NOK	> 10 mill. NOK
	Downtime costs:		< 250,000 NOK	250,000 - 1 mill NOK	1 - 10 mill. NOK	10 - 50 mill. NOK	> 50 mill. NOK
MTBF [Mean time between failures]			1	2	3	4	5
Less than 6 mths		e	M	H	H	VH	VH
6 mths to 1 yr		d	M	M	H	H	VH
1 to 5 yrs		c	L	L	M	H	H
5 to 30 yrs		b	VL	L	M	M	H
Over 30 yrs		a	VL	VL	L	M	H

Table 5, Example of Criticality Matrix, AS Document 2 (2006).

Documenting the Criticality Analysis

It is of great importance that the criticality assessment is properly documented and made easily available for revisions, updates and improvements. Over time, experiences and feedback from operation can give need for updates, and this is much easier if the classification is traceable. As a minimum, the following should be documented (Norsok Z-008):

- Decision criteria
- Definition of consequence classes.
- MF and SF description and redundancy assessment.
- Assignment of equipment (tags) to sub function.
- Assessment of the consequences of loss of MFs and sub functions for all consequence categories, including necessary arguments for assignment of consequence classes.

2.7 Reliability Centered Maintenance (RCM)

The criticality classification of all tagged equipment will provide clear insight to the systems weakest, most critical parts, and this is an important input for assigning maintenance and inspection strategies to components and equipments. “Very Low” and “Low” criticality components can be allocated maintenance programs without further studies; such components will normally be assigned to corrective maintenance or 1st line[1] maintenance strategies. Components considered as “Medium” or “Highly” critical are potentially relevant for further reliability centered maintenance (RCM) analyses, and will undergo a screening for identifying the relevant objects. But performing complete full-depth RCM analyses is a complex, time and resource consuming process; hence the screening will only identify a small number of relevant objects. Previously analyzed components (e.g. by vendors) will therefore not be subject for new analyses. All components found irrelevant for further analyses shall be assigned to a maintenance program in accordance with current best practice, vendor recommendations and authority requirements for similar type components, as shown in Figure 2.9. This will usually be a preventive maintenance strategy, or in some cases where cost beneficial; condition monitoring strategies. Components classified with “Very High” criticality represents such risks that they should not be operated under these conditions, and must therefore be modified with the aim of lowering the risk.

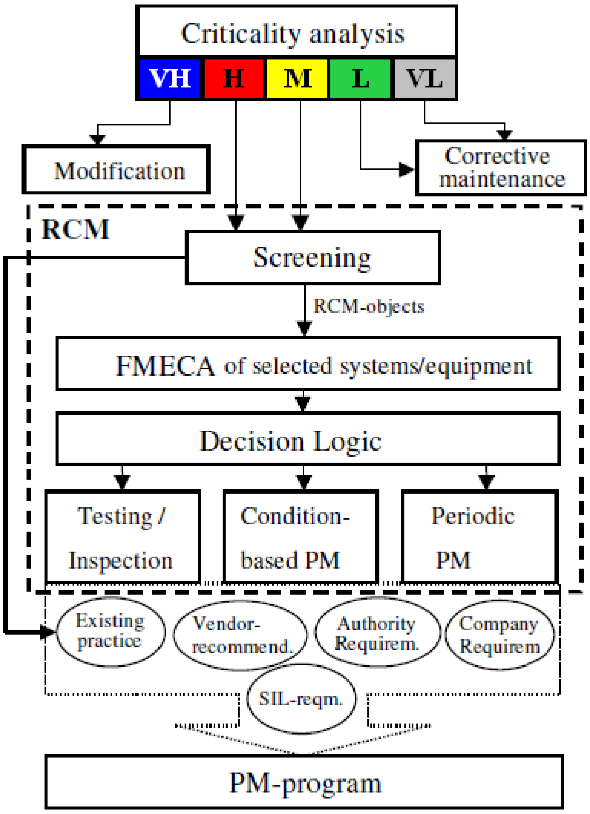


Figure 2.9, RCM process, adapted from AS Document 2 (2006).

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[1] Maintenance activities performed without using work orders, external assistance or interrupting production.

RCM-analyses are best appropriate for systems/equipment with high economic and/or safety criticalities, or where major financial and/or safety gains are possible through further optimization of maintenance activities. Moubray (1997) defines RCM as a “process used to determine the maintenance requirements of any physical asset in its operating context”, and the method is well established for creating or optimizing preventive maintenance programs for offshore topside process equipment. RCM bases on systematic analyses of system/equipment functionality and potential failures, with the purpose of determining effective preventive maintenance tasks for controlling or reducing the failure frequency for critical failure modes. The screening for RCM objects is based on the following criteria (AS Document 2, 2006):

- Equipment not previously analyzed
- Limited/no experience of equipment/system
- Criticality
- High technical/functional complexity of equipment
- High maintenance costs

The identified RCM objects must undergo FMECA analysis and decision logic for identifying relevant failure modes, causes and optimal maintenance actions.

2.7.1 Failure Mode, Effect and Criticality Analysis (FMECA)

Aven, Røed and Wiencke (2007) define the Failure Mode, Effect and Criticality Analysis (FMECA) as “an analysis method used to reveal potential errors and predict the effect of failures in components in a system”. Together, the FMECA analyses and the decision logic for allocating PM actions are the most vital parts of the RCM process. It involves a systematic mapping of failure modes with related failure mechanisms, and identifying effective maintenance actions to prevent or control these. To ensure the highest quality analysis, there is a need for personnel with solid operational knowledge and experience. As a tool for simplifying the process of FMECA, maintenance analyses and allocation of maintenance type; sets of standardized failure mode definitions, equipment classes and decision logic can be selected.

Failure Modes

Moubray (1997) defines a failure mode as ‘any event which causes a functional failure’. ISO 14224 (2006) categorizes failure modes into three different types:

- Desired function not achieved (e.g. failure to start)
- Specified function lost or outside accepted operational limits (e.g. high output)
- Failure indication is observed but there is no immediate and critical impact on the equipment-unit function. (e.g. initial wear)

Márquez (2007) states that only failure modes with a high occurrence possibility are to be recorded in an FMECA, meaning it is not recommended listing every single failure possibility. To simplify the process, a set of standard failure modes based can be defined. The failure mode's criticality is based on their local effect on equipment function, and divided into three levels:

- Critical (C)
- Degraded (D)
- Incipient (I)

The frequency of the failure modes is based on operational experience and any available reliability data, with the same classification as for criticality analysis (Table 2).

Equipment groups

The ISO 14224 (2006) provides a methodology for grouping topside process equipment into equipment classes and types. As a method for simplifying the maintenance analysis, AS Document 2 (2006) advises to use a set of standard equipment groups, partly based on ISO 14224. This means that all of the tag registered equipment will be connected to one of these standard groups, based on its equipment class and type.

2.7.2 Decision Logic

Based on the above-mentioned standardized failure modes and equipment groups, each equipment group will be connected to a set of failure modes. The purpose is to create a generic FMECA-analysis that can be used as basis for specific tag level FMECA-analyses for the chosen RCM objects. The generic model includes the estimation of failure criticality and frequency for each of the modes within the equipment groups.

In addition to the generic FMECA-analysis, a decision logic is used (Figure 2.10) for allocating the best suitable maintenance types for the different failure modes. Ability for failure detection and failure characteristics are used as decision-making criteria, and to identify the relevant maintenance type.

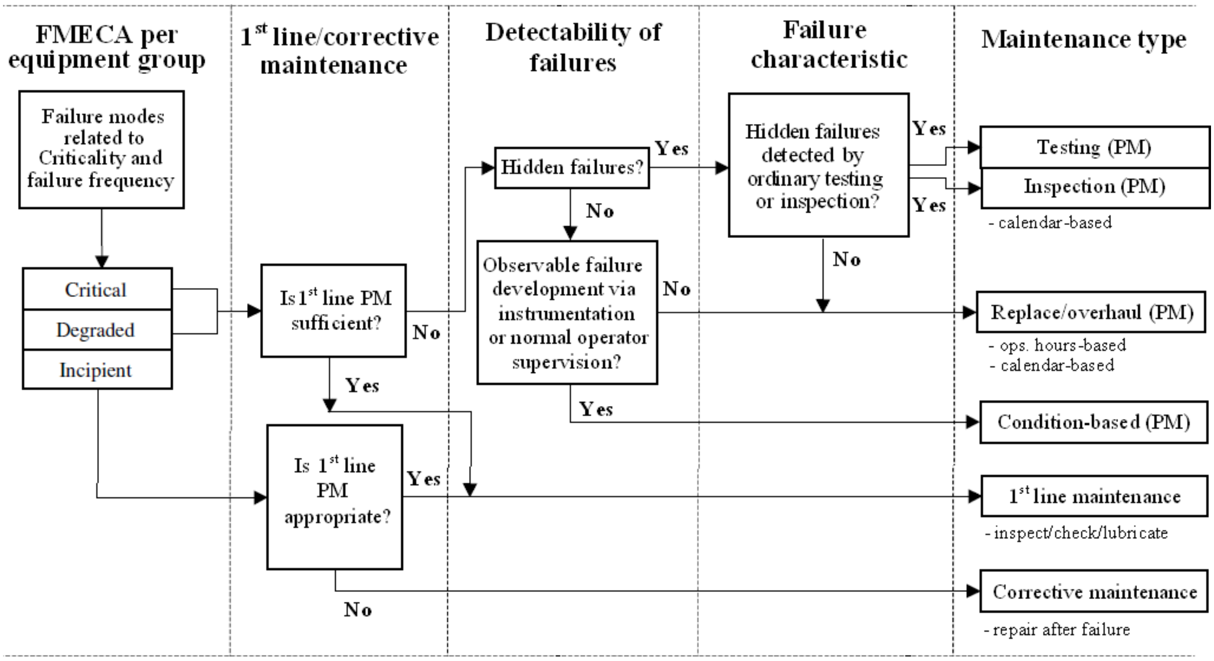


Figure 2.10, Decision Logic, AS Document 2 (2006).

RCM meetings

The RCM objects identified in the screening will undergo specific tag level FMECA-analyses with coherent decision logic for allocating maintenance strategies and activities. The generic analysis will then form the starting point for further evaluations. This part of the analysis is performed in a multidiscipline forum, called an RCM meeting, where experienced operations personnel are vital participants. The meeting procedure requires a consistent and goal-oriented work process to successfully identify and verify all relevant failure modes and assess maintenance actions for component failures on “maintainable item” level. The RCM meetings must be planned and structured systematically to ensure best quality results. Meetings need firm control and thorough preparation and planning in order to involve the right personnel at the right time. All relevant documentation must be available and all preliminary analyses completed. The target outcome of the RCM meetings is to achieve best possible consensus for decisions and the results suited for direct implementation in a PM program without further discussion.

2.8 Risk Based Inspection (RBI)

Inspection analyses focus on the damage caused by degrading mechanisms (corrosion, erosion, fracture and fatigue) that can be detected by inspection, either from visual examination or non-destructive-testing (NDT) methods. These degrading mechanisms can cause failure modes (e.g. leakages or ruptures) that may bring unacceptable consequences to personnel, environment, production loss or repair costs. RBI seeks to categorize analysis objects with regards to criticality. In practice, most risk based inspection analyses are a combination of qualitative and quantitative methods, and RBI is therefore usually recognized as a semi-quantitative method (DnV RP-G101). Before starting the risk evaluations, the decision criteria and detail level are established and agreed upon. The risk assessment should be evaluated regularly, and revised if necessary for including significant changes of input information, such as process and operational data, new design conditions and changes in the field economy. Figure 2.11 illustrates the main activities of an RBI analysis, and the basics of the process will be explained in the following section, in accordance with DnV RP-G101 and AS internal procedures.

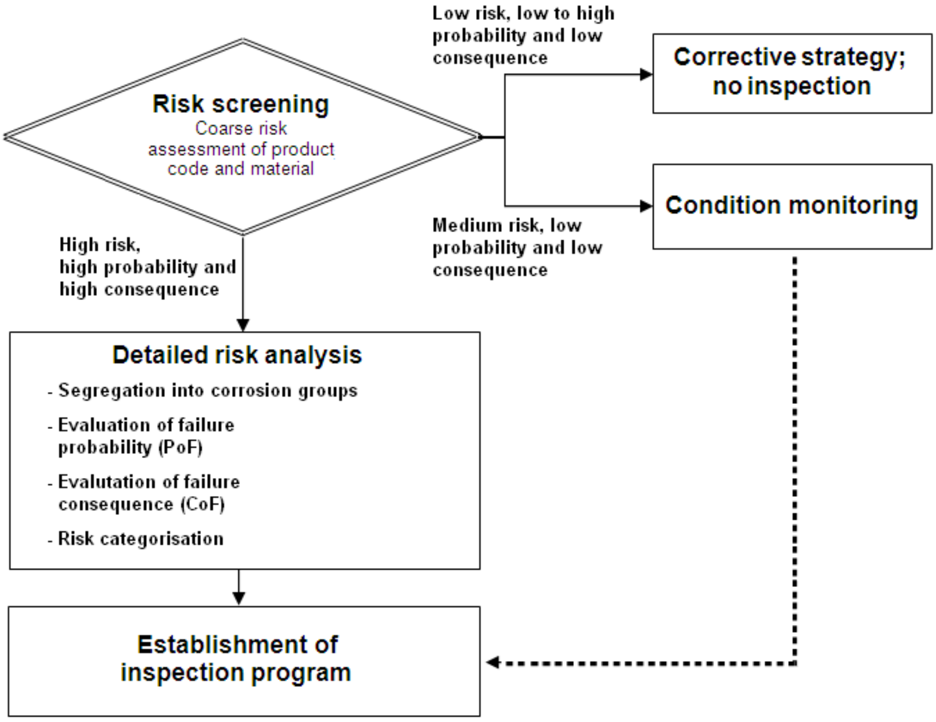
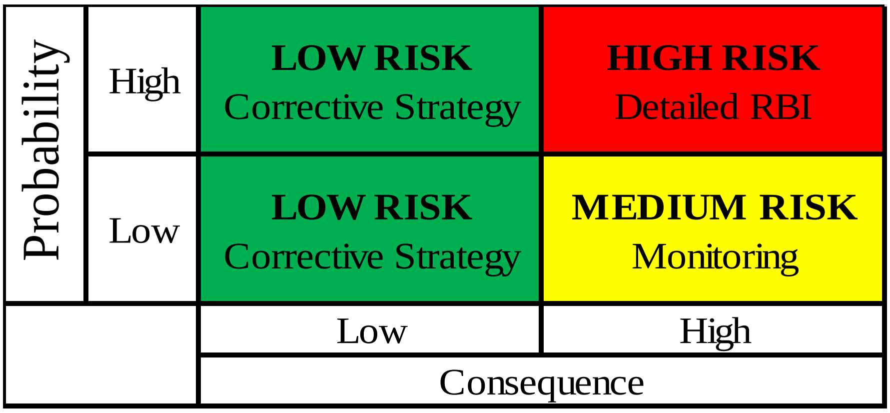


Figure 2.11, RBI Analysis process, AS Document 3 (2006).

2.8.1 Risk Screening

Risk screening is a coarse risk evaluation of component groups with the aim of identifying the objects to be included in further detailed risk analyses. From this, further data collection and assessment efforts can be limited to these objects. The risk screening matrix (Table 6) shows that objects with potentially high risks of leakage are to be included in further detailed risk analyses. Characteristic for these objects is that they have a high probability for “loss of containment”, and will in such cases bring severe consequences to HSE and financial costs. Corrosion and/or erosion prone pipes and vessels containing high pressure and high temperature (HPHT) hydrocarbons can be typical examples. Objects that bring severe consequences for loss of containment but have low probability of leakage will represent significant (yellow) risk levels. For such objects, NDT methods, testing and other condition monitoring activities should be taken to measure the extent of degradation so that actions can be taken before the risk elevates into the high-risk region. Objects with low consequences will be assigned to (planned/unplanned) corrective strategies based on cost-benefit assessments. Generally some minor measures (visual inspections, cleaning, etc) must be performed to confirm the condition of the equipment and ensure that the risk level will remain within the acceptable green region.



Probability	High	**LOW RISK** Corrective Strategy	**HIGH RISK** Detailed RBI
	Low	**LOW RISK** Corrective Strategy	**MEDIUM RISK** Monitoring
		Low	High
		Consequence	

Table 6, RBI screening matrix, AS document 3 (2006).

