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Maintenance Concept Database Solution (MCDS)

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This Thesis is dedicated to my friend, Erik Faarlund,

his wife, Bodil,

and their twin boys, Linus and Sofus.

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MAINTENANCE CONCEPT DATABASE SOLUTION (MCDS)
(Vedlikeholdskonsept og databaseløsninger)

Ineffective or wrong maintenance can result in great economic loss, accident, lost production etc. Maintenance should be looked upon as an investment, not a cost, and it is important to develop and establish a good maintenance function or concept.

The main objective of this master thesis is to evaluate and further develop the AGRFO maintenance concept the work can consist of.

The scope is limited to the following:

1. Evaluate and describe existing database solutions.
2. Evaluate how criticality, based on NORZOK Z-088 and RCM logic, can be implemented into a maintenance concept.
3. Suggest a way to adapt the developed concepts according to a client's requirements (i.e., one concept with several versions based on operational profile).
4. Evaluate the market potential of a database as described above and suggest a feasible way to offer it to the market.

The master thesis shall be documented either as a technical report, or in a scientific article format. The text should be clear and concise, and include the necessary references to figures, tables and diagrams. References shall be given to any external sources used in the text.

Equipment and software developed during the project is a part of the fulfilment of the task. Unless outside parties have exclusive property rights or the equipment is physically non-moveable, it should be handed in along with the final documentation. Suitable documentation for the correct use of such material is also required.

If the candidate encounter unforeseen difficulties in the work, and if these difficulties warrant a reformulation of the task, these problems should immediately be addressed to the Department.

Any expenses in terms of travelling, use of phone, copying etc shall be covered by the student unless otherwise agreed is upon.

A draft version of the final documentation shall be handed in 4th of June 2010. On the 14th of June 2010 the candidate shall present his work, and open up for a public questioning by an evaluation committee. The presentation will continue for approximately 20 minutes, followed by questions. The candidate may improve the final documentation after the draft has been submitted. If major changes are made, this should be documented in a separate one sheet paper submitted together with the final documentation.

The documentation shall be submitted electronically. The Department will print the report/journal paper in a consistent format.

The final due date is set to **14th of June 2010**.

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PREFACE

This thesis, **"Maintenance concept database solution"**, is an assignment written in collaboration with AGR Field Operations (AGR FO) in partial fulfillment of the requirements for the award of MSc. in Reliability, Availability, Maintainability & Safety (RAMS) at The Norwegian University of Science and Technology (NTNU).

The thesis is a task given in the course TPK 4900 within The RAMS Group of The Department of Production and Quality Engineering.

To the following people I give my heart-felt thanks for the guidance and motivation they offered:

- Per Schjølberg, Department of Production and Quality Engineering, NTNU.
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ABSTRACT

Ineffective maintenance has caused several organizations great economic loss in repairs and lost production in addition to the potential threat to both the health and safety of employees and the environment. The cause of this problem may be from outside the organization or within it. Internally, the problem may be borne from outdated maintenance philosophy, unoptimized maintenance, unclosed maintenance process loop, non-conformance to regulatory requirements, lack of human resources development, lack of motivation, unsafe acts/conditions and poor organizational structure. The possible internal causes of this problem are explained briefly as follows.

Outdated Maintenance Philosophy: an organization that focuses on reactive maintenance (instead of value-added functions) based on their belief that maintenance is a necessary evil or liability is already doomed to be ineffective.

Unoptimized Maintenance: unoptimized maintenance strategy, unoptimized spare parts strategy, unoptimized manpower strategy and unoptimized maintenance intervals (i.e. determining intervals without considering criticality and cost) could lead to wasteful maintenance decisions.

Unclosed Maintenance Process Loop: Missing or ineffective feedback and control loops among the six phases of an ideal maintenance process (work identification, work planning, work scheduling, work execution, history recording and analysis) could lead to ineffective maintenance.

Non-conformance to Statutory/Regulatory Requirements: Non-conformances such as breach of work permit system or insufficient classification of systems/equipment could also result in effective maintenance and may in turn lead to major accidents.

Lack of human resources development: Lack of programs to upgrade the knowledge and skill levels of maintenance staff could lead to obsolescence and impede the philosophy of continuous improvement.

Lack of motivation: Maintenance workers who are demoralized by unfavorable organizational factors may become disoriented and prone to poor attitude to work, errors and accidents.

Unsafe acts and unsafe conditions: Unsafe work procedures and habits and unsafe workplace could lead to accidents and incidents and in turn ineffective maintenance.

Poor Organizational Structure: Communication gap between the maintenance department and production department could also lead to ineffective maintenance, for example, the production staff may overrun machines, thus increasing maintenance problems or the maintenance team may require data like machine run time from the production team without getting it on time.

There is the need to help maintenance staff do their jobs more efficiently and effectively, by automating the maintenance process, by using failure data analysis to refine maintenance strategies, by cultivating sound inter-departmental relations, by reducing job and workplace hazards, by training and motivating the workforce, and by conducting periodic maintenance management reviews/audits.

AGR Field Operations-Maintenance Engineering (AGR FO ME) seeks to evaluate, in conjunction with NTNU, the possibility of establishing a database of maintenance and integrity data on a micro level and connecting it to analytical tools, through a Master Thesis.

AGR Field Operations (AGR FO) is a leading provider of global services and technologies to the oil and gas industry, delivering services within Inspection & Integrity, Operations & Maintenance, Project Management & Engineering, Subsea services and Alternative Energy.

This thesis will tackle the issue of unoptimized maintenance among all the aforementioned possible maintenance-related problems.

The scope of the thesis is limited to the following:

1. Description and evaluation of existing maintenance database solutions.
2. Evaluation of how criticality based on NORZOK Z-008 and RCM logic can be implemented in a maintenance concept.
3. Suggestion of a way to adapt the concepts according to a client’s requirements (i.e one concept with several versions based on operational profile).
4. Evaluation of the market potential of a database as described above and suggestion of a feasible way to offer it to the market.

CONTENTS

CONTENTS 1

ILLUSTRATIONS 4

TABLES 5

ACRONYMS 6

1. INTRODUCTION 7

1.1 Background 7

1.2 Objective 8

1.3 Limitations 8

1.4 Research method 8

1.5 Thesis structure 8

2. DESCRIPTION/EVALUATION OF EXISTING DATABASE SOLUTIONS 10

2.1 Background 10

2.2 A Review of CMMS 10

2.2.1 Aims of CMMS 10

2.2.2 Description of CMMS 10

2.2.3 Pros and cons of CMMS 12

2.3 A Review of Other Maintenance Database Solutions 14

KAMFER 14

OptiRCM 15

BI-Cycle Software 16

RCM++ 17

Meridium APM Software and RCMO Software 18

OREDA Software 19

More Database Solutions 21

2.4 Conclusion 22

3. HOW CRITICALITY BASED ON NORSOK Z-008 AND RCM LOGIC CAN BE IMPLEMENTED IN A MAINTENANCE CONCEPT 23

3.1 Background 23

3.2 Criticality 23

3.3 Description of NORSOK Standard Z-008 23

3.3.1 Description of Draft NORSOK Z-008:2009 23

3.3.2 Difference between NORSOK Z-008:2001 and Draft NORSOK Z-008:2009 24
3.3.3 Motivation for Using Draft NORSOK Z-008:2009 for This Thesis 25
3.4 Description of RCM and RCM Logic 25
3.4.1 Reliability Centered Maintenance (RCM) 25
3.4.2 RCM Decision Logic Tree Analysis 33
3.5 How Criticality Based on NORSOK Z-008 and RCM Logic Can Be Applied In a Maintenance Concept 35
3.5.1 MCDS Maintenance Management Model 36
3.5.2 MCDS Modules of Concepts 37
3.6 MCDS: A Promising Maintenance Database Solution 43
3.7 Conclusion 45
4. ADAPTABILITY OF THE MAINTENANCE CONCEPT ACCORDING TO CLIENTS REQUIREMENTS 46
4.1 Background 46
4.2 Adaptability of MCDS to Divers Industrial Applications 46
4.2.1 Criticality 47
4.2.2 Safety 47
4.2.3 Unavailability 48
4.2.4 Punctuality 48
4.2.5 Weibull Standard PM Model 49
Figure 19: Non-observable failure progression (SINTEF & NTNU, 2009) 50
4.2.6 ARP Model 50
4.2.7 PF-Model 51
4.2.8 PFD-Model 54
4.3 How to transform one MCDS version to another 56
4.4 Conclusion 58
5. EVALUATION OF THE MARKET POTENTIALS OF THE MAINTENANCE CONCEPT AND WAYS OF OFFERING IT TO THE MARKET 59
5.1 Background 59
5.2 SWOT Analysis of MCDS 59
STRENGTHS 59
WEAKNESSES 59
OPPORTUNITIES 59
THREATS 60
5.3 Key issues for technology-driven innovation 60
5.4 Marketing and sales 61

5.5 Recommended strategies for established businesses 61
5.6 Recommended Business Model/Strategies for AGR FO 62
5.6.1 The Delta Model 62
5.6.2 Delta Model Winning Steps 65
5.6.3 The Adaptive Processes: Linking Strategy with Execution 65
5.7 Conclusion 66
6. FINAL CONCLUSION AND FURTHER RECOMMENDATIONS 67
6.1 Final Conclusion 67
6.2 Further Recommendations/Further Work 67
6.2.1 Recommendations for the Short Term (1-3 years) 67
6.2.2 Recommendations for the Long Term (>3 years) 68
7. REFERENCES 69