2.8.2 Detailed Risk Analysis

The objects classified as medium and high risk components in the screening process are the elements that need further detailed considerations, meaning they must be broken down to lower level (tag level) and assessed with qualitative, quantitative or semi-quantitative methods. The detailed risk analysis aims to identify the relevant degradation mechanisms, the probability of failure from these degradations and the expected damage extent in case of failure.

Evaluation of Probability of Failure (PoF)

PoF is the likelihood of an event occurring per unit time. For evaluating the probability of failure, the particular object's resistance to degradation under operational conditions (media composition, pressure, temperature, and material properties) must be considered. Failure evaluation firstly involves assessing the possibility of degradation mechanisms to occur, and secondly assessing the probability of it. Differentiation is made between the material properties of carbon and stainless steels, and the relevant degradation mechanisms to be considered are (AS Document 3, 2006):

- Internal corrosion/erosion
- External corrosion
- Fatigue

Evaluation of Consequence of Failure (CoF)

Consequence of failure is defined regarding to three aspects; Personnel Safety, Environment and Economic.

- Personnel Safety
  Should be expressed in terms of potential consequence for physical injuries to personnel, ranging from; no need for medical treatment to death or very serious injuries.

- Environment
  Consequences should be expressed in terms of the toxicity and mass/volume of the medium released to environment. Table 5 presents three different chemical groupings in addition to oil, for estimating the seriousness of leakage.
- Economic consequence should be expressed in financial terms using appropriate currency units.

It is recommended that the ranking of CoF is separately assessed and presented individually, depending on the consequence type (Personnel, Environment, and Economy) (DnV RP-G101, 2009, AS Document 3). This will bring proper focus for each aspect to be addressed.

Risk categorization
The risk category allocated to a component, is a function of the probability and consequence categories previously allocated by the RBI analysis, and presented as a matrix showing the relative contribution of CoF and PoF. For a simplified and consistent decision process, the risk matrix should be standardized throughout the operator/field. DnV RP-G101 recommends a detail resolution of 5 × 5 matrix for adequate resolution of detail.

		Risk category				
		Consequence				
		1	**2**	**3**	**4**	**5**
Probability	**5**	L	M	H	VH	VH
	4	L	M	H	H	VH
	3	VL	L	M	H	H
	2	VL	VL	L	M	M
	1	VL	VL	VL	L	L

Table 7, Risk Categorization, AS Document 3 (2006)

2.9 Establish PM Program & Implementation

After collecting all relevant data and having performed the criticality and reliability analyses the preventive maintenance programs can be developed (Figure 2.7). The maintenance, inspection and test activities seek to detect, prevent and minimize potential failures with regards to the analyzed risk of equipment failure, and are designed to reflect the overall strategy of ensuring to keep the facility within the desired technical condition through performing safe, efficient and economic maintenance. The PM programs define the specific maintenance tasks, the equipment to be used, the frequency maintenance should be performed at, generic work descriptions, discipline man hours, need for spare parts and so on. Inspection programs are established on the basis of the results from the RBI analysis. An RBI program will specify the most probable degrading mechanisms, their location and scope, which inspection methods to be used for detection, the inspection intervals per corrosion group and requirements to reporting the results.

Having defined the PM programs; last step is implementation into the CMMS system, usually SAP. The implementation consists of specifying the maintenance actions with regards to the respective components; define work orders containing job tasks, the sequence of performance, the expected time estimation etc. Further the execution should be specified to clearly indicate how the work should be performed in accordance to requirements and best procedures regarding HSE and maintenance quality. Results from completed maintenance actions should be reported to provide inputs for optimizing the maintenance programs and analyze their efficiency. Collected experiences should be analyzed to identify measures for continuously improving the maintenance programs and also used for updating the criticality assessments.

The increasing use of ICT on the NCS has made it possible to transfer vast amounts of real time data through high speed fiber cables between off- and onshore installations. This has led to increasing use of condition monitoring technology giving operators the possibility to detect degradations at an early stage. This has brought significant opportunities for performing maintenance on a condition based basis; streamlining the maintenance activities by performing “right time” maintenance. Next chapter will present the maintenance developments and possibilities emerging from the presence of ICT and data integration technologies.

3 MAINTENANCE IMPACTS FROM ICT & DATA INTEGRATION

With the growing demand for high levels of HSE, and the before mentioned need for reducing OPEX'es and production downtime on the maturing fields of the NCS; the importance of efficient maintenance strategies becomes unquestionable. But many challenges are still to be solved if the objective is to perform maintenance in a way where action is only taken when required, following a condition based maintenance (CBM) approach. As the price of technology for gathering, processing and acting on information is decreasing, the price for making incorrect decisions is increasing (Jantunen et al. 2010). Growing use of mobile communication and internet technologies brings new possibilities for solving business and maintenance problems, bringing rapid benefits for maintenance strategies like CBM and predictive maintenance by allowing them to become cost-effective for a wider range of equipment types. During the last decade maintenance policies and strategies have undergone major developments; moving from the traditional 'fail and fix' towards 'predict and prevent' strategies (Jantunen et al. 2010), and the term "e-maintenance" has emerged in the field of engineering asset management.

3.1 E-maintenance

Moving towards an e-maintenance approach means utilizing state-of-the-art ICT for integrating and synchronizing various maintenance and reliability applications to deliver maintenance related asset information "*where it is needed and when it is needed*" (Verma, Srividya, & Ramesh, 2010). Numerous authors have proposed various definitions of the concept; Baldwin (2004) defines e-maintenance as an "*asset information management network that integrates and synchronizes the various maintenance and reliability applications to gather and deliver asset information where it is needed when it is needed*". E-maintenance is neither regarded as a maintenance strategy nor a single technology. It is the end result of integration between different technologies that together form a highly innovative and efficient ICT framework for integrated and efficient maintenance. The main objective is to implement ever-present maintenance management. This means that maintenance planning, decision-making and execution as well as data and tools to process and act upon them are made available anytime, anywhere and to anyone with the authorization to access them at multiple levels of operation (Jantunen et al. 2010). It allows for instant technical support and interoperability[2] between maintenance specialists with real-time access to remote information about systems and environments, independent of location. This brings huge benefits to maintenance engineering and decision-making in distributed organizations where plants, people, expertise and/or data is physically separate or isolated. The consistent access and

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[2] Interoperability is the ability two or more systems/components have to exchange information, and to use the information that has been exchanged.

exchange of information also allows for closer collaboration and knowledge sharing between units, departments, companies, experts and processes.

At operations level, e-maintenance involves technologies and tools for integrating functions for monitoring component degradation status and availability condition, provide decision-making personnel with diagnostics and prognostic information, and support the estimation of performance indicators. Higher up the hierarchy, e-maintenance provides enabling tools and information for assisting the implementation of selected maintenance policy at strategic level, while presenting interfaces to the CMMS and ERP systems. At top level, e-maintenance presents the necessary decision-support tools for adopting/defining maintenance policies and assigning these to lower hierarchical maintenance layers (Jantunen et al. 2010). Compared to conventional maintenance practices, e-maintenance can introduce unique possibilities for improved efficiency and transparency into maintenance strategies (Figure 3.1), and also provide possibilities for reducing the number of interfaces; either they are IT systems, departments or personnel (Crespo-Márquez, 2007).

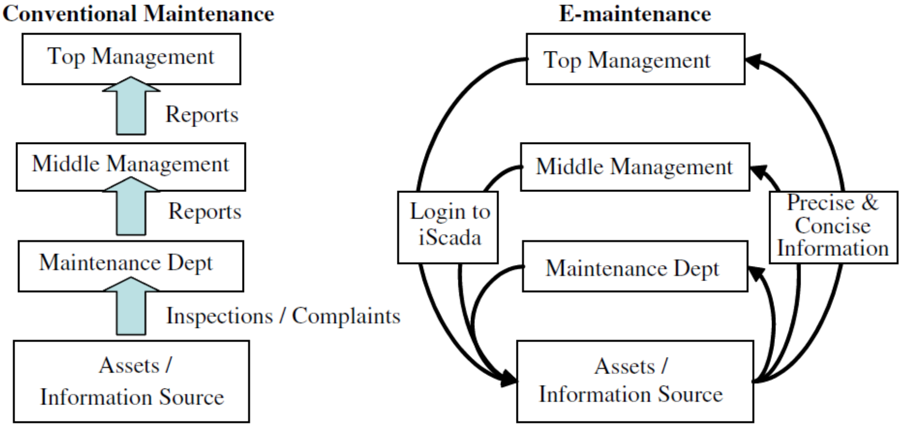


Figure 3.1, Transparency of strategies (Crespo-Márquez, 2007, s. 309)

Figure 3.2 illustrates the main pillars that together form the e-maintenance approach. The pillars represent the four new maintenance strategies enabled by e-maintenance, and will be further presented in the following points (Cannata, Karnouskos, & Taisch, 2009):

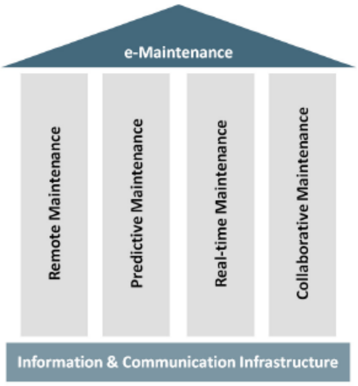


Figure 3.2, e-Maintenance: Basis and main pillars, (Cannata, Karnouskos, & Taisch, 2009)

- Remote maintenance:
  The presence of new ICT developments brings new possibilities for maintenance assistance and consultations, independent of geographical locations. Through remote maintenance applications a maintenance decision maker or expert consultant can perform a job without ever being present at the asset location. This will have a significant influence in terms of response time, downtime costs and the effectiveness of maintenance interventions.

- Predictive maintenance (or CBM):
  E-maintenance and its information and communication infrastructure facilitates for implementation of predictive maintenance, a recent evolution within maintenance and reliability engineering. Through hardware and software components available at floor level; data can be collected, analyzed and maintenance actions requested accordingly to minimize unexpected failures, optimize maintenance interventions and assure appropriate asset operation and availability.

- Real-time maintenance;
  The time delay between the moment when events take place on the shop floor (i.e. a machine failure) and the moment when that information is available for the operator/responsible is significantly reduced. This will allow for increased reactivity of maintenance activities.

- Collaborative maintenance;
  E-maintenance concepts enables collaboration between different areas of the enterprise, both internally (intra-enterprise) and between different enterprises (inter-enterprise). In the maintenance domain, collaboration issues are i.e. reduction of information interfaces, seamless communication, security, and so on.

Figure 3.2 also illustrates that the fundamental element and backbone of e-maintenance concept is the implementation of an appropriate information and communication infrastructure (I&CI) (Muller, Iung, & Crespo-Marquez, 2007).

3.2 Information and Communication Infrastructure

The presence of a consistent infrastructure that can support the management and control of maintenance activities and present them real-time to higher level business layers is a founding issue for moving towards feasible solutions of e-maintenance applications. A typical information and communication infrastructure (I&CI) for a maintenance concept are considered to consist and integrate several information sectors, Moore and Starr (2006) lists some examples:

- Condition monitoring systems (internal/external)
- Control systems and production schedulers
- Maintenance scheduling systems (CMMS/ EAM)
- Plant Asset Management (PAM) systems
- Engineering Product Data Management systems
- Enterprise resource planning (ERP) systems

Cannata, Karnouskos and Taisch (2009) have defined six vital requirements that should be present for an I&CI to be applicable in a maintenance context:

Interoperability
To effectively support the emerging "predict and prevent" maintenance strategies this infrastructure should enable open communication between different actors in different layers, to the right time, and through the implementation of various tools and technologies globally distributed. This can be done by adopting a common language that reduces the requirement for interfaces between different systems. The goal is to achieve common basis for flawless operation of standard functions such as discovery, description, addressing, invocation, etc.

Scalability and flexibility
With rapid technology developments and evolution towards more flexible and adaptive facilities and maintenance strategies it is important that the I&CI is susceptible to changing conditions. This means being compatible with future modifications and changes, such as new types/models of assets monitored, more assets monitored and new future monitoring techniques. This dynamicity must be supported through a scalable and flexible infrastructure for maintenance data and information exchange.

Security
In such open infrastructures where huge amounts of data, business and collaboration processes are exchanged between facilities and companies at several layers, security is a key issue. These systems require a different security approach compared to traditional architectures, in the sense that they must be flexible enough to tailor themselves to application-specific security requirements, but also to be customizable for policy/compliance.

Device to Business (D2B) Integration
With the increasing development and sophistication of personal digital assistants (PDA) and similar portable devices, new capabilities emerge on the floor and enable such devices to actively participate in maintenance applications. The devices can provide information from internal domains, and/or acquire information from enterprise level, as for example trigger an event in the maintenance process and also influence its execution. A consistent I&CI should consider these factors and adopt a general approach to represent information among heterogeneous systems.

Distributed management:
In order to fully exploit remote and collaborative maintenance, a distributed infrastructure is required that does not only consider hierarchical control as this constrains the opportunities enabled by heterogeneous, distributed, and autonomous interaction among single elements (e.g. operators, devices, watchdog agents, etc.). Moreover, this requirement can inherently add flexibility and scalability to the system by reducing the number of centralized points.

Semantics:
The I&CI should inherently support knowledge processing, due to the importance of ontology in the e-maintenance context. In connection to knowledge and information sharing, the term ontology is meant as a specification of a conceptualization. Thus ontology is a description of the concepts and relationships that can exist for an agent or a community of agents (Gilabert & Voisin, 2010). Knowledge processing is vital when implementing effective collaboration between multiple actors, and this requirement allows for collaboration through formal description of elements and relationships in the maintenance domain.

These abovementioned points are regarded to be vital qualities for an information and data exchange infrastructure to be sufficiently applicable in the O&G industry’s operations and maintenance context. With the emerging need for common cross-industry communication protocols several initiatives have been formed with the aim of standardizing the rules of communication so that CM systems and new technology devices from different vendors can be connected and added to factory networks without needing extensive configurations in order to be compatible (Starr & Ball, 2005). Next section will present some of the standards and initiatives taken to accomplish this.

3.2.1 Data Integration Standards and Initiatives

Integration and interoperability between separated islands of maintenance and reliability information are becoming increasingly important in modern maintenance regimes. Therefore, the information and communication infrastructure network must provide seamless exchange of asset-related information from and between multiple sources (Muller, Iung, & Crespo-Marquez, 2007). The development of international standards is an important initiative for making this process as smooth as possible. This section will further introduce some recognized standards regarding smart transducer interfaces for sensors and actuators (IEEE 1451), artificial intelligence techniques in test equipment (IEEE 1232), standardized CBM system architecture (OSA-CBM) and standardized communication among CBM modules (MIMOSA). Adopting these standard information exchange protocols will bring fewer problems with IT and data-acquisition issues when trying to get the systems compatible, and instead allow more focus towards developing and optimizing the new maintenance possibilities that the integration of this technology brings. Implementing standardized communication and interoperability protocols would also provide the users with more technological choices, bring faster technology developments and ultimately reduce the prices of CBM technologies (Bengtsson, 2004).

IEEE 1451: Smart Transducer Interface Standard

The founding level of the CBM systems consists of sensor devices that "collect" the data needed for analyzing the health assessment of systems and machineries. Because of emerging network problems with integrating different vendor products (transducers, sensors and actuators), standards for both hardware interconnection and software module network interoperability is needed. In the mid 90's, the National Institute of Standards and Technology (NIST) and the Institute of Electrical and Electronics Engineers (IEEE) started developing a standardized interface to network smart sensors. By linking sensors together in the same way personal computers are linked to a local area network (LAN), one achieved easy installation and upgrading of sensors. With this, several sensors can be connected via one single cable (or bus), meaning that sensors can be detached without further affecting other sensors (Bengtsson, 2004).

IEEE 1232: Artificial Intelligence ESTATE Standard

The standard for Artificial Intelligence Exchange and Service Tie to All Test Environments (AI-ESTATE) provides a set of specifications for data interchange and standard services for the test and diagnostic environment. "It has the purpose of standardizing interfaces among functional elements of intelligent diagnostic reasoners and representations of diagnostic knowledge and data for use by such diagnostic reasoners. Formal information models are defined to form the basis for a format to facilitate exchange of persistent diagnostic information between two reasoners, and also to provide a formal typing system for diagnostic services. This standard then defines the services to manipulate diagnostic information and to control a diagnostic reasoner" (Techstreet, 2011).

ISO 13373-1: Condition monitoring and diagnostics of machines

The ISO 13373-1 provides general guidelines for measuring and data collection functions for machine condition monitoring, focusing on machine vibrations. The standard was developed to ensure consistency in measurement procedures and practices and contains recommendations on measurement methods/parameters and transducer selection, location and attachment (Bengtsson, 2004).

MIMOSA

MIMOSA^{TM} is an alliance of operations and maintenance (O&M) solution providers and end-user companies who are focused on developing consensus-driven open data standards to enable open standards-based O&M interoperability (MIMOSA, 2008). The association has the objective of standardizing a networking protocol within the community of CBM developers and users that will drive CBM suppliers to produce interchangeable hardware and software components. The development of MIMOSA CRIS (Common Relational Information Schema) (openly published on the Mimosa website) provides coverage for the information (data) managed within a CBM system (Bengtsson, 2004). OSA-CBM is developed around

CRIS, which provides coverage of the data that will be managed within a condition based maintenance system (Gilabert & Voisin, 2010).

Open System Architecture for Condition Based Maintenance (OSA-CBM)

OSA-CBM has been designed as an open non-proprietary communications framework for CBM systems, covering the entire range of functions for the hardware and software components of such systems. It has the purpose of providing a functional, flexible platform compatible with a wide range of applications. The integration difficulties among different vendor products bring limited flexibility of CBM systems. Also, the current range of proprietary industry standards available can lock users into one single source solution (Bengtsson, 2004). Therefore, by introducing non-proprietary open system architecture standards the OSA-CBM development enables better cross-industry interoperability of CBM components. According to the organization itself, the OSA-CBM is believed to bring following benefits (MIMOSA, 2010):

- Cost - significant cost savings since system integrators and vendors will not spend time creating their own architectures.
- Specialization - when not constraining vendors to provide entire CBM systems, it allows them to concentrate on one or few areas. This increased specialization can bring better technology developments.
- Competition - all vendors are allowed to access the same input and output interfaces. Separating functionality from how information is presented to other applications will allow first hand comparison of the developed functionalities. This means that competition now will occur at a functional level and not at system or total solution level.
- Cooperation – with CBM sectioned into separate independent blocks, multiple vendors will be allowed to work on separate modules. As the standard also defines the interfaces, all of the modules can communicate seamlessly if developed from the same technologies.

The OSA-CBM framework consists of seven functional layers interacting together and forming a complete integrated system (Figure 3.3). The architecture includes the typical stages in development, deployment, and integration of condition based maintenance solutions, from data acquisition to decision support and presentation interface.

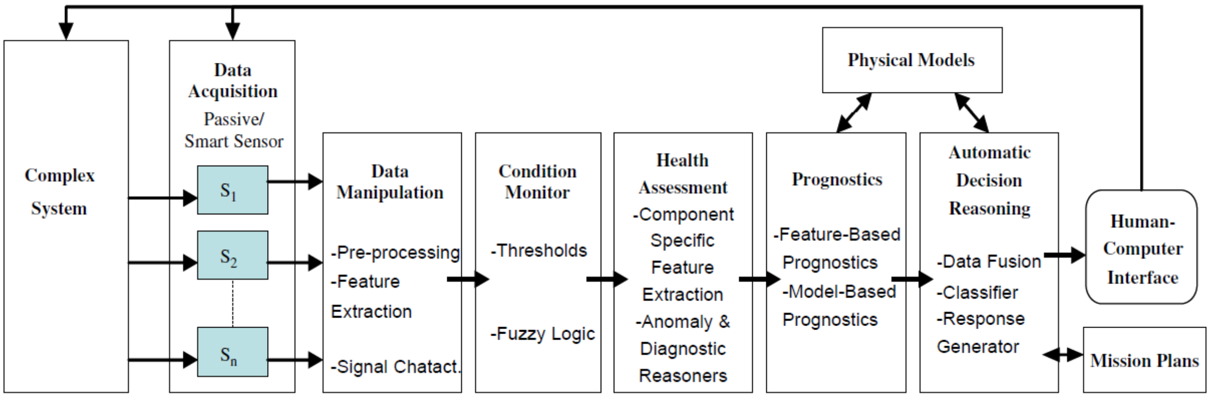


Figure 3.3, OSA-CBM architecture, (Muller, Iung, & Crespo-Marquez, 2007)

Each of the different layers are capable of requesting data from all the other functional layers if needed, however data flow will usually occur between adjacent functional layers. The general functions of the layers will be further specified below (Bengtsson, 2004):

Layer 1: Data Acquisition/Sensor Module:

Provides the CBM system with digitized sensor or transducer data placed on the respective equipment, e.g. vibration probe sensors placed on a bearing.

Layer 2 Data Manipulation/Signal Processing:

Receives the data from the sensor module, process these data and deliver the data on request from the condition monitoring module.

Layer 3: Condition Monitor:

This layer receives measurements data from the sensor and signal processing modules. The main focus is to compare data against preset expected values, and generate alerts in case of anomaly detection or changes in the usual trend.

Layer 4: Diagnosis/Health Assessment:

This layer receives inputs from the different condition monitors and health assessment modules of the CBM system. The primary function is to determine if the health of the monitored asset has degraded, based on anomaly detections on components or sub-systems. The health assessment module should be able to generate health records proposing possible faults, based on health history, operational status and maintenance tasks history.

Layer 5 Prognostics:

The prognostic module should be able to receive its data input from all prior layers. Its prime focus is calculating the future asset health condition, by also taking account of future usage profiles. The module should then report the failure health status of the asset, in form of a specified time or the remaining useful life (RUL).

Layer 6: Decision Support

Decision support receives input data from the health assessment and prognostic modules, and also from CMMS, ERP systems etc. The prime focus is to propose recommended actions and alternatives, such as maintenance intervention methods or recommendations of how to operate the asset until current mission is completed without breakdown.

Layer 7: Presentation

The presentation layer has the ability to access and present data from all of the previous layers. The condition monitoring, health assessment, prognostic and decision support layers would normally represent the most important sources to present. With this, one has the ability to access a wide range of information, from various sources in a single interface. The presentation layer will not be a standardized layer, the design and structure will vary according to the application.

3.3 Summary

The recognition of IO and implementation of modern ICT on the NCS have opened possibilities for increasing levels of CBM within the O&G industry. With the industry gradually moving towards increased use of remote real-time condition monitoring of its assets this chapter has reviewed some of the industry standards and initiatives for standardizing the information and data exchange between CM modules and systems. As mentioned in the introduction of this thesis Aker Solutions have formed an industry alliance SKF and IBM with the aim of delivering Technical Integrity Management Services (TIMS). According to Kumar, Panesar and Markeset (2009) the purpose of TIMS is to *"reduce adverse affects caused by performance killers and cost drivers through a systematic analytical process. Analysis and corrective actions are planned in advance to optimize the availability of facilities by reducing downtimes, to ensure technical integrity, and to enhance knowledge and skills in performing hazard identification and analysis through risk assessment and effective risk management. The main purpose remains ensuring the highest possible HSE level and maintaining world-class system performance"*. In relation to the TIMS initiative the alliance will develop a web-based maintenance portal giving managers, planners and decision makers access to all relevant maintenance information in one single interface, providing decision support and interoperability between actors; internally or externally. Following chapter will further present the TIMS maintenance portal solution.

4 THE TIMS MAINTENANCE PORTAL

As the industry is moving towards increasing use of condition based maintenance regimes that generates vast amounts of data; the need for efficient integration, handling and timely access to this information is becoming ever more important. Today, maintenance decision-makers regularly face the same problem; how to obtain the most relevant information needed for making the most effective decisions. In conventional maintenance, accessing and collecting information often consists of searching across numerous software programs and databases (ERP systems, IMS, CM systems, etc.). This can make information collection a time consuming process. When put in situations that require fast decisions, maintenance managers may be forced to take actions mainly based on "gut-feelings" instead of based on precise, updated maintenance and operation data (Moore and Starr, 2006). State of the art CBM regimes collect data and information from a wide range of sources, and as more and more technology is implemented the number of sources is also increasing. Integrating all these information sources into one single interface can effectively reduce the time spent searching for information, and instead give more time for evaluating the most effective decisions. This is believed to result in better decision making, optimized maintenance and inspection activities, increased levels of HSE and reduced production downtime. Such objectives is also concurrent with the main objectives for Integrated Operations (IO); *"making quicker and better informed decisions in a distributed organization, based on right time information commonly available to the different disciplines independent of location throughout the field lifetime"* (AS Document 6, 2011).

The overall objective of TIMS is consequently to increase the levels of HSE, maximize production and predict degradations for optimized maintenance activities. Utilizing IO in this process; integrating inspection plans, maintenance plans and real-time condition monitoring, the intention is to improve maintenance planning and increase the use of CBM. Ensuring safe, reliable and efficient operations and effective collaboration between all involved disciplines is crucial. The TIMS maintenance portal will coordinate maintenance information from all the separated sources, allowing better sharing among different actors (plant managers, maintenance managers, planners, external expert consultants, etc) on different company levels. In the context of sustainable operations the maintenance portal will be an important tool for decision making based on accurate and real-time information, also considering the relevant components of the production process and their respective impact. The TIMS portal will focus on six identified performance areas to be monitored (Figure 4.1), trended and reported upwards towards senior management.

Figure 4.1, Areas of focus within TIMS, Erstad (2011).

The TIMS system consists of three main layers (Figure 4.2); the Presentation layer (the maintenance portal), the Business Logic layer and the Integration Layer. The integration layer is formed by IBM's Integrated Information Core technology and will ensure that the data is seamlessly integrated and distributed from bottom level information sources (CM systems, IMS, ERP system, etc) to front-end display in the Presentation layer. The Business Logic layer will consist of modules that process the condition data received from the field; analyzing the received data, detecting deviations and aggregating higher level indicators of the technical condition of equipment and systems to be presented in the portal. The TIMS Portal is intended to provide a comprehensive view of the technical condition in different levels; from high-level field overview down to component level technical detail. Simplicity and convenience will be a key objective to the design; giving timely access to a wide range of relevant maintenance information sources. Users will be given role based access privileges, allowing for information sharing and cooperation between offshore, onshore and any external specialists. Figure 4.2 illustrates these three layers and also the underlying work process, to be further introduced in the following sections.

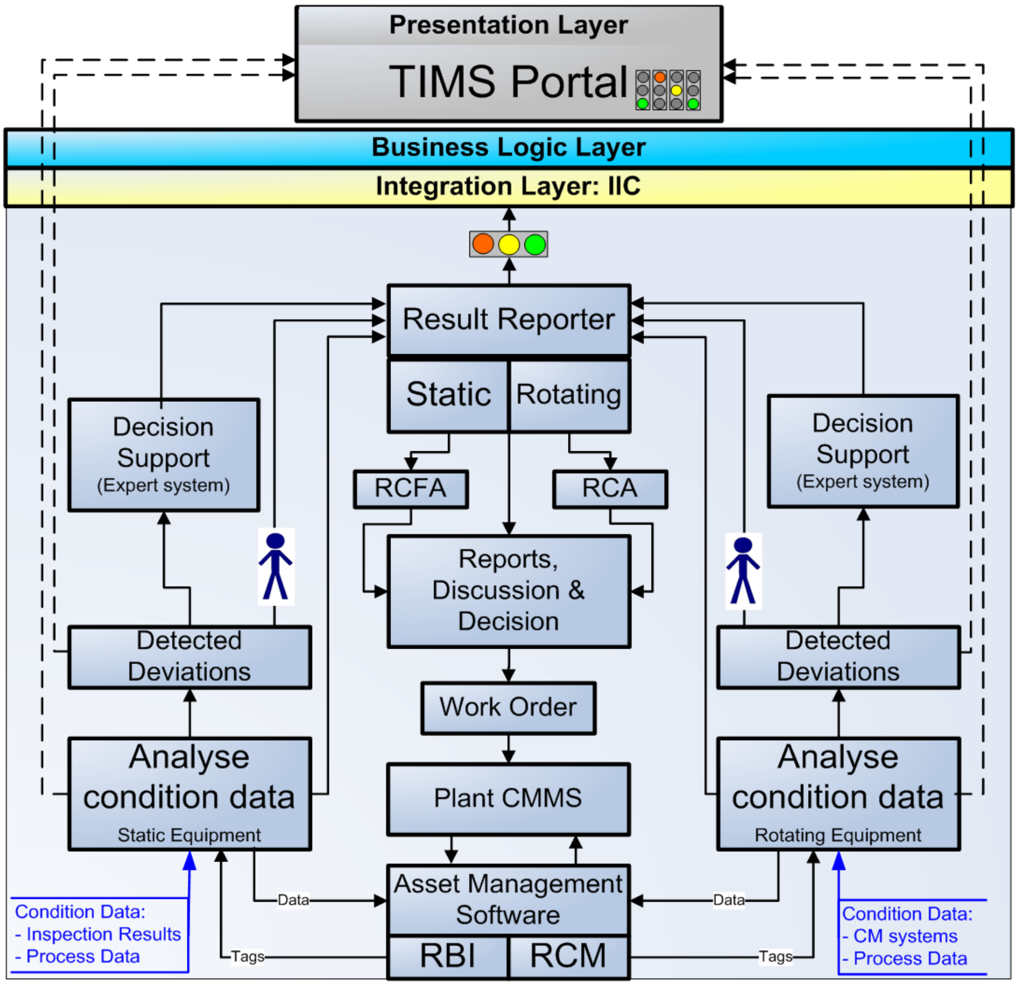


Figure 4.2, TIMS structure, adapted from AS Document 7 (2011)

4.1 The work process

The CMMS is the midpoint of the TIMS system, providing the reference tag structure to the asset management software tool (AMST). The AMST provides maintenance engineering inputs to RBI (static equipment) and RCM (rotating equipment) in form of risk, reliability, failure mode, spare parts and life cycle cost analyses. The obtained field data are compared against predefined expected limits. If no deviations are discovered; condition data are returned back to the CMMS system to update the inspection/maintenance intervals based on condition data. This is to achieve more dynamic inspection/maintenance planning based on real time monitoring of significant influence factors. If the analysis modules discover deviations in the condition data, the deviations will be directed to responsible personnel for manual analyses and forwarded for analysis in the Decision Support module. The deviations will also automatically be indicated in the portal interface. The Decision Support module is an expert system that will consider common fault modes between several units and aid the analyses in the Results Reporter system. The Result Reporter is a web based system that receives inputs from all previous analysis modules for rotating and static equipment. Based on the deviations recorded, the Result Reporter generates technical condition indicators for presentation in the portal, completing the last step of diagnosis. The Results Reporter analyses and Root Cause Failure Analyses (RCFA) lead to the final stage of the system, decision making and issuing work orders back into the CMMS, completing the loop (AS Document 7, 2011). The technology that forms the I&CI and backbone for data flow in the TIMS system is IBM’s IIC technology.

4.2 Integration Layer: The IIC

The integration layer will ensure that all data is seamlessly integrated and distributed to front-end display in the portal. IBM's Integrated Information Core (IIC) technology forms the integration layer of the TIMS system. IIC is a software framework developed for integrating information across multiple source systems, and is based on a reference semantic model (RSM) and service oriented architecture (SOA) approach. Really the key component in the IIC is the RSM; a model that can be used by manufacturing companies for connecting measurements, planning, scheduling, life cycle management etc. throughout the enterprise (see IBM.com). IBMs RSM is directed by the standards that form the basis of the model, presented in Figure 4.3. The standards are linked in a logical fashion to form an enterprise wide information model, to provide an abstract, formal representation of units including properties, relationships and the operations that can be performed on the entities.