ILLUSTRATIONS

Figure 1: Maintenance types according to EN13306:2001 (Marquez, 2007) 7
Figure 2: Maintenance concepts relationship (Haugen, 2009) 8
Figure 3: Thesis structure 9
Figure 4: Equipment history brief view through a web browser (Matusheski, 1999) 11
Figure 5: Maintenance Management Process (Dunn, 1997).. 14
Figure 6: OptiRCM input and analysis screen (Rausand & Vatn, 2008) 15
Figure 7: The Bi-Cycle Software (Bi-Cycle, 2010).. 16
Figure 8: RCM++ Interface (Reliasoft, 2010) 18
Figure 9: Databank Structure (OREDA, 2009).. 20
Figure 10: Main Software Modules (OREDA, 2009) 20
Figure 11: OREDA Data Collection Software-Subsea (OREDA, 2009).. 20
Figure 12: Significant function selection logic tree (NAVAIR 00-25-403, 2005) *(adapted)* 28
Figure 13: Determining redundancy (USEPA, 2008) 29
Figure 14: Maintenance task assignment/decision logic (Rausand & Vatn, 2008) *(adapted)* 35
Figure 15: MCDS maintenance management model 36
Figure 16: Spare parts inventory control decision logic 41
Figure 17: MCDS hierarchical structure 44
Figure 18: Illustration of availability (copied from
www.reliasoft.com/newsletter/3q2002/availabilities.htm) 48
Figure 19: Non-observable failure progression (SINTEF & NTNU, 2009) 50
Figure 20: Illustration of age replacement policy (NTNU & SINTEF, 2009) 51
Figure 21: $Q_{PF}(\tau)$ for different combination of SD_{PF}/E_{PF} and P_I (Vatn, 2007).. 52
Figure 22: Variation in PF-interval (Vatn, 2007).. 53
Figure 23: Observable "sudden" failure progression (SINTEF & NTNU, 2009).................................... 54
Figure 24: Shock model (SINTEF & NTNU, 2009)... 54
Figure 25: Function test with interval length, τ (Vatn, 2007)... 56
Figure 26: Business Model-Three distinct strategic options (Hax & Wilde, 2002)............................... 63
Figure 27: Options for strategic positioning (Investinor, 2010) 63

TABLES

Table 1: Acronyms 6
Table 2: Some RCM tools currently used by maintenance teams (UPM & Adepa, 2000) 21
Table 3: Main functionalities of aforementioned RCM tools (UPM & Adepa, 2000)........................... 22
Table 4: Functional Failure Analysis (FFA) worksheet 28
Table 5: Criticality rating applied in Functional Failure Analysis (FFA)... 29
Table 6: FMECA worksheet 31
Table 7: Risk matrix used for classification and decisions.. 32
Table 8: Consequence classes description 32
Table 9: Example of degrees of redundancy definitions 34
Table 10: Example of risk based scheduled overhaul plan 38
Table 11: Illustration of Excel worksheet for fast-moving spares inventory control analysis (FSICA) .. 39
Table 12: Illustration of Excel worksheet for slow-moving spares inventory control analysis (SSICA). 40
Table 13: Illustration of Excel worksheet for rotable inventory control analysis (RICA) 41
Table 14: Example of spare parts location matrix (Draft NORSOK Standard Z-008, 2009).................. 42
Table 15: Spare parts consequence classes description (Draft NORSOK Standard Z-008, 2009) *(adapted)* 42
Table 16: Minimum required maintenance data reportage (ISO 14224, 2006) 42
Table 17: Maintenance Optimization (involving punctuality) Excel worksheet (Vatn, ProM@in EXCEL files, 2001) 49
Table 18: Illustration of PM interval optimization Excel worksheet (Vatn, 2007) *(adapted)* 50
Table 19: P-F Interval Excel Worksheet (Vatn, ProM@in EXCEL files, 2001) 53
Table 20: Examples of possible data sources for transformation of MCDS versions........................... 57
Table 21: Recommended concepts for different industries... 58
Table 22: "Best Product" Delta Strategy (Investinor, 2010)... 64
Table 23: "Total Customer Solutions" Delta Strategy (Investinor, 2010)... 64
Table 24: "System Lock-in" Delta Strategy (Investinor, 2010) 65
Table 25: The Role of the Adaptive Processes in supporting the Strategic Options of the Triangle (Hax & Wilde, 2003)... 66

ACRONYMS

Some abbreviations used are given below; others are defined where there occur in the thesis:

Table 1: Acronyms

AGR FO	-	AGR Field Operations
ARP	-	Age Replacement Policy
BS	-	British Standard
CBM	-	Condition Based Maintenance
CM	-	Corrective Maintenance
CMMS	-	Computerized Maintenance Management System
DSC	-	Data Sharing Consortium
EN	-	European Standard
FFA	-	Functional Failure Analysis
FMECA	-	Failure Modes, Effects and Criticality Analysis
IEC	-	International Electrotechnical Commission
INSC	-	International Nuclear Safety Centre
ISO	-	International Organization for Standardization
MCDS	-	Maintenance Concept Database Solution
MTBF	-	Mean Time Between Failures
MTTF	-	Mean Time To Failure
NORSOK	-	Norsk Sokkels Konkuranseposisjon
OREDA	-	Offshore Reliability Data
PDA	-	Personal Digital Assistant
PF	-	Potential Failure – Functional Failure (Interval)
PFD	-	Probability of Failure on Demand
PM	-	Preventive Maintenance
RAC	-	Reliability Analysis Centre
RAM	-	Reliability, Availability and Maintainability
RBI	-	Risk Based Inspection
RBM	-	Risk Based Maintenance
RCM	-	Reliability Centred Maintenance
RFID	-	Radio Frequency Identification

1. INTRODUCTION

1.1 Background

The idea behind the thesis "Maintenance Concept Database Solution" is the need to contribute to the continuous improvement of maintenance effectiveness in industries.

A maintenance concept is a standard way of implementing the maintenance routines on a certain piece of equipment/system.

According to (Draft NORSOK Standard Z-008, 2009), a generic maintenance concept is "a set of maintenance actions, strategies and maintenance details, which demonstrates a cost-efficient maintenance method for a defined generic group of equipment functioning under similar frame and operating conditions." Draft NORSOK Z-008:2009 also described a generic maintenance concept as "a collection of best practices for a company" that "should ensure that all defined HSE, production, cost and other operating requirements are met."

Also, according to (Business Dictionary, 2010), a maintenance concept is a "statement of broad concept, policy, or planned approach that governs the maintenance levels and type of maintenance actions to be performed for a equipment, machine, plant, or system."

The fundamental maintenance concept presents maintenance as being the combination of all technical and corresponding administrative actions, including supervision actions, intended to retain an entity in, or restore it to, a state in which it can perform its required function [IEC 50(191)]. This concept gives rise to a first classification of the maintenance actions in two main categories: Preventive Maintenance and Corrective Maintenance. On the basis of this criterion, EN 13306:2003 presents the different types of maintenance classified according to Figure 1 (Marquez, 2007). It is on the basis of this concept that other maintenance concepts (such as RCM and RBI) stand, as illustrated in figure 2.

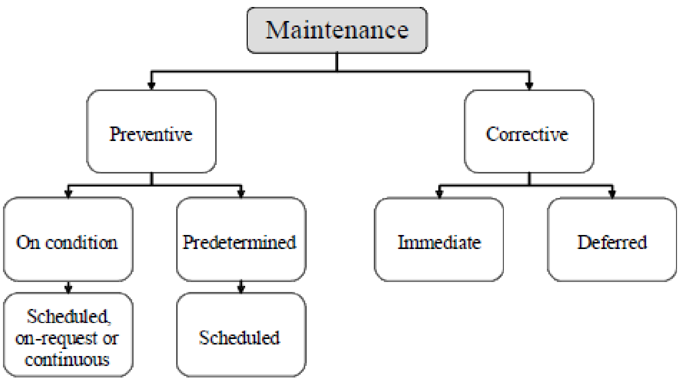

Figure 1: Maintenance types according to EN13306:2001 (Marquez, 2007)

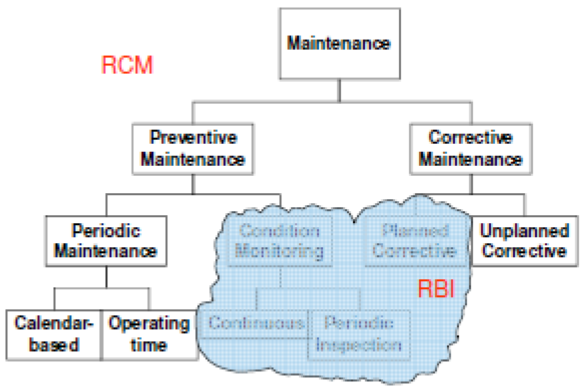

Figure 2: Maintenance concepts relationship (Haugen, 2009)

The main idea behind figure 2 is that modern maintenance concepts such as RCM, RBI, RBM, CBM etc. are functions of preventive maintenance (PM), corrective maintenance (CM) or both.

1.2 Objective

The main objective of the thesis is to evaluate and propose further development of AGR FO maintenance concepts, where the concepts can be adapted to the operations of the installation. The thesis is expected to serve as a maintenance optimization solution.

1.3 Limitations

- The issue of criticality will be based on NORSOK Z-008 and the standard RCM logic.
- Draft NORSOK Z-008:2009 will be used for this thesis.
- Earlier versions of NORSOK Z-008 will not be used.

1.4 Research method

The thesis will be written based on literature study and experience from industry experts, AGR FO and other organizations.

1.5 Thesis structure

The structure of the thesis is shown in Figure 3 as follows.

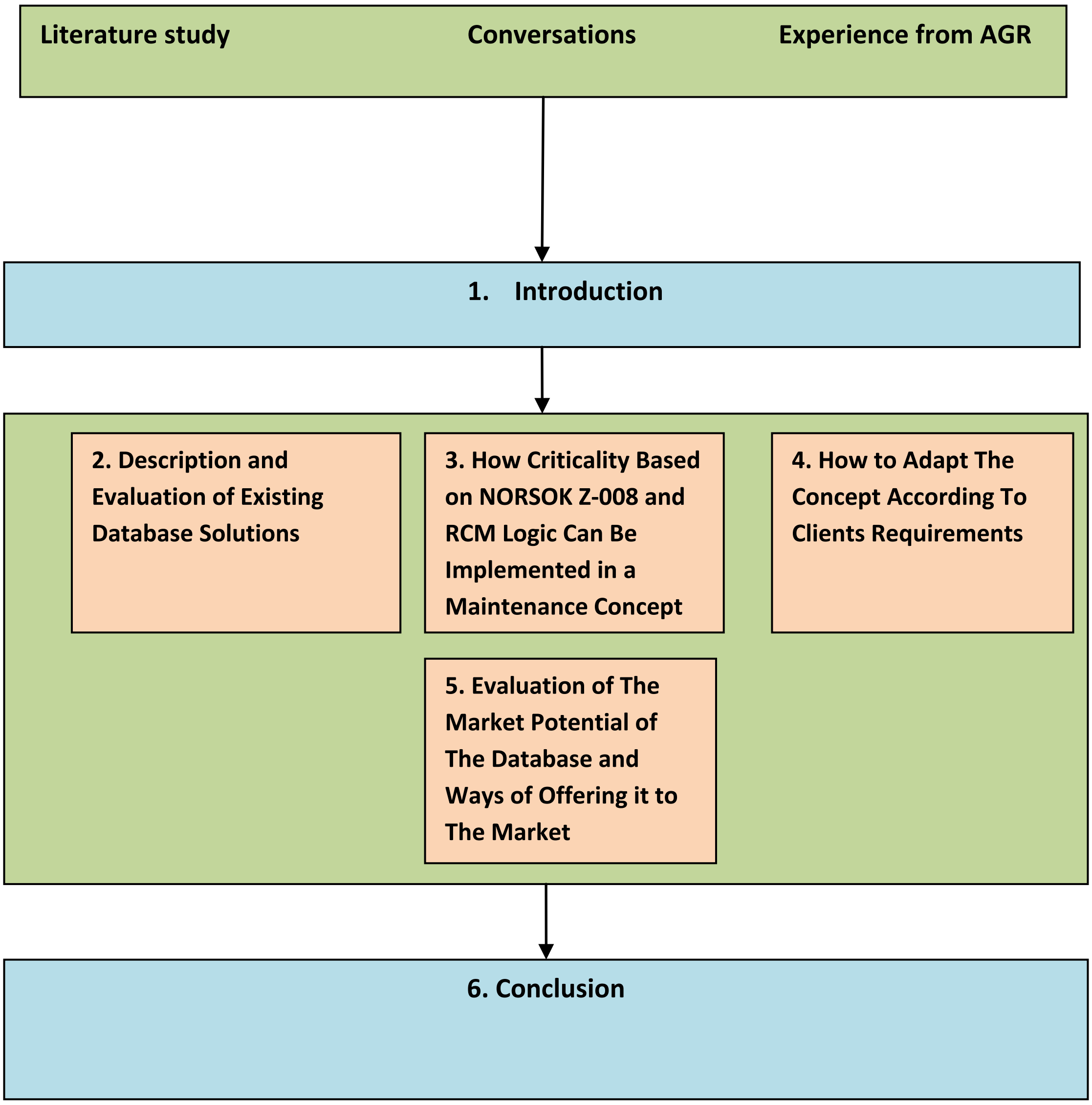

Figure 3: Thesis structure

2. DESCRIPTION/EVALUATION OF EXISTING DATABASE SOLUTIONS

2.1 Background

The implementation of optimized maintenance management database solutions is crucial in establishing an effective maintenance system in modern technology based operating environment. Maintenance database solutions can help maintenance staff to do their jobs more effectively (for example, applying the appropriate maintenance strategy to a given piece of equipment and determining which store units contain the required spare parts) and make informed decisions (for example, evaluating the cost of corrective maintenance versus preventive maintenance per equipment, possibly resulting in improved resource allocation).

2.2 A Review of CMMS

2.2.1 Aims of CMMS

The aims of a Computerized Maintenance Management System (CMMS) include the following:

- To maintain a database of information about an organization's maintenance-related activities (Wikipedia, 2010). This is a storage function.

- To automate most of the logistical functions executed by maintenance personnel (DOE, 2002). This is an efficiency improvement function.

2.2.2 Description of CMMS

Computerized Maintenance Management Systems (CMMS) is a common name for computer-aided asset maintenance management systems (Wilson, 2002), which are also known as Enterprise Asset Management (EAM) systems and Computerized Maintenance Management Information System (CMMIS) (Wikipedia, 2010).

CMMS packages are either web-based or LAN-based. A web-based CMMS is hosted on an external server by the company selling the product, while a LAN-based CMMS is hosted on a local server by the company buying the software. An example of a web-based CMMS package is shown in figure 4 below.

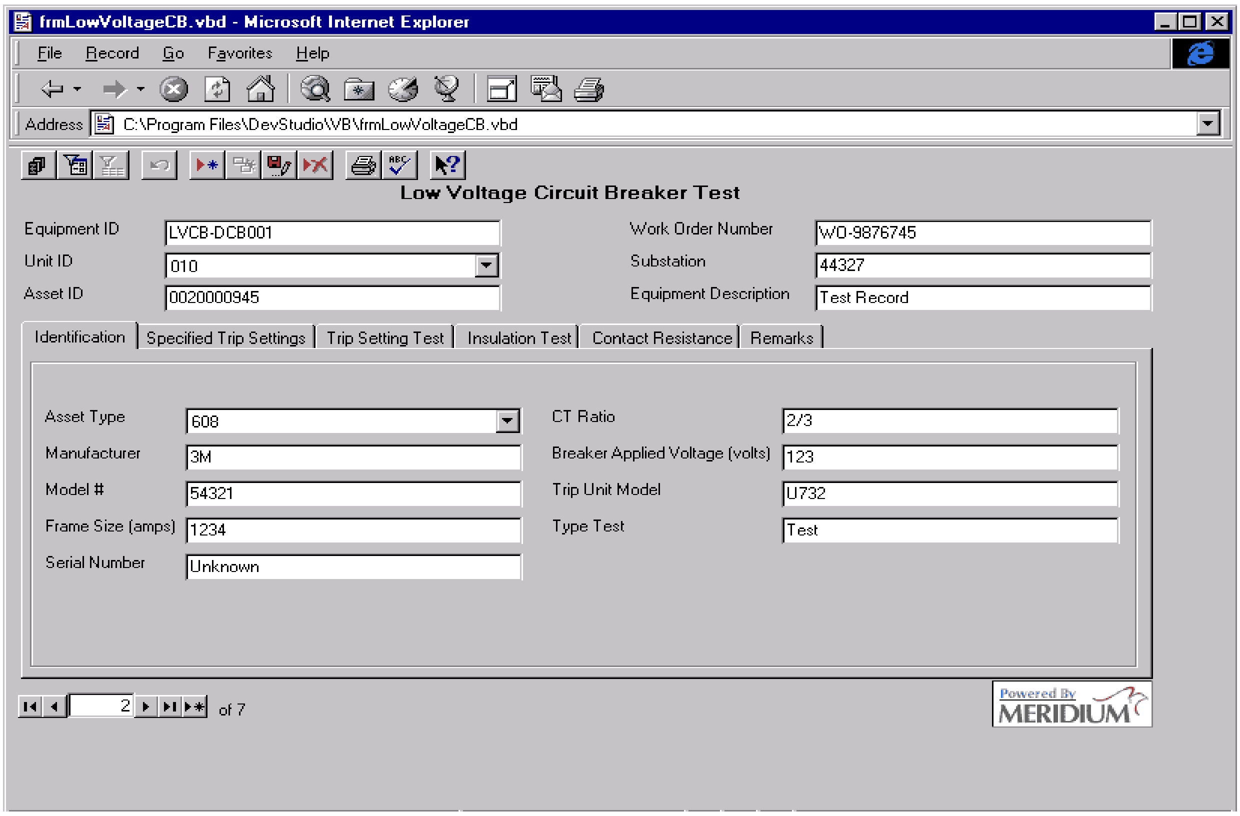

Figure 4: Equipment history brief view through a web browser (Matusheski, 1999)

From the perspective of (Technology Concepts Group, 2008), "Computerized Maintenance Management Systems provide a way for companies to track equipment and inventory assets, detail when and how work orders are to be performed in maintaining those assets, and accumulate all of the associated costs for labor, materials and tools."