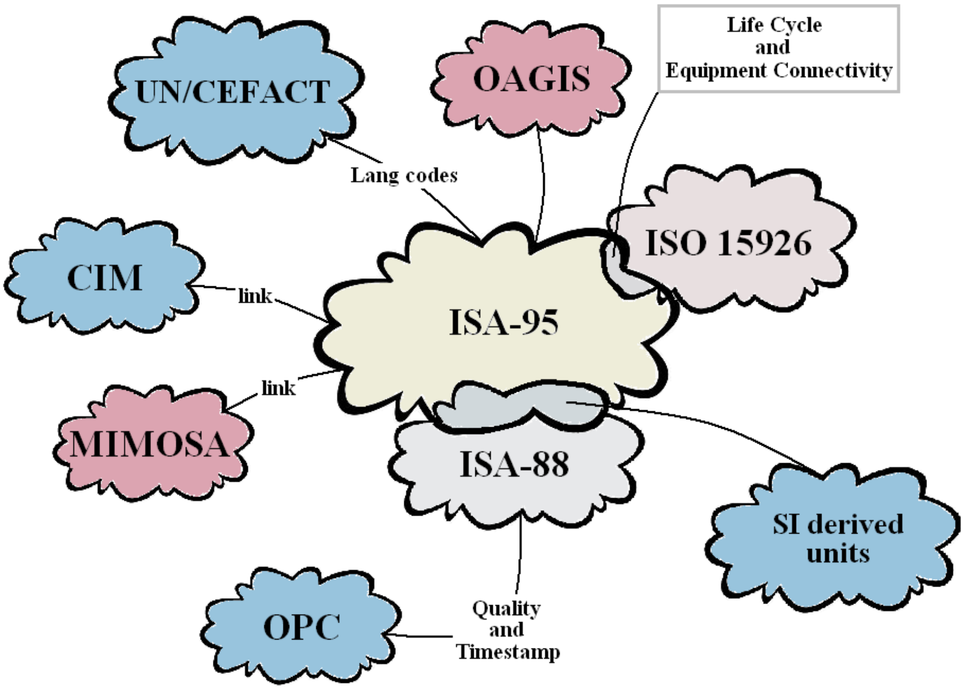


Figure 4.3, IBMs IIC Conceptual Reference Semantic Model, (Erstad, 2011)

Below follows a short introduction of the main standards that form the basis of the IIC:

- **ISA-95: International Standard for the Integration of Enterprise&Control Systems**
  The ISA-95 is an international standard for creating automated interfaces between enterprise and control systems. It consists of models and terminology for determining which information that should be exchanged between sales, finance, logistic systems and production, maintenance and quality systems (ISA-95.com, 2010). It has the objective of providing a consistent terminology to form the basis for supplier and manufacturer communication. The standard also aims to provide consistent information and operations models that lay the foundation for clarifying application functionality and information use. The ISA-95 is meant for global manufacturers, and designed to be applicable in all industries and processes; batch, continuous and repetitive processes (Wikipedia/ISA-95, 2010).

- **ISA-88: International Standard for Flexibility in Production.**
  The ISA-88 is an international standard created to help industries produce in more flexible ways. The standard consists of terminology and models for structuring production processes and for developing the control of equipment, and can be applied in all production processes, either fully automated or completely manual (ISA-88.com, 2010). The ISA-88 address the needs for of a universal batch control model, the difficulties in communicating user requirements, the integration between batch automation suppliers and difficulties in batch control configurations (Wikipedia/ISA-88, 2011).

- **ISO 15926: Industrial automation systems and integration - Integration of life-cycle data for process plants including oil and gas production facilities.**
  The ISO 15926 has been created for integration, sharing, exchange and hand-over of data between computer systems. The purpose of the standard is to be a common language for computer systems, and thereby integrating the information they produce (Wikipedia/ISO 15926, 2011). The ISO 15926 is supposed to assure that the data model is sufficiently generic in order to cope with all applications through a very generic set of entities (Nystad, 2008).

In order to integrate all data sources and provide the right information to the end-user via the portal, the information management system must be defined with transport mechanisms, quality requirements and models to obtain the data needed for integrated operations of the platform. Once the semantic model is built the information flow is automated in the IIC; automatically collecting and gathering information from the individual objects (IBM, 2010). With multiple CM systems installed in an offshore process system, the integration layer will inevitably process huge amounts of data. But all this information will not be useful all the time; hence quality assurance of the data obtained becomes an important issue. Data fusion is a process for combining information and knowledge from different sources with the objective of maximizing the useful information content whilst minimizing the quantity of data ultimately retained (Starr & Ball, 2005). Therefore it is important that high quality information is automatically retrieved, allowing decision makers to determine which maintenance activities to focus resources on, optimizing return on investment (Muller, Iung, & Crespo-Marquez, 2007). The integration layer is the key component for providing the foundation for applications and analyses regarding the overall asset technical condition performed in the Business Logic layer.

4.3 Business Logic Layer

The Business Logic Layer will contain modules that process the information received from bottom level sources through the IIC and then aggregate technical condition performance indicators to be presented in the portal. One of the objectives of this thesis is to propose a way to aggregate a system level technical condition indicator to be visualized in the TIMS maintenance portal (Chapter 5). This will be done through an example of a water injection (WI) system. Following section will further introduce the design and functions of the presentation layer (the portal) to create a basis for the WI system case study in Chapter 5.

4.4 Presentation Layer (the Portal)

The presentation layer forms the visual interface towards the end users. As the TIMS Portal has yet to be developed, this section is based on available AS documentation and inputs from my supervisors regarding the proposed design, layout and specifications of the portal.

Similar to the presentation layer in the OSA-CBM system (Chapter 3.2.1), the design of the TIMS portal can be adapted according to the respective system and the user's requirements and will therefore not necessarily have one single "standard" layout. The portal is intended to be readable through a standard web browser and be accessed through the organizations intranet. The portal will provide a comprehensive view of technical information and condition indicators for the installations at different levels; from high-level field overview down to component level technical detail. Simplicity and convenience is a key objective to the design; giving timely access to relevant maintenance information from multiple sources (CM systems, process data from the IMS, ERP system) using a graphical information interface.

Consequently, the portal is supposed to present technical condition indicators on various levels, highlighting areas that need focus and attention;

- Field Level: Overview of Installations, both onshore/offshore, with performance indicators as depicted in Figure 4.4.
- Facility Systems: Overview of the systems of the facility (Figure 4.5), presenting system level technical indicators aggregated from sensor/tag level measurements. The procedure for aggregating these system level indicators will be further addressed in Chapter 5.
- Equipment level: Detailed view of systems and equipment, with access to real-time measurements, process conditions and aggregated performance indicators.
- Instrument/Tag level: All measurements, inspection results and calculated condition indicators at sensor level.

The portal is also meant to be a tool for optimizing and coordinating the maintenance and inspection activities performed among the different disciplines (static, rotating and electrical) in order to align interventions and thereby increase the total plant availability. Other relevant functional issues for the portal can be (AS Document 8, 2010):

- Event management, scheduling, planning
- Security management
- Message and data management
- Repositories and databases for storage of relevant information

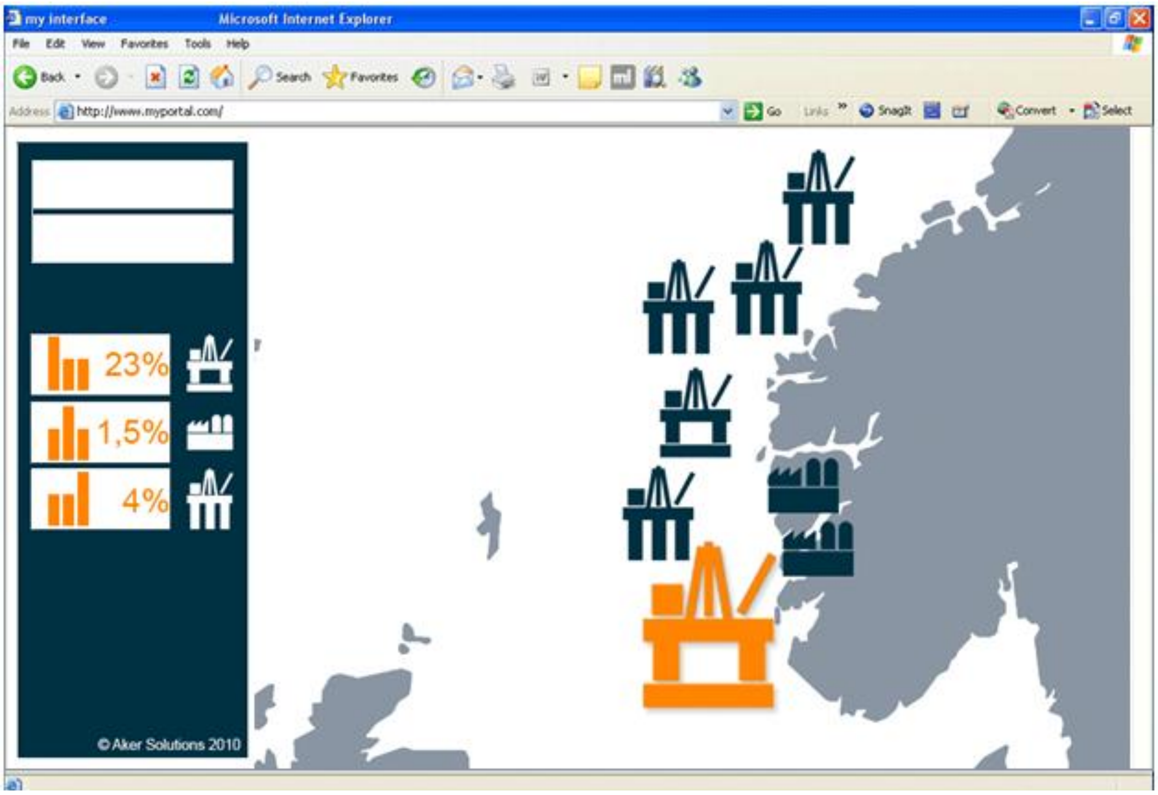
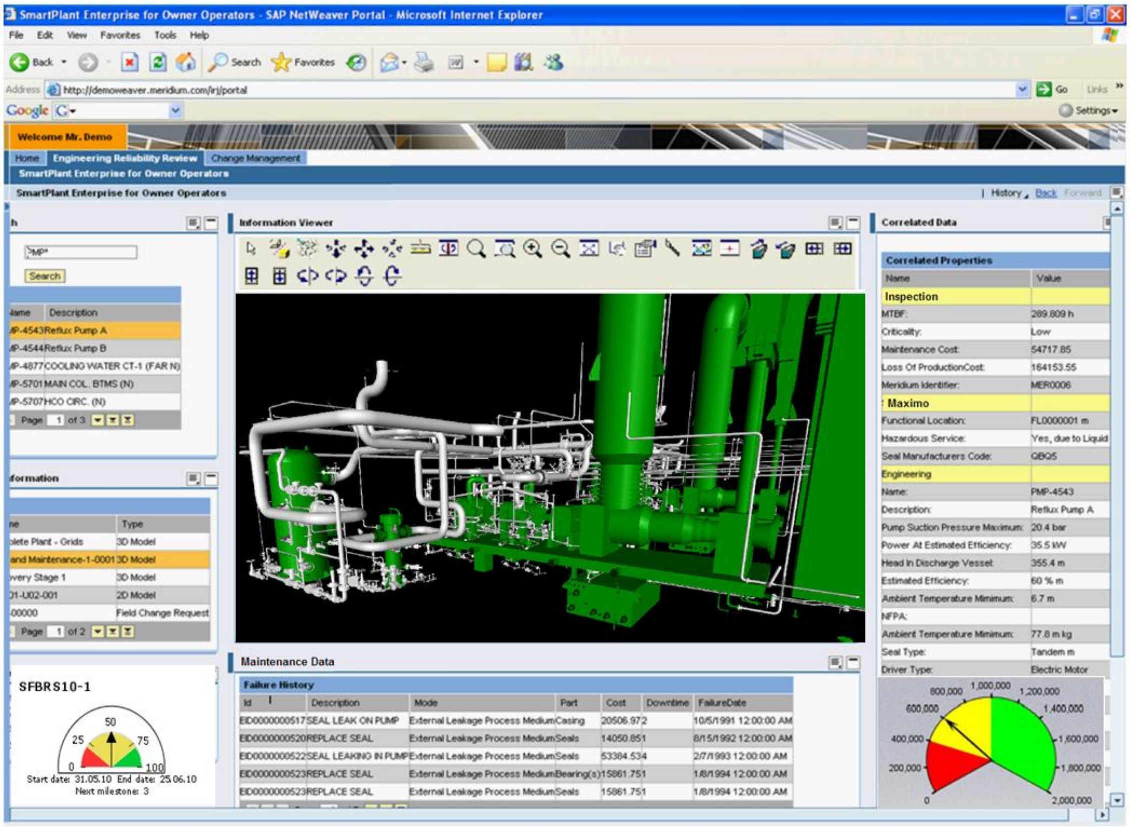


Figure 4.4, Top level field view in the TIMS portal, Aker Document 8, 2010.



SmartPlant Enterprise for Owner Operators

h

?MP*

ame	Description
P-4543	Reflux Pump A
P-4544	Reflux Pump B
P-4877	COOLING WATER CT-1 (FAR N)
P-5701	MAIN COL. BTMS (N)
P-5707	HCO CIRC. (N)

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formation

ne	Type
lete Plant - Grids	3D Model
and Maintenance-1-0001	3D Model
very Stage 1	3D Model
01-U02-001	2D Model
00000	Field Change Request

Page 1 of 2

Start date: 31.05.10 End date: 25.06.10
Next milestone: 3

Correlated Properties

Name	Value
Inspection	
MTBF:	289.809 h
Criticality:	Low
Maintenance Cost:	54717.85
Loss Of ProductionCost:	164153.55
Meridium Identifier:	MER0006
Maximo	
Functional Location:	FL0000001 m
Hazardous Service:	Yes, due to Liquid
Seal Manufacturers Code:	QBQ5
Engineering	
Name:	PMP-4543
Description:	Reflux Pump A
Pump Suction Pressure Maximum:	20.4 bar
Power At Estimated Efficiency:	35.5 kW
Head In Discharge Vessel:	355.4 m
Estimated Efficiency:	60 % m
Ambient Temperature Minimum:	6.7 m
NFPA:	
Ambient Temperature Minimum:	77.8 m kg
Seal Type:	Tandem m
Driver Type:	Electric Motor

Failure History

Id	Description	Mode	Part	Cost	Downtime	FailureDate
EID000000517	SEAL LEAK ON PUMP	External Leakage Process Medium	Casing	20506.97	2	10/5/1991 12:00:00 AM
EID000000520	REPLACE SEAL	External Leakage Process Medium	Seals	14050.85	1	8/15/1992 12:00:00 AM
EID000000522	SEAL LEAKING IN PUMP	External Leakage Process Medium	Seals	53384.53	4	2/7/1993 12:00:00 AM
EID000000523	REPLACE SEAL	External Leakage Process Medium	Bearing(s)	15861.75	1	1/8/1994 12:00:00 AM
EID000000523	REPLACE SEAL	External Leakage Process Medium	Seals	15861.75	1	1/8/1994 12:00:00 AM

Figure 4.5, System level interface in the portal, Aker Document 8, 2010.

The views in the portal can be tailored to fit the required needs of the end-users. Figure 4.5 presents a proposed system view, where the system condition is visualized through indicators aggregated from bottom level condition measurements. The actual sensor level measurements could be accessed by navigating further down the hierarchy by simply clicking on the respective components. The process system will be presented in a virtual 3D-model, providing a new dimension for the communication and collaboration of maintainability data and real time decision-making by working in a common visual interface.

4.4.1 Decision Support

In addition to indicators and real time condition data, the portal will present additional relevant information to provide support for analyses and planning of maintenance and inspection activities. Examples of such information can be:

- Maintenance/Inspection procedures
- Maintenance/Inspection history and plans
- Operational/failure history
- Criticality analysis
- RBI/RCM analysis
- Active work orders/Backlog
- Drawings (ISO), PFDs, P&IDs,
- Data sheets/Technical info
- Spare Part status/tracking/availability
- Component serial numbers

The portal will be an important tool for communication and collaboration between planners, decision-makers and managers, including external expert centers, vendors and experts. Onshore and offshore activities will be considered as integrated parts of the same work processes, and external expert centers can be alerted and involved for assisting problem assessments and supporting the operation. Communication within the portal can be structured into tasks, activities and follow-ups with responsible roles and schedules. Users will be given role-based access to the portal, which allows the possibility for tailored presentation according to the role of the user. Managers can restrict the access of certain users (i.e. external experts, vendors etc), for limiting the ability to access sensitive operation data or strategic policies and documents.

5 TIMS PORTAL CASE STUDY

As described in chapter 4, the TIMS portal shall give access to technical condition information and indicators at different levels of a facility; from bottom level tag/sensor measurements to higher level system and platform indicators. Figure 5.1 illustrates this; the IIC integrates information from various sources making it available for end users at different levels in the portal.