According to (Wireman, 1998), "CMMS is, in reality, nothing more than a computerized version of a maintenance information system. In fact, anything that can be done with a CMMS can be done with a manual system. In theory, though the CMMS should make it faster and easier to collect data and then manipulate it into a meaningful report format."

Depending on the complexity of the selected system, typical CMMS functions may include (DOE, 2002):

- Work order generation, prioritization, and tracking by equipment/component.
- Historical tracking of all work orders generated which become sortable by equipment, date, person responding, etc.
- Tracking of scheduled and unscheduled maintenance activities.
- Storing of maintenance procedures as well as all warranty information by component.
- Storing of all technical documentation or procedures by component.
- Real-time reports of ongoing work activity.
- Calendar- or run-time-based preventive maintenance work order generation.

- Capital and labor cost tracking by component as well as shortest, median, and longest times to close a work order by component.
- Complete parts and materials inventory control with automated reorder capability.
- PDA interface to streamline input and work order generation.
- Outside service call/dispatch capabilities.
- Management of permit-to-work (PTW), lockout-tagout (LOTO) and other safety requirements. *(adapted)* (Wikipedia, 2010)
- Key Performance Indicators (KPI) *(adapted)*
- Mobile work order management with RFID *(adapted)* (Plate, Richter, & Muller, 2009)

The descriptions of CMMS above are similar to those from other sources that are too numerous to write down, thus seemingly representing a general perception of the features and characteristics of the system. To this end, some experts [for example, Prof. Jørn Vatn (via discussion) and Terry Wireman (as indicated above)] imply that CMMS is actually a misnomer for a system with the given attributes and it would rather be appropriate to refer to such a system as CMMIS. The inference is that the traditional CMMS is basically information-oriented and not management-oriented, and more features are required to be added to it to justify the acronym CMMS.

This point is buttressed by (Nyman & Levitt, 2001) as follows: "Note to maintenance professionals who follow the field: The generally accepted term for maintenance computer systems is Computerized Maintenance Management Systems (CMMS). Computerized Maintenance Management Information Systems (CMMIS) is preferred because current systems by design and by use are not, for the most part, used to manage maintenance but rather to inform about maintenance. Both acronyms are used in this text. The "I" is inserted into the CMMIS acronym to emphasize that a computerized support system is only an informational tool and is only one building block of an integrated maintenance excellence process."

The findings of a study conducted by Engineer's Digest in 1992 indicate that majority of organizations possessing and using a CMMS only used approximately 50% to 60% of it (Wireman, 1998). Yet another study reveals that a staggering 94.7 percent of plant maintenance managers feel they are not using their computerized maintenance management software system to its maximum capability, according to the results of a national CMMS survey conducted for *Reliable Plant* magazine by educator, consultant and author Kris Bagadia (Bagadia, 2006). It can be deduced, based on this and the aforementioned literature review, that the shortcomings of the CMMS are two folds: Incompleteness and mishandling of the incomplete entity.

2.2.3 Pros and cons of CMMS

CMMS (or EAM systems) have not been designed to improve plant performance, only the efficiency of the maintenance work force and records keeping. CMMS do not reduce failures or increase reliability by themselves, but play a vital role in optimizing the efficiency of work execution. A CMMS automates the writing of a work order, helps in planning and scheduling work, tracks work history and records all costs (Smith, 2008). Furthermore, Ricky Smith of Ivara Corporation in (Smith, 2008) says: "Most companies that I have visited claim to have no link between equipment reliability and their EAM system. I believe it is very important to link the two. The goal of those involved in equipment reliability should be asset performance, and EAM's were not built to help with that objective. Despite the fact that every good EAM provides very valuable capabilities, and virtually every large plant has implemented an EAM, plants continue to fall apart. I believe that most plant maintenance and operations groups have a huge opportunity to make a much bigger contribution to the bottom line, and the way to do it is to link their reliability efforts with their EAM system."

The position in the aforementioned literature review has been maintained earlier by another industry expert, Prof. Jørn Vatn, in a discussion where he said that the typical CMMS was not designed to perform analysis and cannot be used alone to optimize maintenance. He stated that data could rather be retrieved from it to perform analysis in a software package that has the capability.

In the same vein, Daryl Mather in (Mather, 2008) stated that though companies do achieve results in the apparently logical CMMS approach for problems relating to asset performance, they must consider the management of critical failures (which is centered on the reliability of the asset) if an asset management program is aimed at maximum cost-effectiveness over an assets life.

According to (Wireman, 1998), the lack of CMMS effectiveness is characterized by a collection of wrong actions, inactions, insufficiencies and inaccuracies listed as follows:

1. Lack of Maintenance Dedication
2. Poor or Incomplete Implementation
3. Lack of end user training on CMMS
4. Lack of sufficient resources
5. Inaccurate data in the CMMS
6. Not utilizing the data in the CMMS
7. Poorly configured CMMS
8. Poor acceptance by the organization

Failure of CMMS implementation, the second item among the list above, was considered in (Mather, 2003) to be of several different kinds, some of which may include:

- Cost overrun
- Time overrun
- Lack of end user usage of the system
- Failure to achieve promised benefits
- Even failure to become part of the everyday life of a corporation

Daryl Mather in (Mather, 2003) further presents the reasons for this implementation failure as:

1. Lack of understanding of the requirements of the assets that we are charged with managing. That is lack of definition of the business processes, current business rules and maintenance process in use.
2. Lack of executive support and "push"
3. Even more dangerous, lack of middle management support.
4. Lack of understanding of the benefits and implications of the implementation
5. Poor change management. (Continuance of "fiefdoms" within the organization.)
6. Lack of training in either the systems usage, or in the processes that we have, or have developed, to proceed in our maintenance mission.
7. Poor follow up on processes and impact of the implementation
8. Lack of cross department usage and or understanding (Lack of the internal client focus)

One of the reasons for "Failure to achieve promised benefits", the 4th bullet point among the ways by which CMMS implementation could fail (Mather, 2003), is according to (Dunn, 1997) attributable to the event of missing or ineffective feedback and control loops in the maintenance management process shown in Figure 5 below.

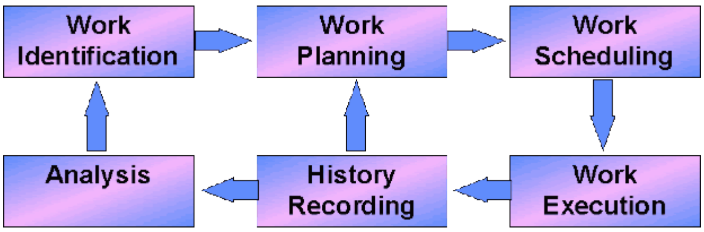

Figure 5: Maintenance Management Process (Dunn, 1997)

An typical example of a missing or weak link is seen in the following: In most CMMS as reiterated in (Dunn, 1997), the *history recording* phase lacks some necessary information (such as, the number of failures, the root causes of those failures, the maintenance costs associated with those failures, the production costs associated with failures, any safety or environmental costs associated with failures etc.); consequently, the *analysis* phase is not well-fed and fails to perform or performs failure analysis and RCM analysis ineffectively.

2.3 A Review of Other Maintenance Database Solutions

This section's focus is on other existing maintenance database solutions that have been designed to perform analysis on reliability data with the aim of refining maintenance strategies. Some examples of such database solutions are described as follows.

KAMFER

This is a software package offered by AGR Field Operations to ensure cost-effective use of maintenance resources. Some of its features include criticality analysis, establishing technical hierarchy (plant structure), appropriating maintenance strategy, data transfer between it and a CMMS and data retrieval from other data sources.

A con of this software is its assessment of criticality based on consequence of failure (CoF) only rather than on the combination of probability/frequency of failure (PoF) and consequence of failure (CoF).

OptiRCM

This is a computerized tool developed by Prof. Marvin Rausand and Prof. Jørn Vatn, which uses a 3-step procedure to optimize maintenance intervals: (i) establishes the component performance (ii) establishes the system model and (iii) calculates the total cost (Rausand & Vatn, 2008). OptiRCM performs the quantitative part of interval optimization while it imports the qualitative (FMECA) part of the RCM analysis from MANIFER software. The inputs to the tool are: reliability parameters (failure rate/MTTF without maintenance, aging parameter and PF interval), cost figures (corrective maintenance cost, preventive maintenance cost and inspection cost), TOP events safety and punctuality, barriers and barrier probability against the TOP event, and generic probabilities for each end consequence *(Vatn, Hva er RAMS, og hvordan bruke RAMSmetodikk i vedlikeholdsplanlegging?, 2008)*. OptiRCM is currently being applied by the Norwegian National Railway (NSB) and the Norwegian National Rail Administration (JBV). The software is still undergoing development and it is hoped that in future it would incorporate additional features such as more maintenance-strategy-related methods and grouping of maintenance tasks (Rausand & Vatn, 2008). In a discussion with Prof. Jørn Vatn (one of the developers), he affirmed that it is possible to create an integrated framework made up of OptiRCM, MANIFER and CMMS, although the inventors had yet to consider it. Figure 6 below shows how a typical OptiRCM screen appears.

A con of this tool appears to be its not cutting across industries, being tailored specifically to railway application.

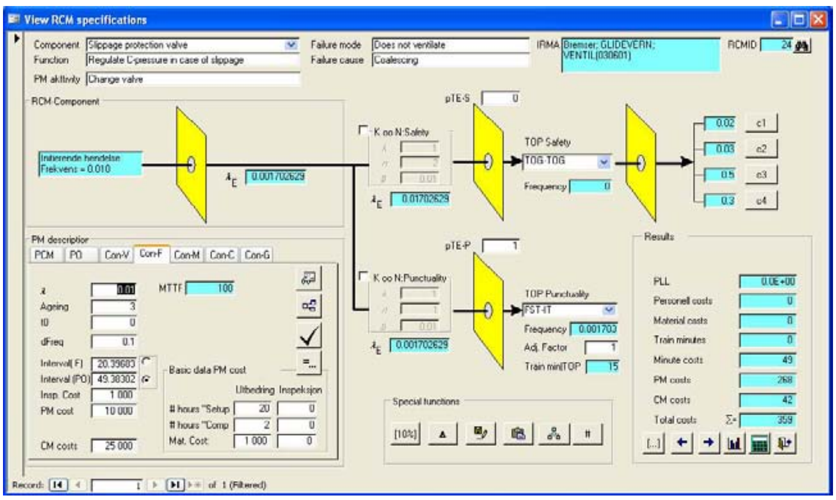

Figure 6: OptiRCM input and analysis screen (Rausand & Vatn, 2008)

BI-Cycle Software

According to Bi-Cycle BV, this is an integrated software package in the Enterprise web portal, containing the following tools (Bi-Cycle, 2010):

BI-Cycle Plant Information Data Mart: "This Data Mart resides on the main Data Warehouse BI platforms such as SAP BW, Oracle and Microsoft SQL Server. The Data Mart prepares Plant Information for standard OLAP reporting and fast Analysis. The data are extracted from the operational databases, such as the Maintenance Management System, the Opportunity Loss Database, Condition Monitoring and more. The BI-Cycle Data Mart comes with a Configuration tool to manage and optimize the Data Mart."

BI-Cycle RCM Analysis Tool: "This tool allows the Maintenance Engineer to analyze the data stored in the Data Mart. Reliability statistics including Weibull Analysis and Failure Prediction is standard functionality of the BI-Cycle Analysis Tool. The BI-Cycle Analysis Tool supports the RCM and LCC/LCP decision-making process, pointing to effective maintenance tasks at efficient intervals. This way the user can produce a structured reliability study on a plant or group of equipment, based on its own history."

BI-Cycle KPI Management Tool: "The KPI Management Tool allows the customer to monitor Regulatory Compliance, Plant Performance and the Maintenance Planning and Scheduling. It gives complete control over (Key) Performance Indicators and builds intuitive Digital Dashboard and Balanced Score Cards Web Reports. It is used by customers to build systems such as Asset Information Management, Enterprise Performance Tracking, Asset Performance Management and Mechanical Integrity Management."

Bi-Cycle BV further claims that the implemented maintenance decisions are stored in an Oracle database such that a link to the ERP/MMS is preserved and that their reference customers include Total, BP, Repsol, Arkema, Premcor, Vattenfall, Danisco, seadrill and statnett. Figure 7 below is a schematic of the network of elements comprising the Bi-Cycle software.

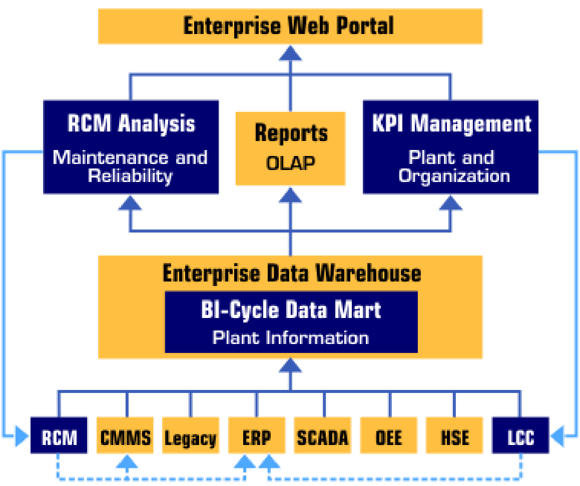

Figure 7: The Bi-Cycle Software (Bi-Cycle, 2010)

I have yet to see a demo version of this software. The descriptions of the software are yet unverified claims of the vendor. However, the software looks interesting although it does not account for spare-parts-strategy optimization.

RCM++

This software, according to the developer-Reliasoft (Reliasoft, 2010), "provides a flexible and intuitive interface for defining your system configuration and recording the functional failure analysis. The software tool includes configurable equipment selection, failure effect categorization and maintenance task selection capabilities. RCM++ also provides simulation-based calculations that can be used to compare the costs of potential maintenance strategies and a calculator to estimate the optimum maintenance interval for preventive repairs/replacements." The summary of the aforementioned features are presented by Reliasoft as follows (Reliasoft, 2010):

Equipment Selection: "In order to focus resources where they can provide the greatest benefit, RCM++ supports two configurable methods for selecting the equipment that will be analyzed with RCM techniques: Selection Questions (yes/no) and Criticality Factors (rating scales)."

Failure Effect Categorization and Maintenance Task Selection Logic Charts: "RCM++ supports the Failure Effect Categorization (FEC) and Maintenance Task Selection logic charts in the major industry RCM standards and also provides the ability to customize the questions and categories to meet specific application needs. Analysts can use these logic charts to categorize the effects of failure and then to select the maintenance tasks that will be applicable and effective."

Optimum Maintenance Interval and Operational Cost Comparisons: "RCM++ goes beyond calculations based on MTBFs and the often-inappropriate assumption of an exponential failure distribution. Analysts can use the Weibull, exponential, normal, lognormal or mixed Weibull distributions to describe the equipment's failure behavior and then use the same powerful calculation and simulation engines that are available in ReliaSoft's *BlockSim software* to estimate the optimum maintenance interval and to compare the operational costs of various maintenance strategies."

Maintenance Task Packaging: "RCM++ makes it easy to group individual tasks into packages based on interval, labor crew, etc. Both manual and automated packaging options are available."

Reports, Charts and Queries: "RCM++ provides a complete set of print-ready reports for your analysis, which can be generated directly in Microsoft Word® or Excel®. The software also provides a variety of Pareto (bar), pie and matrix charts to demonstrate the analysis information graphically; as well as a flexible query utility."

Figure 8 below shows the appearance of a typical RCM++ tool.

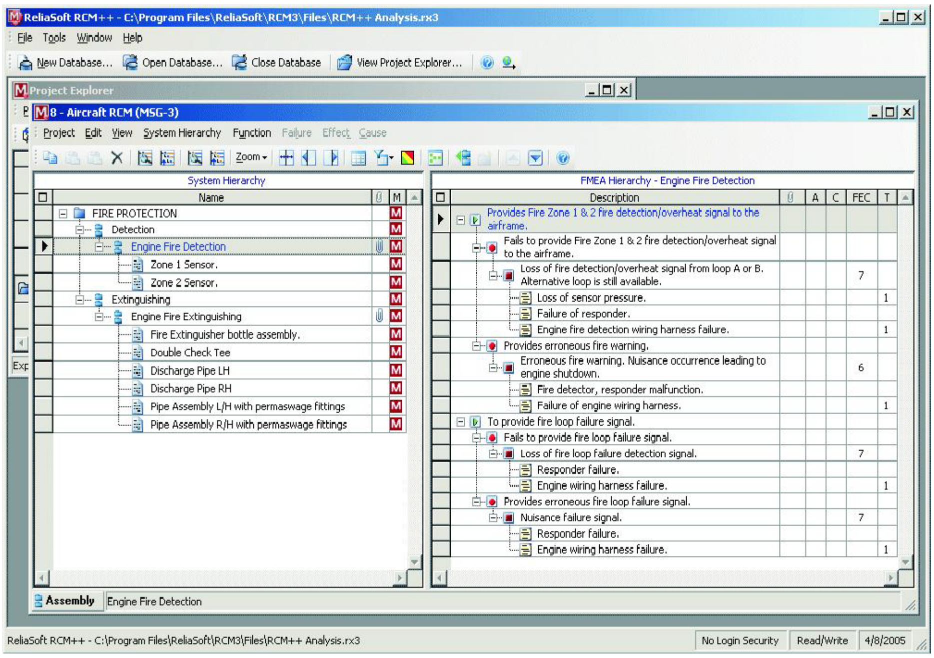

Figure 8: RCM++ Interface (Reliasoft, 2010)

I have yet to see a demo version of this software. The descriptions of the software are yet unverified claims of the vendor. However, the software looks interesting among RCM tools.