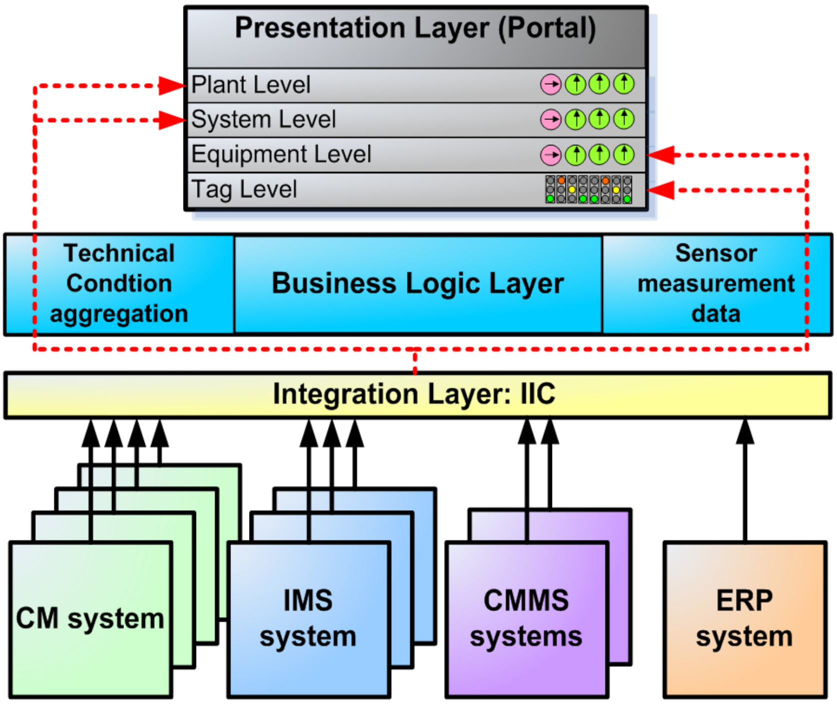

Figure 5.1, Hierarchical Levels in the TIMS information flow, (Erstad, 2011)

The objective of this case study is to propose a way for using the technical information coming from bottom level sources like CM sensors, process data and inspection results to aggregate higher level indicators visualizing system level technical condition in the portal. These higher level indicators are important inputs for measuring the total performance of the systems, the efficiency of maintenance strategies and for assisting managers and planners in decision making of maintenance and inspection activities. The higher levels of the TIMS portal will consequently measure the performance on six different contexts; HSE, Finance (Cost), Availability, Quality, Risk and Volume (Figure 4.1). This study will only focus on technical condition in the context of “Availability”. The TIMS portal will be exemplified through a typical - but simplified - example of a topside water injection (WI) system, consisting of relevant static and rotating mechanical equipment. The first section of this case study will introduce the methodology to be used for aggregating technical condition indicators through hierarchical weighting of the system’s smaller building blocks. The methodology used in this study is based on the EUREKA project “Ageing Management” discussed by Steinebach & Sørli (1998) and Nystad (2008).

5.1 Defining the Technical Condition

Steinebach and Sørli (1998) defined the technical condition as *"the degree of degradation relative to the design condition. It may take values between a maximum and minimum value, where the maximum value describes the design condition and the minimum value describes the state of total degradation"*. Indicators that are only affected by changes in the plant's technical integrity will detect and point out degradations at an earlier stage compared to traditional indicators like regularity, environmental emissions, costs and safety statistics. These indicators offer little sensitivity regarding the technical condition of equipment as there would often be a long time between the point of actual technical degradation and the point where these indicators are actually alerting the management of the organization (MarinTek, 2010). Early detection of degradations is naturally a huge advantage, giving maintenance managers and planners more time to evaluate the best decisions and plan the most effective maintenance interventions.

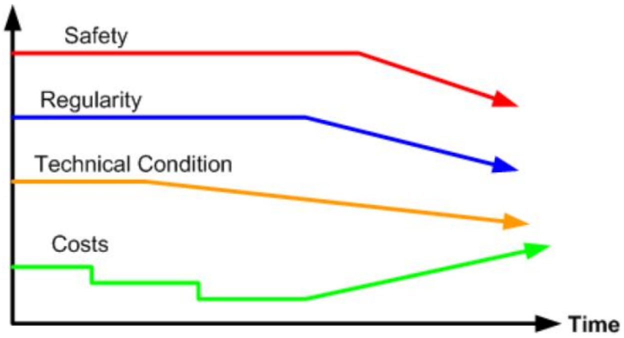

Figure 5.2, Early detection through technical condition, (MarinTek, 2010)

The technical condition of industrial systems is influenced by several factors during the operational lifetime. The main contributors are degrading mechanisms from operational loads (e.g. production rates, process medium characteristics, machine usage, etc) and the following maintenance actions for restoring the technical condition back to the desired "as good as new" level. As mentioned above the technical condition is defined between "design condition" and "total degradation". The design state is used as a reference in order to make technical condition independent of the demands of the respective system in focus. As design state is a fixed condition usage might change over time which would complicate the ability of comparing a system's technical condition over longer periods. But defining a "perfect" or "totally degraded" condition is very difficult since the technical condition will vary according to the operating conditions and the applied context. Therefore the technical condition of a system should be related to a context and not be used as an expression for the absolute technical condition. With this, Steinebach and Sørli (1998) defined five main contexts that the technical condition should be related to;

1. Safety
2. Environment
3. Availability
4. Man-hours (for maintenance)
5. Costs

Consequently, the technical condition is not evaluated as a standalone indicator, but evaluated according to its importance in the respective context.

5.1.1 The Technical Condition Index (TCI)

The EUREKA project "Aging Management (1996-1999)" developed and introduced a measure named the "Technical Condition Index" (TCI) (Nystad, 2008). The purpose of developing the TCI was to find a way of utilizing the increasing amount of available technical condition information and create a reliable variable that was only affected by the degradation of a system's technical integrity. It was determined that the technical condition can generally be obtained on the basis of three different information sources; measurement data from CM systems (online/offline), process data from the IMS and subjective reports/results from inspections and maintenance actions.

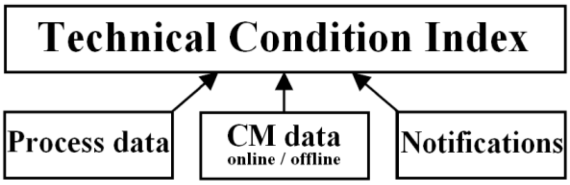

Figure 5.3, Information inputs to the Technical Condition Index, Erstad (2011)

The EUREKA project defined the TCI to be a value between 100 (design condition) and 0 (total degradation). In this case the temperature of a bearing can be used as an example. An expert on bearings can define the acceptable limits regarding the temperature under normal operation. In Figure 5.4 the technical condition of the bearing is be regarded as "design condition" up to a temperature of 75^{o}C. If the temperature exceeds this level, the condition is considered to be degraded. When the temperature reaches 120^{o}C the bearing condition is defined as "totally degraded" and has a TCI value of 0. Between these preset limits the associated TCI can be obtained from relatively simple "input functions", in this case a linear interpolation.

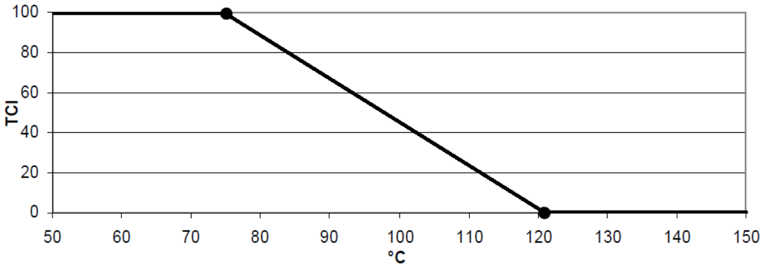

Figure 5.4, Linear interpolation of TCI value according to temperature in a bearing, Erstad (2011)

Consequently, the obtained condition data are converted to TCIs through input functions comparing measurements against preset expected operational limits. The preset limits are defined by personnel with key knowledge to the respective equipment and the operational conditions, e.g. vendors or experts with solid operational experience. If the measured data levels are below the specified “HI” limit (Figure 5.5); the condition is considered to be “as good as new” (design condition). If the measurement crosses a “HIHI” limit the component is considered “totally degraded” and must be replaced.

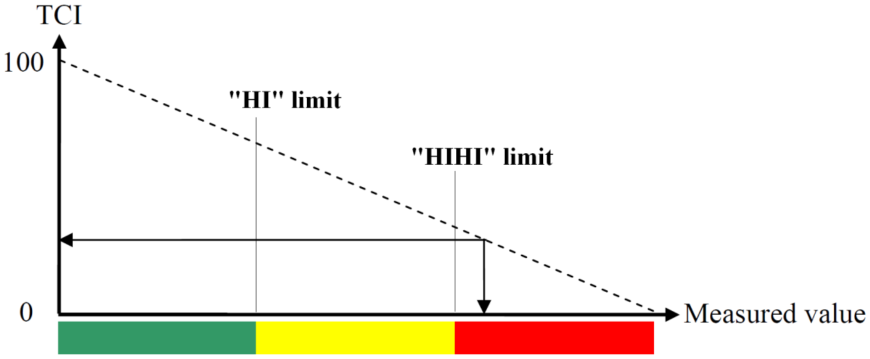

Figure 5.5, Linear relation between measurement and the TCI, (adapted from Nystad, 2008)

Calculating the technical condition (TCI value) of an entire industrial system is done from a bottom-up approach. This means that calculations start at the lowest level (e.g. from bearing temperatures or probe vibration levels) and from this aggregated upwards a hierarchy representing the actual system. The aggregation methodology to be followed in this case study consists of the following steps (Steinebach and Sørli, 1998):

- Establish a hierarchy of objects which represents the actual industrial system.
- Denote a weight to each of the objects according to their criticality within the system
- Assign relevant input variables that characterize the technical condition to the objects (mainly at the bottom level)

The three above-mentioned steps will be further addressed in the following sections.

5.1.2 Establishing the Hierarchy

Establishing a sufficient hierarchy is an important part for technical condition aggregation and should be done in cooperation with experienced maintenance and operations personnel. Hierarchies can be established from different approaches, there is not a single method regarded as the right one. But it is important that the hierarchy reflects the natural connection between systems, functions and components. The hierarchy could be based on the existing hierarchy already defined in the ERP system (MarinTek, 2010), or it could be defined through a system or function breakdown. The functional breakdown procedure is similar to the procedure for Criticality Classification, presented in Chapter 2.6. This method gives a hierarchy with good top to bottom visibility, but a drawback is that there will be many levels and also the fact that some equipments is performing more than one function and thereby will appear several places in the hierarchy. System breakdown is easier to establish, but will have a drawback by lacking links towards the function performed by the machinery (Nystad, 2008, Steinebach and Sørli, 1998). As both methods have their pros and cons neither method is used exclusively but applied where best fitted. Figure 5.6 illustrates how measurements is collected at lowest level, converted to TCIs through input functions and aggregated upwards through specific aggregation functions for obtaining and visualizing higher level technical condition. The most common aggregation functions will be described in the following section. At top level, which in this case study would be the TIMS maintenance portal, the visualization can be in the form of traffic lights for selected systems or sub-systems, graphs showing how degradation have been contributed from components on lower levels, or TCI trending over time (Rødseth, Mo, & Steinebach, 2007).

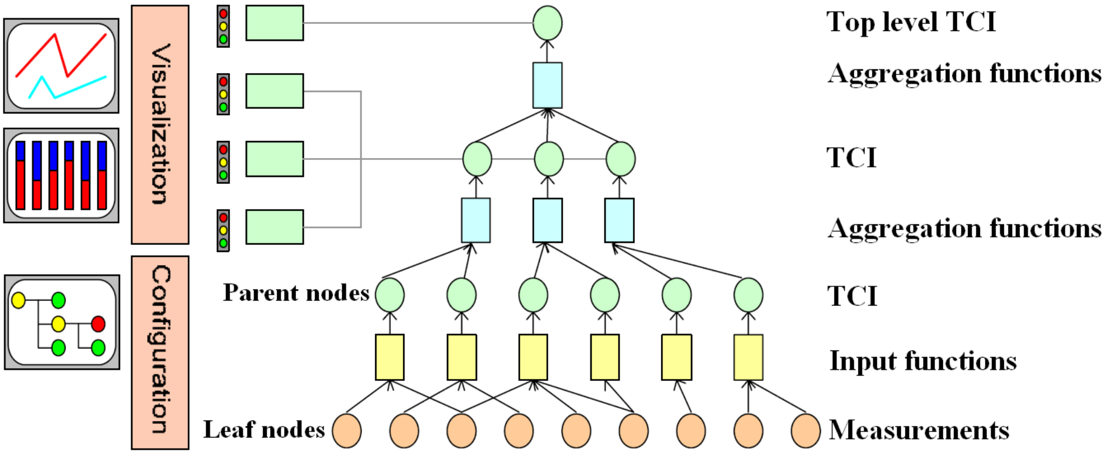

Figure 5.6, Higher level TCIs aggregation, adapted from (Rødseth, Mo, & Steinebach, 2007)

The benefit of such hierarchic structures is that they provide a high level view of the overall condition, while at the same time enable the possibility of tracking down lower level problems by navigating down the aggregation hierarchy. These qualities make the TCI method well suited for supervising complex industrial systems. After designing the hierarchy, next step is weighting the sub objects within the system.

5.1.3 Weighting objects according to criticality

Obtaining precise higher level TCIs through hierarchical aggregation is also dependent on a realistic weighting of the sub objects according to their criticality within the total system. The weighting process is therefore dependent on personnel with significant knowledge to the respective equipment and its operational behavior. Also, the weighting of objects will vary depending on which of the five contexts the TCI is regarded to. In relation to the safety context a plant can have a different technical condition than when related to the economical or environmental context. Associating bottom level measurement deviations with failure modes in the higher level hierarchical structure is a challenge of technical condition monitoring. The idea of aggregating TCIs from smaller building blocks is to associate the failure modes with the hierarchy (Figure 5.6) and the lowest level TCIs should affect the level of degradation of every failure mode in the hierarchy. Weighting the significance of the different leaf node TCIs can be done through expert judgments, e.g. criticality index from the FMECA analysis (as presented in Chapter 2.7.1), or through regression parameters in regression analyses (Nystad, 2008). However, a general advantage is to have a small amount of independent leaf node TCIs and that these together will reflect the technical condition in the best possible way of the failure mode in the hierarchy (e.g. bearing health is estimated not only from temperature monitoring alone, but also vibrations). As depicted in Figure 5.6; the measurements are converted to TCIs (input functions) and further aggregated upwards the hierarchy through aggregation functions. The most common aggregation functions and the only ones involved in this study are the weighted sum, penalty and worst case aggregation methods (Nystad, 2008):

1) *Weighted sum aggregation method:*

   Equation (1): $TCI = 100 - \sum_{i=1}^{n}(100 - TCI_i) \cdot w_i \;,\; \sum_{i=1}^{n} w_i = 1$

   TCI_i is the technical condition of the leaf node i, w_i is weight of the leaf node i, and n is the number of leaf nodes. The total sum of weights has to be equal to one.

2) *Penalty aggregation method:*
   Similar to the weighted sum aggregation, but here the sum of the weights are allowed to be different than one.

   Equation (2): $TCI = 100 - \sum_{i=1}^{n}(100 - TCI_i) \cdot w_i \;,\; \sum_{i=1}^{n} w_i \neq 1$

   If the total TCI value obtained from the penalty aggregation method ends up being negative the TCI is set to zero. The total sum of weights can be unequal to one.

3) *Worst case aggregation method:*

   Equation (3): $TCI = Min_{i=1}^{n} \cdot TCI_i$

   The parent node is given the same TCI value as the smallest TCI value of its leaf nodes, similar to a chain not being stronger than its weakest link.

These aggregation equations are used in various levels of the hierarchy, and will be further introduced and demonstrated in Section 5.5. After weighting the sub objects of system next step is to define the input variable at bottom level nodes.

5.1.4 Input variables to define Technical Condition

The best suited input variables for describing the technical condition will naturally vary according to the type of equipment in question. For static equipment - like pipes and vessels - degradations is normally occurring in a slower and much more predictable way compared to many of the degrading mechanisms in rotating equipments like pumps or compressors. This means that there is generally a higher degree and frequency of monitoring rotating equipment than most static pipes and vessels. But even though the monitoring techniques and methods will vary between static and rotating equipment, common for both groups is that notifications; daily observations from plant personnel is an important source of information for assessing the technical condition.