Meridium APM Software and RCMO Software

Meridium Asset Performance Management (APM) software is developed by Meridium Inc. (Meridium, Inc., 2010). In the words of the company: "Meridium (APM) improves the performance of production assets with effective asset strategies based on best practices, rigorous analytics and plant history. Meridium APM software also aligns key performance indicators with corporate goals and provides critical analyses to decision makers about their production assets on an enterprise, plant, system, equipment, and component level." The company re-iterates that Meridium accomplishes the aforementioned functions by (Meridium, Inc., 2010):

- Identifying critical manufacturing assets by assessing risk to environmental, safety and production targets.
- Measuring performance of assets through advanced analytical and simulation techniques utilizing data from EAM or CMMS and operational sources.
- Defining and establishing optimal maintenance and operational strategies for assets in EAM or CMMS and other applications.
- Providing the framework and capabilities to apply best practices across the enterprise.
- Ensuring continuous improvement and sustainment of best practices.

According to (Meridium, Inc., 2010), the software is multi-staged, consisting of the following stages and corresponding modules: *Strategy Development stage* (RCM & FMEA module and Risk Based Inspection module), *Strategy Management stage* (asset strategy implementation module and asset strategy management module), *Strategy execution stage* (calibration management module, inspection management module, operator rounds module and thickness monitoring module), *strategy evaluation stage* (generation management module, metrics and scorecard module, reliability analytics module and root cause analysis module) and *APM framework* (provides the infrastructure for the business processes supported by the individual Meridium modules to create a fully integrated system)

RCMO (Reliability Centered Maintenance & Optimization for SAP) is another tool from, which the company says, is “an RCM solution integrated with SAP” that (Meridium, Inc., 2010):

- Provides the framework for you to define maintenance strategies based upon RCM and Failure Modes and Effects Analysis (FMEA) principles.
- Integrates the recommendations from an RCM analysis into SAP Maintenance Plans in SAP.
- Drives automated re-evaluation of maintenance strategies to ensure effectiveness is constantly measured for continuous improvement.

I have yet to see a demo version of this software. The descriptions of the software are yet unverified claims of the vendor. However, the software looks interesting although it does not account for spare-parts strategy optimization.

OREDA Software

This is a combination of data collection, data acquisition and data analysis software developed by OREDA (a project organization that maintains a comprehensive database of reliability data collected from different offshore installations worldwide). The data are collected by software and stored in a database covering 270 installations, 16 000 equipment units with 38 000 failure, 68 000 maintenance records and subsea fields with more than 2100 well-years operating experience. The data are retrievable unreservedly by OREDA member companies (BP, ConocoPhillips, Eni, ExxonMobil, Gassco, Shell, Statoil and Total) and temporarily by contractors to OREDA companies, through the use of search and analysis software. The data are recorded against a corresponding owner and installation. Every single item (e.g. a gas turbine) is stored in a single inventory record in the database. This record is characterized by a technical description (e.g. manufacturer information) and operating and environmental conditions. All failure events for each inventory are stored and identified individually by the following details: item name, failure date, failure impact, failure mode, failure cause etc. The maintenance records keep data on corrective maintenance linked to the corresponding failure record, and data on preventive maintenance linked to the corresponding inventory record (OREDA, 2009). Some of the data analysis features include lifetime analysis, frequency analysis and cumulative analysis (OREDA, 2009). Important features of the OREDA package are shown in figures 9, 10 and 11 below.

A very strong plus for this database is its being readily empowered by a large historical failure data source.

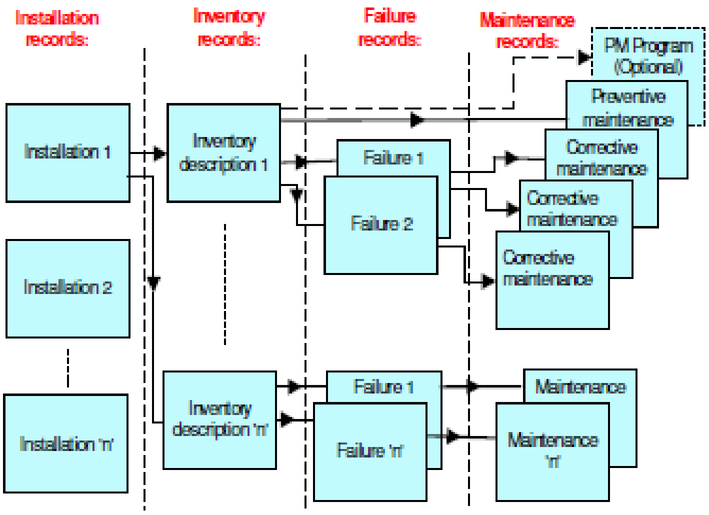

Figure 9: Databank Structure (OREDA, 2009)

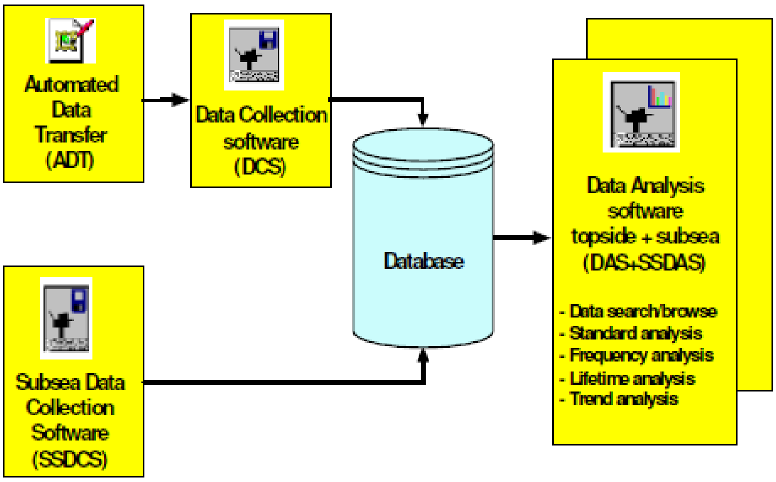

Figure 10: Main Software Modules (OREDA, 2009)

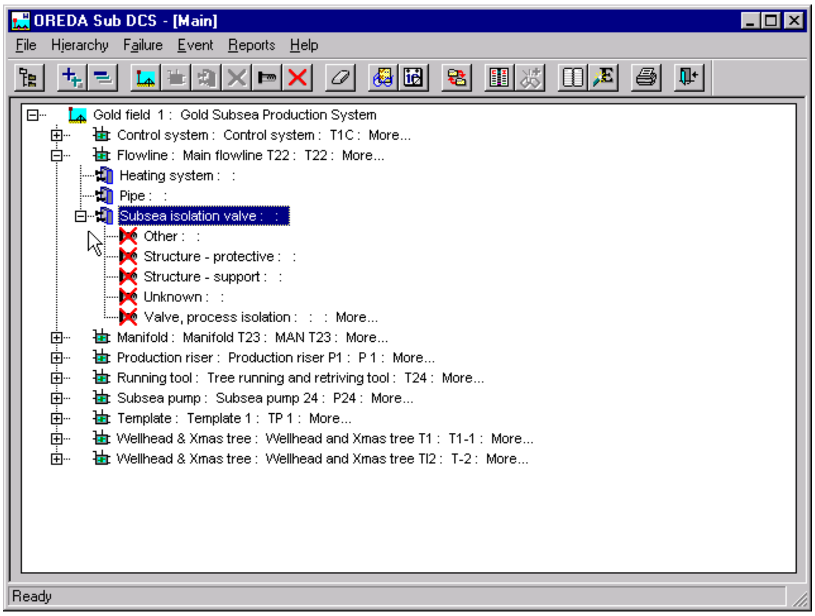

Figure 11: OREDA Data Collection Software-Subsea (OREDA, 2009)

Figures 9 (OREDA database) and figure 11 (OREDA subsea data collection software) are integral parts of figure 10 (OREDA main software modules). Figure 10 represents the complete OREDA software package.

More Database Solutions

Some other database solutions in the form of RCM tools are shown in the following table (UPM & Adepa, 2000).

Table 2: Some RCM tools currently used by maintenance teams (UPM & Adepa, 2000)

Web Link	Name of the tool	Company	Software kind	Restrictions	Interesting?
Demo FMECA Manager	**FMECA Manager**	Baas&Roost	RCM	CD demo	****
DemoWINMBF	**WinMBF**	Corim Solutions	RCM	CDdemo	****
Http://www.nalda.navy.mil	**IRCMS 6.0**	*US Navy*	RCM+LCC	Software	****
Http://www.powertechnic.com.au	**Analyst**	*Powertechnic Pty Ltd*	LCC	demo	**
Http://www.itemsoft.com	**AvSim**	*Item Software*	LCC+Reliability	CDdemo	*
Http://www.itemsoft.com	**LCC Ware**	*Item Software*	LCC	CDdemo	***
Http://www.itemsoft.com	**Reliability Workbench**	*Item Software*	RCM	CDdemo	**
Http://www.itemsoft.com	**RCMcost**	*Item Software*	RCM+LCC	CDdemo	****
Http://www.itemsoft.com	**Hazop Plus**	*Item Software*	RCM	CDdemo	**
Http://www.itemsoft.com	**Failmode**	*Item Software*	RCM	CDdemo	**
Http://www.itemsoft.com	**TelStress**	*Item Software*	Reliability	CDdemo	**
Http://www.bqr.com	**CARE**	*BQR Reliability Engineering Ltd.*	RCM	demo	**
Http://www.udc.net	**Gtrack**	*United Dynamics "AT"*	RCM	demo	***
Http://www.barringer1.com	**LCC Modelling**	*Barringer and Associates*	LCC	freeware	**
Http://www.pragma.co.za	**ON KEY Analyser**	*PRAGMA*	RCM	demo	**
Http://www.relexsoftware.com	**Relex**	*Relex Software Corp.*	RCM+LCC	demo	**
Http://www.ozemail.com.au	**TDBU**	*Maint. Management Sol.*	RCM	demo	**
Http://www.zip.com.au	**RCM Turbo**	*Strategic*	RCM	X	
Http://www.fractalsoln.com	**Software in Reliability**	*Fractal Solutions*	RCM	X	
Http://www.aladon.co.uk	**Aladon Limited**	*Aladon*	RCM	X	
Http://www.jmssoft.com	**Some Products**	*Jmsoft*	RCM	X	
Http://www.fmeca.com	**FMEA tools**	*Haviland Consulting*	RCM	demo	**
Http://www.lincolntechnology.co	**Reliability Imp. Software**	Lincoln technologies	RCM	X	
Http://www.logistic.com.au	**Omega PS RCM**	*Logistic*	RCM	X	
Http://manufacturing.software-directory.com	Ivara.EXP	*Ivara corporation*	RCM	X	

The following table summarizes all the main functionalities of each software, which are (UPM & Adepa, 2000):

- F1: Study of the criticality of the “equipment” in its context.
- F2: Study of the LCC aspect of the “equipment” in its context.
- F3: A FMECA analysis is proposed.
- F4: Study of the task with a logic decision tree.
- F5: Study of the maintenance programme with a cost aspect (benefits)
- Fi: Others functionalities

Table 3: Main functionalities of aforementioned RCM tools (UPM & Adepa, 2000)

Name of the tool	F1	F2	F3	F4	F5	Fi
FMECA Manager	*High*	*	*High*	*Lower*	*	*
WinMBF	*High*	*Lower*	*High*	*Lower*	*Medium*	*
IRCMS 6.0	*Medium*	*	*High*	*Medium*	*	*
Analyst	*	*High*	*	*	*	*
AvSim	*	*	*	*	*	*MonteCarlo Sim*
LCC Ware	*	*High*	*	*	*	*
Reliability Workbench	*	*	*High*	*	*	*Failure Tree*
RCMcost	*Lower*	*Lower*	*High*	*Medium*	*Medium*	*
Hazop Plus	*Medium*	*Lower*	*High*	*	*	*
Failmode	*Medium*	*	*High*	*	*	*
TelStress	*	*	*	*	*	*Reliability pred.*
CARE	*High*	*Lower*	*Medium*	*Medium*	*High*	*MTTR MTBF*
Gtrack	*	*	*Medium*	*	*	*
Life Cycle Cost Modelling	*	*High*	*	*	*	*
ON KEY Analyser	*Medium*	*Medium*	*High*	*Medium*	*Medium*	*
Relex	*High*	*Lower*	*High*	*Lower*	*High*	*Failure Tree*
TDBU	*High*	*Medium*	*High*	*High*	*Medium*	*
RCM Turbo	*Lower*	*	*High*	*High*	*Medium*	*
Software in Reliability	*	*	*Medium*	*	*	*
Aladon Limited	*High*	*	*High*	*Lower*	*	*
FMEA tools	*Lower*	*	*High*	*	*	*
Reliability Improvement Software	*Medium*	*Medium*	*High*	*High*	*High*	*
Omega PS RCM	*High*	*	*High*	*	*	*
Ivara.EXP	*Medium*	*Medium*	*High*	*High*	*Medium*	*

2.4 Conclusion

The reason I considered only the aforementioned database solutions is because there are several of such products in existence and analyzing every one of them is impracticable due to time and space constraints. The main idea is the need for the integration of CMMS with good analytical software for a comprehensive maintenance solution.

3. HOW CRITICALITY BASED ON NORSOK Z-008 AND RCM LOGIC CAN BE IMPLEMENTED IN A MAINTENANCE CONCEPT

3.1 Background

The benefits of an RCM analysis is not experienced to the fullest by an organisation, if the RCM is not applied only on a prioritized list of equipment and systems that will yield optimal return from it. Yet, in order to identify such equipment and systems we have to rely on the screening and prioritization criteria called criticality ranking.

3.2 Criticality

Criticality, according to the military standard, is defined as "a relative measure of the consequences of a failure mode and its frequency of occurrences" (MIL-STD-1629A, 1980).

Criticality analysis, according to the military standard, is "a procedure by which each potential failure mode is ranked according to the combined influence of severity and probability of occurrence" (MIL-STD-1629A, 1980).

Criticality analysis, according to the British standard, is "a quantitative analysis of events and faults and the ranking of these in order of the seriousness of their consequences" (BS 3811, 1993).

Criticality assessment according to (Healy, 2006) "is a structured methodology that provides a proactive approach for the assessment of risks in the organisation."

Critical equipment as defined by (Smith & Mobley, 2007) "is that equipment whose failure has the highest potential impact on the business goals of the company."

Criticality, in my opinion, indicates the risk associated with the event of equipment failure, where risk, according to (ISO 17776, 2000) is "combination of probability of an event and the consequence of the event." Hence equipment with the highest criticality are those whose failures will have negative impact on Health, Safety and Environment (HSE).

3.3 Description of NORSOK Standard Z-008

3.3.1 Description of Draft NORSOK Z-008:2009

The purpose of this standard titled "Risk based maintenance and consequence classification" is to provide requirements and guidelines for:

- Consequence classification of equipment
- How to use consequence classification in maintenance management
- How to use risk analysis to establish and update preventive maintenance programmes
- How to aid decisions related to maintenance using the underlying risk analysis

This standard considers risk elements in the following categories:

- Risk related to personnel
- Risk related to environment
- Risk related to production loss
- Risk related to direct economic cost (everything other than cost of production loss)

The latest draft of this standard - *revision 3 (2009)*, substitutes the term "criticality analysis" in *revision 2 (2001)* with "consequence classification". The reason for the change is the conflicting use of criticality analysis in the industry, where some people use it to describe a consequence analysis while others use it to describe a risk (probability/frequency and consequence) analysis. The *revision 2 (2001)* of the standard used criticality analysis based on BS 3811 to describe consequence analysis.

The Draft NORSOK Standard Z-008, as regards applicability, is intended for preparation and optimization of maintenance activities for plant systems and equipment including: offshore topside systems, subsea production systems and oil and gas terminals. It also recommended for systems consisting of the following types of equipment: Mechanical equipment (static equipment, rotating equipment and piping), instrumentation and electrical equipment. However, load-bearing structures, floating structures, risers and pipelines are not considered in this standard. All types of failure modes and failure mechanisms are covered by the standard.

The Draft NORSOK standard covers:

- Definition of relevant nomenclature
- Brief description of main work flow related to maintenance and which elements this typically involves.
- Definition of risk model and failure consequences classes
- Guidelines for consequences classification, including:
    - Functional breakdown of plants and plant systems in main functions and sub functions.
    - Identification of main function and sub function redundancy.
    - Assessment of the consequences of loss of main functions and sub functions.
    - Assignment of equipment to sub functions and associated consequence classes.
- Description of how to establish an initial maintenance programme, and how to update an existing programme.
- Description on how to use the classification for decision making related to prioritization of work orders and handling of spare parts.

3.3.2 Difference between NORSOK Z-008:2001 and Draft NORSOK Z-008:2009

Some differences between the aforementioned documents are stated as follows:

- NORSOK Z-008:2001 is titled “Criticality analysis for maintenance purpose” while Draft NORSOK Z-008:2009 is titled “Risk based maintenance & consequence classification”
- In NORSOK Z-008:2001, criticality is based on consequences of failures only, while in Draft NORSOK Z-008:2009, criticality is based on both consequence of failure and probability/frequency of failure.

3.3.3 Motivation for Using Draft NORSOK Z-008:2009 for This Thesis

My main motivation for using Draft NORSOK Z-008:2009 instead of NORSOK Z-008:2001 are:

- Provision for the application of risk analysis (risk decision matrix) which translates consequence and frequency of failure to criticality.
- The flexibility of the risk decision matrix, which can be used in maintenance and inspection planning, classification, prioritization or work orders, spare parts location decision and for evaluation of risk in other areas within an organization.

Regarding criticality analysis, I share the opinion of Ramesh Patel in (Patel, 2005) that a combined report on prioritized risks (combination of probability and consequence of failure) and a prioritized list of equipment by both probability of failure only and consequence of failure only will enable an organization to focus on the specific issues that increase total risk, and to understand whether total risk is driven primarily by probability of failure or primarily by consequence of failure. Such an understanding will help in the making of informed decisions about how to reduce risk levels associated with each piece of equipment.

3.4 Description of RCM and RCM Logic

This section will present a brief and concise description of Reliability Centered Maintenance (RCM) and RCM logic (i.e. maintenance task assignment/decision logic).