5.1.4.1 Notifications

Notifications is the common term that includes results and reports from daily observations, periodic inspections and periodical preventive maintenance activities should therefore be quantified and also used as inputs for calculating the TCI, together with CM and process data. But in order to make use of these subjective inputs in correlation with the TCI; a specific notification procedure for reporting these deviations must be developed, as proposed by Nystad (2008). The idea is that as long as nothing is reported, the technical condition remains unchanged. If a deviation is found i.e. from visual inspection of a component, the deviation must be reported manually into the ERP system (e.g. SAP) by the mechanic. When the deviation is reported through SAP the TCI will automatically be influenced according to defined rules. Defined rules means that failure modes, or quantitative accept limits have been specified for all equipment groups (pumps, compressors, vessels, pipes, etc.), and given a severity grade according to expert assessments. Hence when the notification is submitted it contains a failure mode code related to the tag number of the particular component, and the TCI will be impacted according to the defined severity of the failure mode. When the notification is defined “Complete” the impact of the respective notification on the TCI will be neutralized. Consequently notifications are an important input to both static and rotating equipments. The subsequent sections will further specify other input valuables regarded as relevant for calculating TCIs of static and rotating equipment respectively.

5.1.4.2 Static equipment

There are a number of factors that contribute to the degradation rate of a pipeline, as shown in Figure 5.7. Influenced by these factors, degradation mechanisms will occur in various forms (corrosion, erosion, fracture and fatigue) and with various rates.

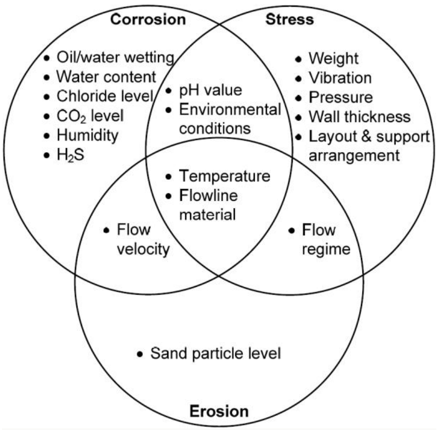

Figure 5.7, Pipeline degradation factors, Ratnayake & Markeset (2010)

Over time the wall thickness of a pipe will inevitably degrade to some extent, and therefore inspections are performed to assess the technical condition of the pipes as a way of minimizing risks and avoiding unacceptable ruptures and loss of containment. The dimension and material selection of a pipeline is mainly based on the operating conditions (pressure, temperature and process medium specifications) that the pipeline is to be installed in. The American National Standard ASME B31.3 (Process Piping) specifies the required ($T_{nominal}$) and minimum ($T_{minimum}$) wall thickness levels of a pipe according to its dimension and classification. When in operation, the actual wall thickness can be determined through various non-destructive methods (visual inspection, ultrasonic testing, radiographic testing, etc) for measuring the degree of pipeline degradation, to detect the areas that are approaching an undesirable state.

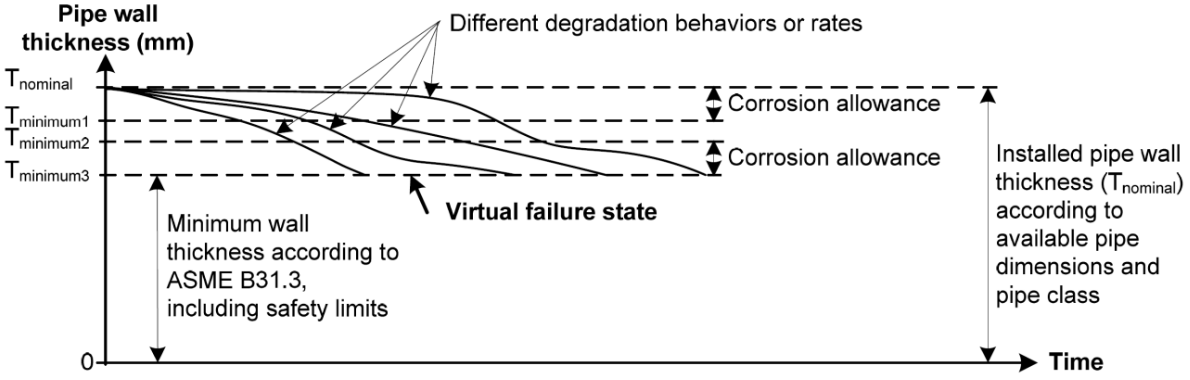

Figure 5.8, Degradation in form of reduced wall thickness, Ratnayake & Markeset (2010)

Calculating the TCI of pipelines and vessels in this case study would have to be quantified in form of the measured wall thickness from an inspection versus the minimum allowed wall thickness. Immediately after installation the wall thickness $T_{nominal}$ would equal to design condition, Figure 5.8 (TCI=100). If a pipeline's wall thickness reaches the virtual failure state it would be regarded as completely degraded and earn a TCI value of 0. Therefore this study will propose that the reported wall thickness of a pipe will be compared to the scale between design condition and state of total degradation. Between these two extremities, acceptable limits for each pipe class can be determined. Further a routine for including inspection coverage could be incorporated into the TCI. Another relevant aspect could be the monitoring of process data. The degradation behavior or rate will vary according to process parameters (Figure 5.8). Experienced personnel could specify accepted limits for process parameters of a pipe (e.g. temperature, pressure, etc), and if there are significant (negative) changes in the operating conditions this would automatically influence the TCI of a pipe, and thereby give the operator a warning that the area might need attention.

5.1.4.3 Rotating Equipment

Rotating equipment will often have periodical overhauls based on hours of operation, and some preventive maintenance tasks, like lubricant analyses, filter changes etc. Analyzing contaminations, additives and debris in lubricants will indicate the level of wear particles from machine components and also indicate the condition of the lubricant itself. This will give better knowledge of the degradation processes occurring in the machinery, and also give positive environmental impacts by avoiding unnecessary oil changes. In addition to periodical overhauls and some preventive tasks, rotating machinery is usually the most obvious candidates for real time condition monitoring. CM data can be a comprehensive source of information, providing important knowledge regarding the technical condition of equipments. Measurements can consist of single value, time series or more complicated data sets performed at varying intervals. The rate of sampling is usually depending on the criticality and reliability of the respective equipment (Appendix A). Numerous sophisticated techniques and technologies are currently available for monitoring specific problems, and the most industry recognized methods will be briefly introduced in the following:

Temperature monitoring:
Temperature sensors can detect temperatures inside, or on the surface of many different systems, e.g. mechanical components (bearings, seals), electrical equipments, coolants, lubricants etc. Increasing temperatures is often signs of increasing friction, a clear sign of degradation.

Vibration analysis:
Measures the acceleration, velocity or displacement of moving mechanical components, and will give an indication of the internal status of the machinery without interrupting the process or containment. Excessive vibration levels can lead to audible noise, critical stresses and subsequent failures. Vibration measurements and analyses are able to detect lots of common machine faults, and the raw data are typically processed for the following:

- Overall vibration levels and selected band levels, consistent with known fault types
- Frequency spectra searching for signs consistent with many specific fault types
- High frequency emission for rolling element bearings; processed through event counting and thresholding or sometimes simply banded.

Also monitoring the performance of a machine, e.g. the pressure, flow rate and energy consumption of a centrifugal pump can be a good indicator of the total machinery health. Using the expected performance level of the equipment as a reference will clearly indicate if it isn’t delivering what it supposed to deliver, and thereby serve as a good indicator of the technical condition. Today engineers often have the process data easily available, but there is generally little systematic monitoring of these in relation to monitoring the technical condition of machineries. However when detecting deviations (e.g. increasing vibrations) the process data are usually very relevant involve for estimating the technical condition (Appendix A).

5.1.5 Summary of TCI aggregation methodology

Section 5.1 have described the process to be used in this thesis for proposing a way to obtain the system level technical condition of a WI system; based on low level inputs aggregated through a weighted hierarchy. The methodology is consequently based on the EUREKA project (Rødseth, Mo, & Steinebach, 2007). Here they developed a Technical Condition Management (TeCoMan) tool to support the TCI calculation of industrial systems. TeCoMan is a software that basically uses the same methodology as described in this section, but will automatically calculate the TCI after the user has set up the hierarchy and defined the weighting of objects, input variables and acceptable limits of these. As described in Section 4.3, the Business Logic layer will process the information from the IIC and then aggregate technical condition performance indicators to be presented in the portal. This case study will propose to adopt a similar approach for automatically calculating the TCI (from use of TeCoMan or similar type software) to be implemented in the Business Logic layer and then results are presented in the portal. The next sections will use the methodology presented to aggregate a system level TCI of a water injection system. This case would only present the methodology as a brief description to how it could be done.

5.2 Water Injection (WI) System Description

The methodology for obtaining higher level technical condition presented in the previous Section 5.1 will be used as a reference for proposing a method for visualizing the technical condition of a WI system. The system in focus of this study is depicted in Figure 5.9. Initially, water is filtered to remove solid particles, and then fed into the deoxygenation unit. This vessel is typically between 15-20 meters high, with the water flowing across 2-3 stages of tower packing, ending in a hold-up sump in the bottom of the tower. The objective of removing oxygen is to prevent corrosion and bacteria growth that degrades both internal surfaces of the system and also is unhealthy for the reservoir. Vacuum is created by a vacuum package consisting of a vacuum pump with ejector arrangement on the suction, drawing vacuum from each stage of the deaerator. Downstream the deaerator, water is fed into two parallel 2x50% booster pumps feeding the two parallel 2x50% single stage centrifugal WI pumps. All pumps of this WI system are considered to be equal; driven by high voltage electrical motors and having integrated utility systems (lubrication, cooling and seal systems).

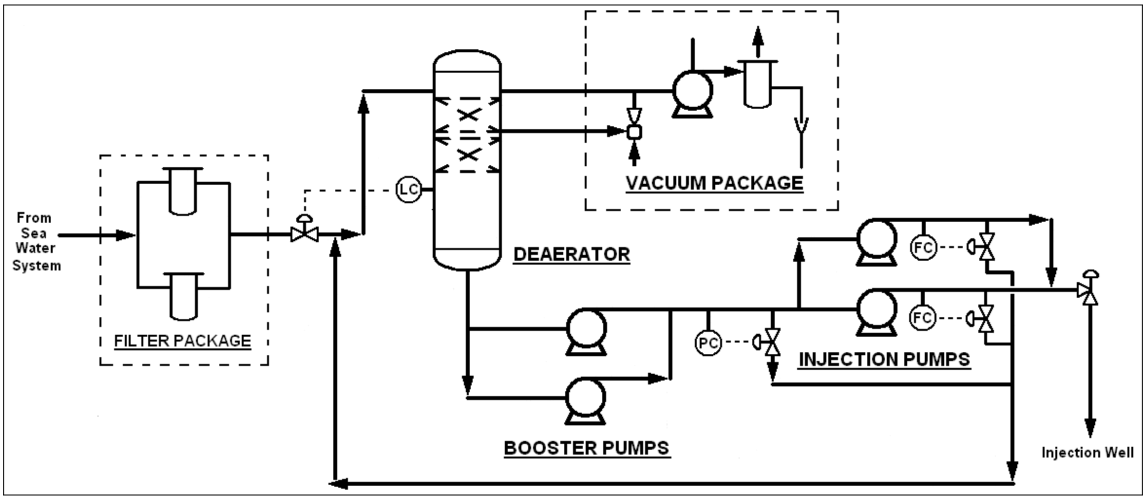

Figure 5.9, Water Injection system (Erstad, 2011)

All tagged components within the WI system are assigned to respective maintenance or inspection programs, resulting from criticality, FMECA and RBI analyses. Components like filters, valves, actuators, transmitters and indicators are inspected, tested, maintained and calibrated with periodical intervals. Static equipment (pipelines and vessels) are inspected on time based intervals according to the probability of failure (PoF) and consequence of failure (CoF) assessments performed in the RBI analysis. The rotating machinery will have some periodical preventive maintenance tasks (e.g. lubrication, lube oil analyses, etc.) in addition to vibration and temperature monitoring for early detection of degradation and imminent failures, (Appendix A).

This case will be a simplified approach for obtaining a system level technical condition indicator. The components to be included in this case are the following;

- 2 x WI Pumps with drivers
- 2 x Booster Pumps with drivers
- 1 x Vacuum Pump with driver
- 1 x Deaeration Vessel
- Filter package
- Piping

The main focus of this study has not been to propose realistically “correct” weighting within the hierarchy or aggregation calculation. This would in real life be decided through in-depth analyses by expert personnel. Rotating machineries are complex systems consisting of several sub systems that performs principal tasks for the machinery to function. For simplicity in this case study all pumps are considered to consist of the same components and have the same bottom level monitoring inputs. The lube oil, cooling and seal systems have been merged into a system called Utility, and the technical details of these systems will not be further specified.

5.3 Defining WI system hierarchy and weighting

The first step of the process is to define a complete system hierarchy representing the actual system down to lowest level parent nodes. The hierarchic structure needed for aggregating higher level TCIs is dependent on the respective system in focus and the desired level of detail. Consequently there is not a standard way of doing it. According to the system in focus of this case, the author identified three principal sub systems performing the required functions of the WI system (Figure 5.10). These systems together perform the principal functions that must be performed within accepted limits in order for the total technical condition (related to the availability context) of the system to be regarded as a satisfying state. However, the author realizes that with this approach it must be assumed that if the water treatment system does not deliver within the accepted limits (e.g. the deaerator is out of function and no oxygen is removed from the water) this would represent such threat to the reservoir that the water injection would be stopped. In real life this would probably not be the case, however it is an assumption made in this case.

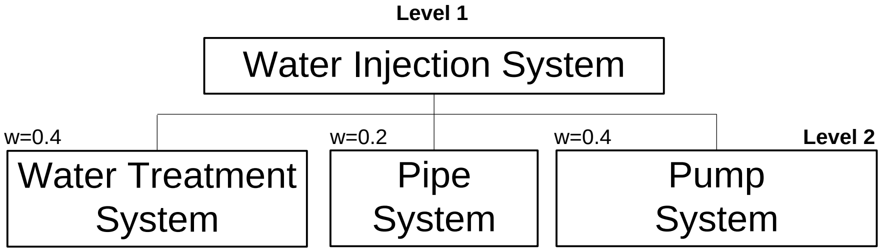

Figure 5.10, WI system with main sub systems (Erstad, 2011)

The Water treatment system and the pump system have been given an equal amount of weight, as they are the most complex systems. The piping system is given a lower significance as the medium in this system is not considered to be of the most critical character; not especially corrosive and not containing any hydrocarbons. In another system (e.g. gas compression) with pipes containing HTHP hydrocarbons they would probably be given a higher significance. In relation to redundancy and parallel components the weighting of sub systems in this case might be argued, as the Pump system is redundant and the Water Treatment system is not. The weighted sum has been selected for aggregating the TCI of the sub systems into the TCI of for the total WI system. The following sections will present the lower parts of the WI hierarchy. Level 2 elements are presented one by one, before addressing the leaf nodes of the hierarchy.

5.3.1 Water treatment

The water treatment system consists of both static and rotating equipment. The water is filtered to remove solids and thereby minimize the erosion of internal surfaces. The oxygen is removed in the deaeration unit to minimize bacteria growth. The oxygen removal stage is dependent on a vacuum pump creating vacuum pressure inside the deaerator. As the oxygen level of the water is regarded as a significant factor in this case, the oxygen removal function is given the majority of weighting. The oxygen removal depends on vacuum inside the deaerator created by the vacuum pump, hence the pump has been considered more significant than the deaerator unit itself, in the context of delivering water with a sufficiently low level of oxygen. All pumps in this case is consequently assumed to be identical, consisting of four sub components; a pump house, gear box, driver unit, and utility systems. These components are weighted equally significant, although an expert on pumps most likely would have done a different assessment.

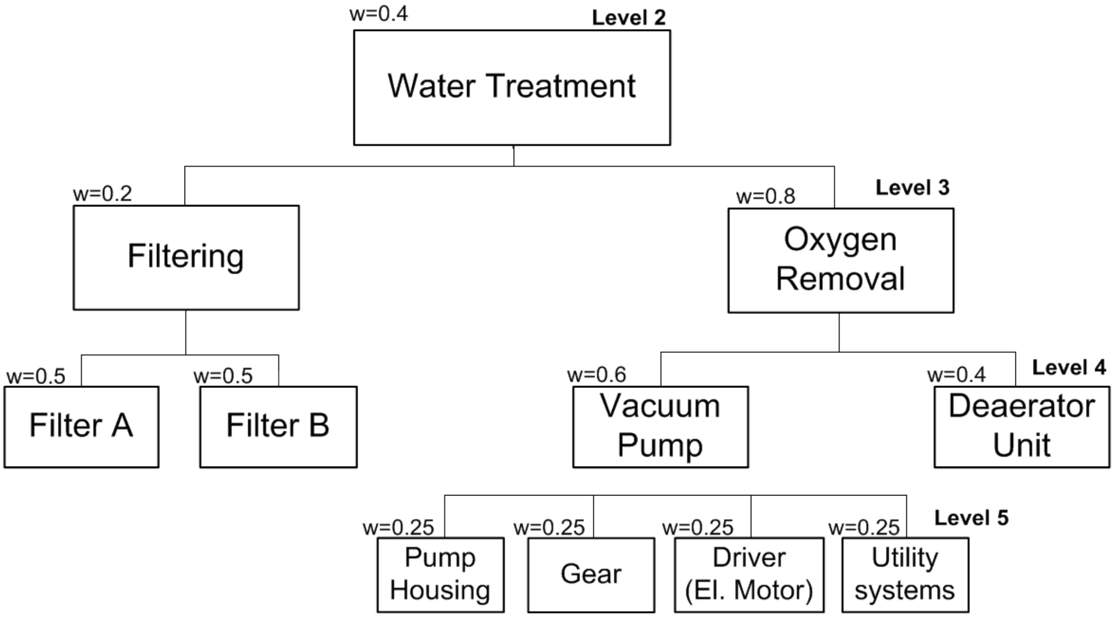

Figure 5.11, Water Treatment System with weighting (Erstad, 2011)

5.3.2 Pump System

The required injection pressure is dictated by the reservoir pressure, and is usually in the range of 150 - 300 barg. To reach this pressure the water is accelerated through two stages (Figure 5.9). As the water pressurizing are performed downstream the deaeration vessel which is working at (or close to) vacuum pressure, two low NPSH designed centrifugal booster pumps will build up the initial pressure required by the two centrifugal injection pumps. Once again a simplified weighting approach; both stages are considered equally important for delivering the required volume at the required pressure.

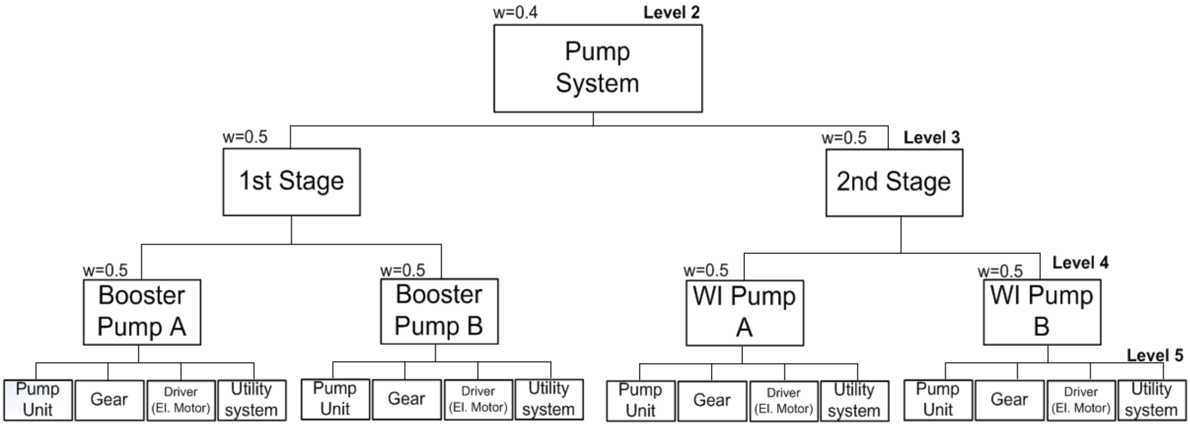

Figure 5.12, Pump System with weighting (Erstad, 2011)

5.3.3 WI System Piping

Detailed RBI analyses are performed for product code-material-groups where the screening process has identified unacceptable risks from leakage (as explained in Chapter 2.8 on RBI analyses). Tags rated with identical criticality, material quality, process parameters and external stress/environment influence are grouped into corrosion groups and allocated a common probability category. The analysis identifies failure probability and consequence at corrosion group level, and then uses the risk matrix to allocate a risk category for each group. For simplifying the task of designing a hierarchy of the pipelines in this system, the piping has been grouped into three different corrosion groups based on the pressure of the medium they are containing; upstream booster pumps (Group 1), downstream booster pumps (Group 2) and downstream WI pumps (Group 3). Weighting/significance has been assigned according to the assumed criticality within the system, using the weighted sum method.

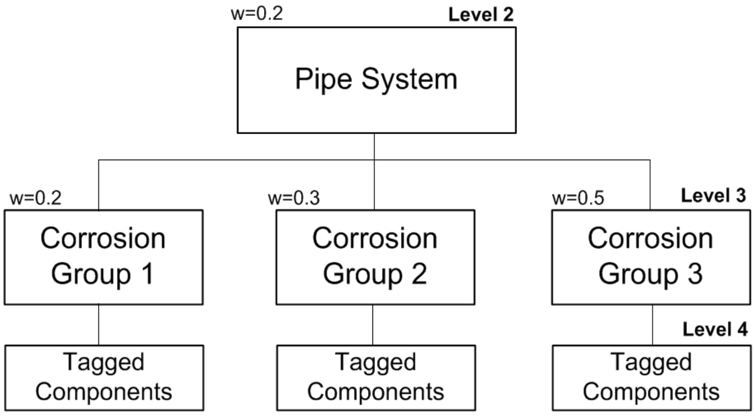

Figure 5.13, Pipe System with weighting (Erstad, 2011)

The hierarchy has now been defined down to the lowest level parent node. Next step is defining what types of input data could best describe the lowest level TCI.

5.4 Defining Input Variables at bottom Level

Consequently, after configuring the hierarchy the bottom level input variables of the system can be defined. This case study will define the input variables to the following components;

- Filters
- Deaerator Unit
- Piping
- Pumps (Vacuum, Booster, WI)

Specific limits within the variables (e.g. temperature, vibration, performance limits) will not be considered in this case, but examples will be used where relevant. Each variable will have defined “HI” and “HIHI” limits, and then the equivalent TCI value can be obtained through input functions, the same way as already described in Figure 5.5.

5.4.1 Filters

Filter TCIs will be based on pressure differential measurements indicating pressure build up; a sign of filter degradation or changing process environments. An acceptable range of pressure differential would be defined, and measurements exceeding this level would reduce the TCI. Also subjective reports from inspection results could be reported through notifications in SAP for influencing the TCI value if deviations are observed in the field.

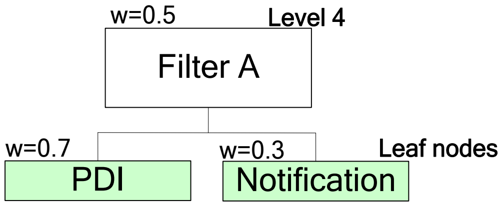

Figure 5.14, Filter component TCI input variables (Erstad, 2011)

5.4.2 Piping

The technical condition status of the piping in the system would mainly be based on inspection results reported through the ERP system. As the minimum required wall thickness is specified in pipe specification standards, the TCI can be derived by comparing the measured wall thickness values against the minimum required thickness.

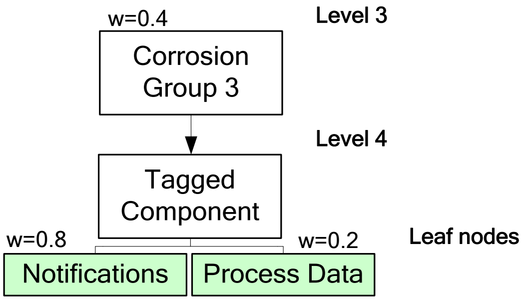

Figure 5.15, Pipe corrosion group component TCI input variables (Erstad, 2011)

Also significant changes in process data should be monitored, and unacceptable limits defined to negatively influence the TCI.

5.4.3 Deaerator Unit

The technical condition of the Deaerator could be measured through inspection results in form of measured wall thickness, and in similar way as with pipelines a TCI value can be derived from these results according to the relation with minimum allowed wall thickness. From the assumption made regarding the significance of acceptable oxygen levels, the quantity of oxygen in the water downstream the deaerator unit should be measured. If this limit is approaching an unacceptable limit it should be reflected in the TCI, so that measures can be taken to improve the performance. Hence the majority of weighting is put on oxygen level and notifications.

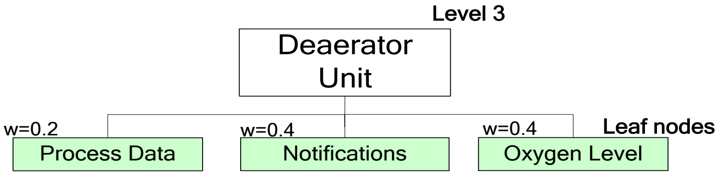

Figure 5.16, Deaerator TCI input variables (Erstad, 2011)

5.4.4 Pumps

The pumps represent the most complex equipment of this WI system. As mentioned earlier, the pumps are assumed to be of similar structure. Figure 5.17 illustrates the information sources that will provide inputs to the calculation of the TCI for an entire pump unit.

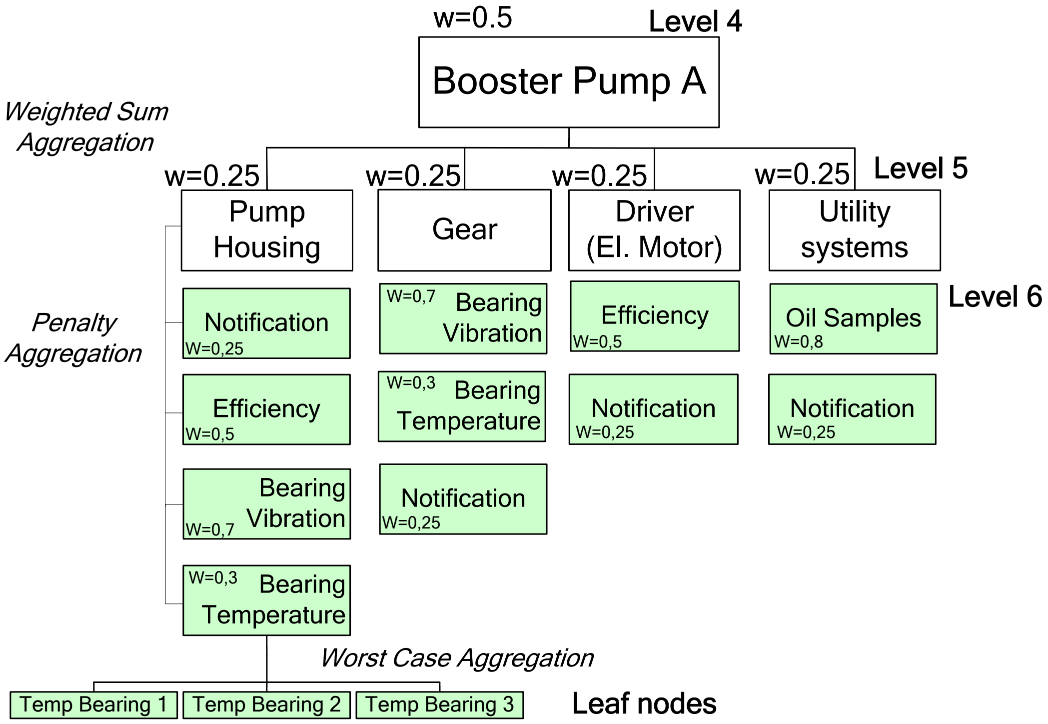

Figure 5.17, Pump Unit TCI input variables (Erstad, 2011)

Notifications will impact the TCI on all sub systems of a pump. Failure modes defined in the FMECA analysis could be used for quantifying the significance and impact on the technical condition of the notification reported. The expected efficiency (input/output comparison) of the pump provided from vendor performance tests could be measured against actual efficiency, and accepted vibration and temperature levels of bearings could be quantified for obtaining TCIs. Oil samples will be taken at regular intervals to analyze the quality and the accepted levels of debris will determine the TCI.

5.5 Aggregating WI System TCI

The WI system has been broken down into a hierarchy of objects, the objects have been weighted according to the criticality, and the relevant input variables at bottom level have been defined. The following sections will give a short simplified explanation to how the TCI value of the total WI system could be aggregated and then visualized in the TIMS portal. It is important that the applied aggregation methods will give a correct reflection of the impact of a reduced low level TCI throughout the hierarchy. The three earlier mentioned aggregation equations “worst case”, “penalty” and “weighted sum” are used in this thesis. Figure 5.17 contains all of these methods and will be used as a reference in this process.

5.5.1 Converting sensor measurements to TCIs

The aggregation of a single TCI for the complete Booster Pump A unit (and also the entire WI system) will start at bottom level; detecting measurements (e.g. bearing temperatures, vibrations etc) and according to the preset limits a TCI for each measurement is obtained through an input function. The “worst case” aggregation method will be used for deriving the TCI from bearing temperature levels. This means that the TCI value of the parent node (Bearing Temperature) will be equal to the lowest registered bearing sensor value.

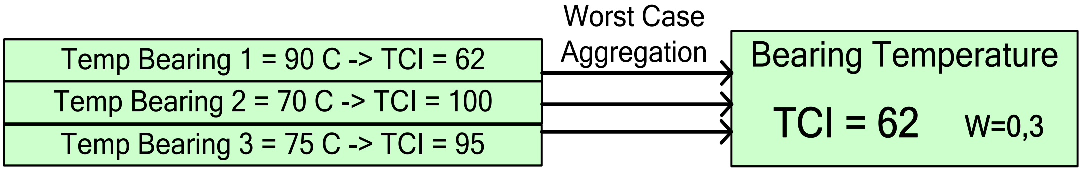

Figure 5.18, Obtaining TCI from "worst case aggregation" (Erstad, 2011)

5.5.2 Obtaining TCIs from “penalty aggregation”

Moving one level up the hierarchy (ref. Figure 5.17) the next step is calculating the TCI of the pump housing. Having shown the previous step, the other values are assumed to provide an example. The TCI value for the Pump Unit will be done through the “penalty” aggregation method. Here the sum of the weights is not required to be equal to one.

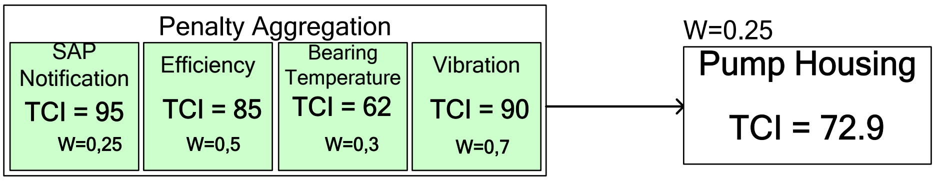

Figure 5.19, Obtaining TCI from "penalty aggregation" (Erstad, 2011)

Calculating the TCI of the pump housing through Equation 2 (penalty aggregation function):

$$TCI_{Pump\ Housing} = 100 - \sum_{i=1}^{5} (100 - TCI_i) \cdot w_i \quad , \quad \sum_{i=1}^{n} w_i \neq 1$$

$$TCI_{Pump\ Houseing} = 100 - \big((100-95)\cdot 0.25\big) - \big((100-85)\cdot 0.5\big) - \big((100-62)\cdot 0.3\big) - \big((100-90)\cdot 0.7\big) = \underline{72.9}$$

5.5.3 Obtaining TCIs from "weighted sum"

Next step is obtaining the TCI value of the Booster Pump A using the weighted sum aggregation method (Equation 3).

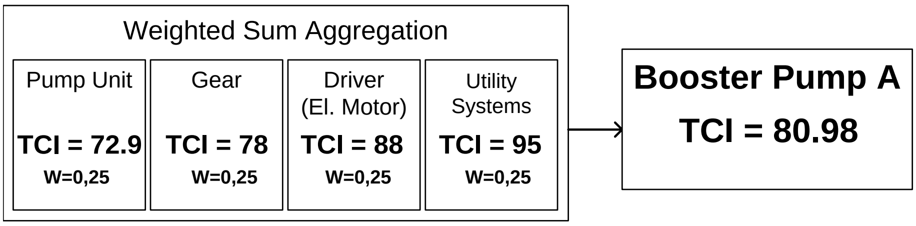

Figure 5.20, Obtaining TCI from "weighted sum aggregation" (Erstad, 2011)

$$TCI_{Booster\ Pump\ A} = 100 - \sum_{i=1}^{4}(100 - TCI_i)\cdot w_i \ \ , \sum_{i=1}^{4} w_i = 1$$

$$TCI_{Booster\ Pump\ A} = 100 - ((100-72.9)\cdot 0.25) - \big((100-78)\cdot 0.25\big) - \big((100-88)\cdot 0.25\big) - \big((100-95)\cdot 0.25\big) = \underline{83.48}$$

The remaining aggregation up the hierarchy towards obtaining the system level TCI value would consist of using the weighted sum aggregation method.

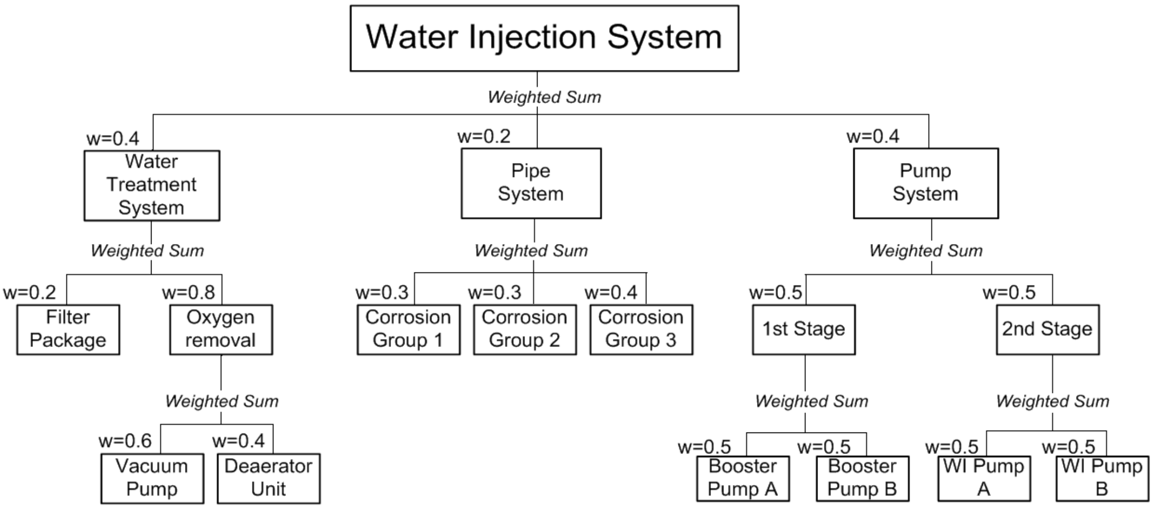

Figure 5.21, Obtaining System level TCI through "weighted sum aggregation" (Erstad, 2011)

5.6 Visualizing the WI System TCI in the TIMS portal

The obtained TCIs will be visualized at different levels in the TIMS portal. The visualization could be presented in various ways; through a traffic light concept, system condition variation over time or contributions from the main sub systems over time (Figure 5.22).

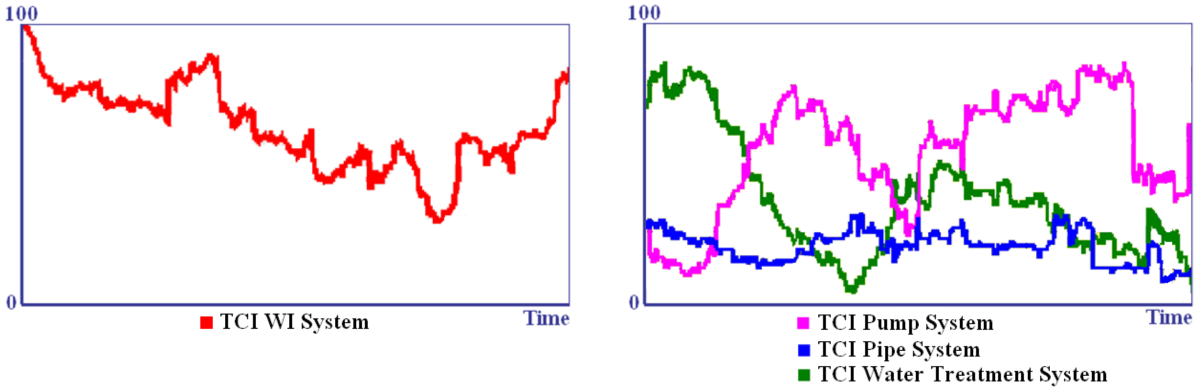

Figure 5.22, Examples of TCI presentation in the portal (Erstad, 2011)

The technical condition indicators will serve different purposes for personnel working at different levels of the TIMS portal. Maintenance personnel and specialists working with condition monitoring on equipment and component level will have easy access to all measurements from CM systems (e.g. bearing temperature and vibration) and IMS system (process data; pressures, temperatures, flows), giving red light indications when measurements are deviating from preset accepted limits. This will provide the engineers with an overview picture of all measurements, highlighting areas that need focus and attention. The ability to study the behavior of the technical condition and process parameters over time will provide possibilities for uncovering negative trends and performance killers. The integrated access and the relief of manually assessing all sensor measurements will save time from data collection and give engineers more time to evaluate focus areas.

On the higher levels of the portal (system/facility) the obtained TCIs will not serve as main inputs for exact condition assessments and day-to-day operational decisions. This is because the higher level aggregated TCIs are often obtained from complex system hierarchies that have many variables and uncertainties to consider. In this case a WI system consisting of a wide variety of equipment with very different degradation mechanisms. Therefore these higher level TCI values will most likely not be able to consider all of these variables perfectly and are consequently not 100% exact condition indicators. However the main purpose for these TCIs is not to be flawlessly precise but to be a tool for supporting managers and decision-makers over longer terms; making strategic decisions regarding maintenance, production, modifications and higher level revisions regarding the technical condition of the installations. The system indicators will also be an important tool for measuring the actual effect of maintenance strategy changes, modifications and can also be used for quantitatively comparing the performance of systems or sub-systems across different installations, if carefully designed.

6 DISCUSSION

Based on the aspects discussed in this thesis regarding maintenance developments, CM and ICT technologies and future implementations of maintenance portals, the meeting with Mr. Gunnar Ølmheim (Head of Rotating Machinery and Condition Monitoring, Statoil) and Mr. Trygve Marken (Chief Engineer, Rotating Machinery, Statoil) (Appendix A) provided some interesting points for discussion.

Maintenance Impacts from IO and ICT

Over the last decade or so integrated operations (IO) has been recognized as an important tool for increasing the efficiency and safety level of O&G operations. The implementation of modern ICT has allowed for significant developments of maintenance activities; allowing onshore experts to monitor offshore assets in real time, improving the support towards offshore operations and personnel. This thesis has addressed some of the possibilities and impacts that IO and modern ICT has brought to the traditional preventive maintenance regimes; pushing the industry towards “predict and prevent” strategies performing maintenance more on a condition based basis. This development has been discussed with Mr. Ølmheim and Mr. Marken (Appendix A) confirming that Statoil is aiming to increase the amount of CBM and perform less periodical PM activities, particularly regarding rotating equipment. This can be further recognized as the online surveillance and CM of rotating equipment has increased from covering 19 to 28 installations during the last two years, and additionally all new projects in Statoil demands specifications for remote CM.

ICT infrastructure importance for future development

Today condition monitoring systems is generally applied for the heavy rotating equipment that is regarded as critical for safety and production availability. Very little online CM technology is applied to the static equipment on Statoil’s installations; only limited to some corrosion probe monitoring. Some pilot projects have been run on online condition monitoring of valves but haven’t led to significant developments in this area within Statoil. However it is recognized that the potential within this field isn’t fully exploited today, and the reason for this comes from justifying the cost-benefit of implementation and also possibly the lack of a sufficient ICT infrastructure. This thesis has addressed the importance of a sufficient ICT infrastructure laying the foundation for implementing real time CM of offshore assets. The ICT infrastructure coverage on the NCS must be assumed to be under expansion when referring to the above mentioned increase in surveillance and demanded specification for new projects. As the ICT infrastructure is increasingly available the initial cost and threshold of implementing CM technology becomes significantly lower. Whether or not to implement new technologies will always come down to a cost-benefit evaluation, but as the price of technology decreases and the experience and effects of real time CM is growing it could be assumed that future real time CM systems will cover a broader range of equipments. In this aspect standardization is regarded as an important step for pulling the CM wagon forward.

Standardizing communication and interoperability protocols

This thesis has presented some of the industry initiatives made for standardizing and "unifying" the information and data exchange protocols between CM technologies and systems. The intention of these efforts is solely meant to benefit the users of such technology, in the sense that standardized communication protocols will open up a wider selection of products available to the consumer, allowing the possibility for choosing between the best suited technologies instead of being limited to single vendor technologies. This can also contribute to lowering prices and allow more focus towards developing and optimizing the new maintenance possibilities instead of putting extensive amounts of energy into getting compatibility between devices. An additional advantage of standardization will be that competition will occur at a functional level and not at system or total solution level.

Integrated Information Portals

Better utilization and timely access to the increasing amount of available technical condition data are one of the main drivers for developing the TIMS maintenance portal presented in this thesis. With better utilization of the available condition data the intention is to streamline maintenance and inspection activities to achieve improved technical integrity and lowered maintenance costs. Today maintenance engineers and operators have access to a wide range of real time technical and operational data; however they are scattered between separate systems and databases. From Mr. Marken it was stated that the combined use and access to the available data isn't optimal with current implemented CM systems. In Statoil the maintenance engineers browse through CM data for all equipment every 24 hours; searching for deviations and negative developments. Process data is not systematically included and monitored in this routine, however when detecting deviations (e.g. increasing vibrations) they are usually very relevant to be involved for estimating the technical condition of the equipment. In lack of a total system solution that integrates information from all relevant sources into one single interface; time consuming manual work is needed to collect all relevant data. From this it is recognized that utilizing integrated systems providing timely and effective access to multi source maintenance data could save the engineers a lot of time by significantly reducing the need for working between multiple systems. As presented in this thesis, the TIMS portal is intended to consist of a Business Logic layer for processing the obtained maintenance data to generate traffic lights for visualizing negative developments. From Mr. Marken and Mr. Ølmheim it has been recognized that the future lies in implementing systems that includes both CM and process data for assessing the technical health of machineries, and with more automated deviation detections the need for manual browsing of vast amounts of data will be significantly reduced. Having a clear overview of deviating measurements will give possibilities for special focus on the areas that need attention.

Condition indicators for management support

Consequently the TIMS portal will be used as a tool for maintenance engineers working with day to day condition assessments and decisions regarding maintenance and inspection activities. But on higher levels the TIMS portal is also meant to support the organization’s management in the longer strategic terms. Chapter 6 of this thesis proposed a methodology for visualizing the technical condition from indicators aggregated from lowest level input variables. The methodology proposed in Chapter 6 addressed system condition visualization in the aspect of availability, but the same methodology could be used to aggregate performance indicators according to all the defined main focus areas of the TIMS portal (Figure 4.1).

7 CONCLUDING REMARKS

With ever more stringent requirements for HSE and production availability, the operators wish to have knowledge regarding the technical condition and degradation mechanisms at their fingertips to best avoid adverse events and unplanned production shutdowns. In discussions with Statoil maintenance engineers (Appendix A) regarding today’s CM systems it has been confirmed that there is need for better utilization and timely access to the different technical condition data available. Also as the quantity of condition data from monitoring systems could be expected to increase, the need for efficient handling and access to this information becomes ever more important. Such needs for integrated access is a key factor in developing the TIMS maintenance portal; making maintenance decision makers and managers spend less time collecting information and instead give more time evaluating decisions.

The TIMS maintenance portal presented in this thesis will provide comprehensive access to maintenance information from bottom level sensors to platform and field level. The intention is to provide a clear total picture, utilizing technical condition and process data to detect deviations; indicating abnormal measurements, reducing the need for time demanding data collection and searching for negative developments. Monitoring significant influence factors like process parameters and technical condition data in the portal will facilitate for optimized and coordinated maintenance and inspection activities based on real time information.

The aggregation of higher level technical condition indicators can be a valuable support for managers to measure the performance of the maintenance strategies, effect of strategic changes and for pointing out performance killers and bad actors. The methodology proposed in Chapter 6 can be used for measuring the performance of all main areas of focus in the TIMS portal; HSE, finance, availability, quality, risk and volume.

When considering the complexity and risks of performing offshore O&G operations it is clear that operational decisions and technical condition assessments is unlikely to be based on artificial intelligence in any near future. Even though technology developments have come a far way, the safest and most efficient decisions are still made by experienced personnel base their actions on precise, updated information material. Hence it is important to use the technology where it’s best appropriate; developing system technologies that provides the decision makers with the most accurate condition data in a timely and effective manner creating the best possible foundation for well considered decisions.

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APPENDIX A: MINUTES OF MEETING

Subject: Maintenance and Condition Monitoring of Rotating Equipment
Date: 12.04.2011
Location: Statoil's facilities at Sandsli, Bergen.

Participants:

Gunnar Ølmheim	*(Head of Rotating Machinery and Condition Monitoring, EPN JO MFO RCM Statoil ASA)*
Trygve Marken	*(Chief Engineer, Rotating Machinery, MFO RCM OWE Statoil ASA)*
Christian Erstad	*(University of Stavanger)*
Anja Farstad	*(University of Oslo)*

Main topics of discussion:

1. Current level of condition monitoring (CM) and condition based maintenance (CBM) of (mainly) rotating equipment.
2. Future directions for CBM and increasing use of real-time data as basis for performing maintenance activities.

Summary:

Online CM is mostly applied on heavy rotational equipment that can be described as critical equipment in regards to Safety (e.g. fire water pumps) or Production (turbines, generators, compressors, water injection pumps). Vibration and temperature levels of bearings is generally the most applied online monitoring methods for rotating equipment. The rate of sampling varies between different CM systems and also with the criticality of the respective equipment. All systems are checked every 24 hrs to detect deviations. Software alarms will indicate developments to onshore personnel at an earlier stage than for the operators offshore, so that the onshore personnel are given more time to evaluate conditions and plan potential maintenance interventions. The engineers also have easy access to a wide range of process data (pressures, flow rates, temperatures) but as of today there is no systematic monitoring of these in relation to monitoring the technical condition of machineries. However when detecting deviations (e.g. increasing vibrations); process data are usually very relevant to be involved for estimating the technical condition. Consequently there is no total system for this, so engineers are working between different systems to collect these data. As an example there is one particular system for collecting flow data, but it demands a bit of manual work to select the desired tags to collect data from, and this procedure can often be time consuming. By having automatic systems that would automatically perform this kind of data collection could save the engineers a lot of time.

The organization is aiming to move towards less periodical preventive maintenance activities and perform more condition based maintenance, particularly on the rotating equipment. Over the last two years surveillance of equipment has expanded from 19 to 28 installations.

Very little CM is performed on static equipment, mostly inspections and some corrosion probe measurements. Condition monitoring of valves have been performed to some smaller extent; in the form of acoustic measurements to detect leakage. Some pilot projects on this subject have been run in cooperation with Solberg Andersen. But there has not been a significant development on this aspect within Statoil as it is regarded to involve relatively expensive equipment. It all comes down to a cost benefit evaluation. Control valves are equipped with a lot of different sensors; regulators and flow controllers that could extract a wide range of valve data which could be communicated towards a CM system. However, as of today the potential is not fully exploited in this field. The reason for this can be the missing infrastructure for the online condition monitoring of valves. Once again this will stem back to the cost benefit evaluations; why spend a sum of money on monitoring a valve when the whole valve could be demounted and replaced for half the monitoring sum?

Predictive maintenance systems are the next generation of systems; considering a wider range of data sources, both technical condition data and process data to determine the health of the machineries. By pre-setting accepted operational limits the system will generate alarms if detecting deviations. The future lies in implementing systems that give red light indications when negative developments are registered, to remove the need for engineers having to browse through specialist systems searching for negative developments. Future lies in collecting data from a wide range of data sources automatically, and then be provided with an overview picture which is easier to relate to. Even though the development of CM systems and expert systems has come a far way, the decisions are still made by humans using computer technology as tools for making more effective and successful decisions. When looking at industries like aviation and nuclear power; they might be the industries that really are sitting at the tip of this technology, but even in these industries it is still humans making the final decisions.

Some of the older, marginal installations of Statoil will never be susceptible to CM on “not so critical” components like pipes or valves. However all new projects in Statoil demand specifications for CM.

It will always be a matter of cost benefit, even though the technology is sophisticated and revolutionary.