3.4.1 Reliability Centered Maintenance (RCM)

According to (Shiihara, 2008), Reliability Centered Maintenance (RCM) is “a common method of maintenance wherein maintenance procedures are arranged for each piece of machinery based on its failure pattern and reliability.” In the words of (Moubray, 1997), “Reliability-centred Maintenance (RCM) is a process used to determine, systematically and scientifically, what must be done to ensure that physical assets continue to do what their users want them to do.” On a generic note, IEC 60300-3-11 (IEC, 2010) defines RCM as a “systematic approach for identifying effective and efficient preventive maintenance tasks for items in accordance with a specific set of procedures and for establishing intervals between maintenance tasks.” It is widely recognized by maintenance professionals as the most cost-effective way to develop world-class maintenance strategies (Moubray, 1997). RCM generally leads to a prioritization of maintenance tasks based on some indices that indicate equipment condition and the equipment importance (PSERC, 2006).

Benefits of RCM

RCM leads to speedy, sustained and substantial improvements in (Moubray, 1997):

- Plant availability and reliability
- Product quality
- Safety and environmental integrity

The Seven Fundamental Questions of RCM Process

According to the SAE JA1011 (SAE, 1999), the minimum criteria that any RCM process must fulfill in order to be a true RCM process, is to be able to answer the following seven questions:

1. What are the functions and associated desired standards of asset in its present operating context?
2. In what ways can it fail to fulfill its functions? (functional failures)
3. What causes each functional failure? (failure modes)
4. What happens when each failure occurs? (failure effects)
5. In what way does each failure matter? (failure consequences)
6. What should be done to predict or prevent each failure? (proactive tasks and task intervals)
7. What should be done if a suitable proactive task cannot be found? (default actions)

RCM Analysis Process

Although a number of variations exist in the application of RCM today, any credible RCM analysis process must satisfy the stipulations of SAE JA1011 above. The following is an abridged approach from (Rausand & Vatn, 2008) and (Vatn, 2007).

1. Study preparation
2. System selection and definition
3. Functional failure analysis (FFA)
4. Data collection and analysis
5. Failure modes, effects and criticality analysis (FMECA)
6. RCM decision logic tree analysis *(adapted)*
7. Determination of maintenance intervals
8. Preventive maintenance comparison analysis
9. Treatment of non-critical items
10. Implementation
11. In-service data collection and updating

Step 1: Study Preparation

This involves preliminary work done preparatory to the actual RCM analysis process. This includes setting up a cross-functional team composed of maintenance personnel, operations personnel and an RCM expert. The objectives, scope of the analysis and boundary conditions are defined at this stage which also involves the collection and review of relevant system information. The main goals of an RCM analysis are to (Rausand & Vatn, 2008):

1. Identify maintenance tasks that are effective
2. Evaluate the cost-effectiveness of these tasks, and
3. Develop a plan for executing the identified, cost-effective maintenance tasks at optimal intervals.

According to (Nilsen & Christensen, 2010), to benefit from the RCM analysis process, "the objective should be to ensure that critical system functions are analysed, unnecessary analysis work is eliminated and relevant generic maintenance tasks are considered.

Step 2: System Selection and Definition

RCM analysis takes time and resources. So, an unwise application (i.e. on every piece of equipment) will lead to cost overruns rather than savings. Hence, it is advisable to perform it only on equipment or levels of assembly (plant, system, subsystem) that will yield dividends from it (Rausand & Vatn, 2008).

The system selection may be based on the following criteria (Rausand & Vatn, 2008):

- The consequences of potential system failures must be considerable in terms of safety, environmental impact, production loss, quality loss *(adapted)*, or maintenance cost.
- The complexity of the system must be reasonably large.
- Information on reliability and operation of the actual system (or similar systems) should be available.

The system selection and definition is supported by the establishment of a technical (or assembly) hierarchy (i.e. plant structure), *for e.g.*, Plant-systems-subsystems-and-so-on levels (Rausand & Vatn, 2008).

Step 3: Functional Failure Analysis (FFA)

This step involves the following sub-steps (Rausand & Vatn, 2008):

- *Identifying system functions:* Classification of functions as essential, auxiliary, protective, information, interface and superfluous functions or online and offline functions.
- *Identifying potential functional failures (i.e. failure modes):* Complete failure to perform a function, under-performance of function, over-performance of function or performance of an unintended function.
- *Identifying functional failure effects (or consequences) and establishing criticality ranking based on this and the probability/frequency of functional failure for every operational mode:* This aims to set a threshold for further analysis by eliminating insignificant functional failures.

- *Identifying Functional Significant Items (FSI):* FSIs are potentially critical items at the functional failure level. They may be identified with or without formal analysis depending on the nature of the system, whether simple or complex. Formal analysis may involve the use of fault tree analysis (FTA) or reliability block diagram (RBD) to calculate the relative importance of each analysis item, if comprehensive failure data are available.
- *Identifying Maintenance Cost Significant Items (MCSI):* Failure and maintenance data (e.g. high failure rate, high repair costs, low maintainability, long lead-time for delivery of spare parts, level of dependence on external maintenance support etc.) are considered for this classification.
- *Listing Maintenance Significant Items (MSI):* This is the resulting list from the combination of FSIs and MCSIs.

A proposed FFA worksheet, suitable for preliminary screening, in order to save time and money, is shown as follows.

Table 4: Functional Failure Analysis (FFA) worksheet

System: *Performed by:*
Ref. Drawing No: *Date:* *Page: of:*

							Criticality			
Opera-tional mode	Function	Function require-ments	Functional Failure	Evident or Hidden Function	MSI	Freq-uency	HSE	Production Volume	Quality	Maint-enance Cost

The task of column 2 (listing of relevant functions) of the FFA worksheet above could be made easier by applying the function selection decision tree shown in figure 12 below.

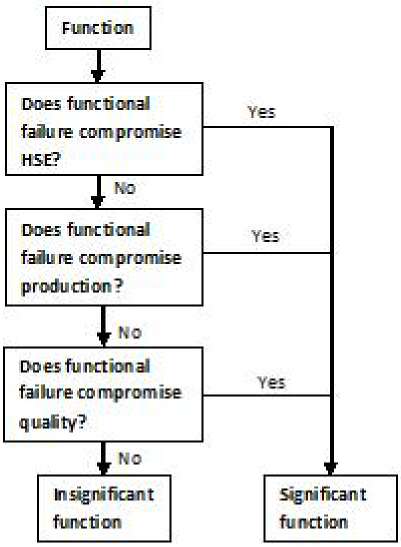

Figure 12: Significant function selection logic tree (NAVAIR 00-25-403, 2005) ***(adapted)***

The functional failure (in column 4 of the FFA) should be considered as significant, if the criticality falls within the category range A to F in the following proposed quick criticality rating:

Table 5: Criticality rating applied in Functional Failure Analysis (FFA)

Criticality	**Description**
Criticality **A**	Failure of equipment compromises HSE (HSE-critical) without redundancy.
Criticality **B**	Failure of equipment does not compromise HSE, but stops production (Production-critical) without redundancy.
Criticality **C**	Failure of equipment does not compromise HSE and does not stop production, but reduces quality (quality-critical) without redundancy.
Criticality **D**	Failure of equipment has no effects on HSE and production and quality, but cost of maintenance is above NOK10K (Maintenance-critical) without redundancy.
Criticality **E**	Equipment is HSE-critical/production-critical/quality-critical/maintenance-critical and full redundancy exists.
Criticality **F**	Equipment is HSE-critical/production-critical/quality-critical/maintenance-critical and partial redundancy exists.
Criticality **G**	Failure of equipment has no effects on HSE and production and quality, but cost of maintenance is below NOK10K (mostly run to failure)

Redundancy identification: The identification of redundancy in HSE-critical, production-critical, quality-critical or maintenance-critical systems is important in order to classify a given system in an appropriate criticality category in Table 5 above. This could be realized through the application of the decision tree shown in figure 13 below.

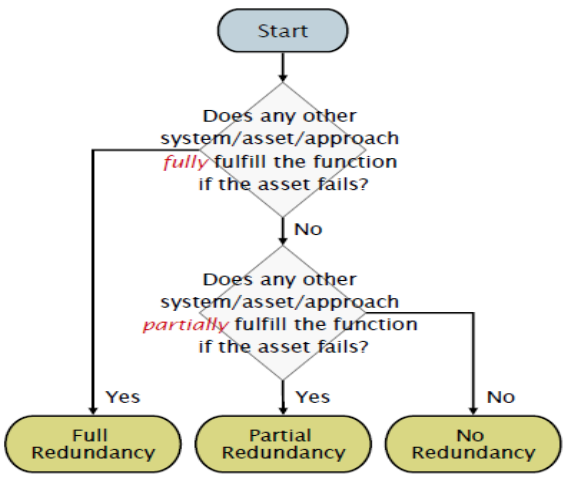

Figure 13: Determining redundancy (USEPA, 2008)

If the criticality does not fall within the range of Table 4 above, but the frequency of failure is medium or high, the functional failure should be considered for further analysis although with less priority compared to the significant functional failure case.

Safety-critical systems: They are systems that have the potential to pose a serious risk to the safe operation of the whole facility, *e.g.,* (1) structural integrity systems, (2) ignition control systems, (3) process containment systems, (4) fire, smoke, gas detection systems, (5) fire protection systems, (6) shutdown systems, (7) blowdown and relief systems, (8) emergency response systems, (9) life saving systems, (10) blast walls, (11) Heating, Ventilation and Air Conditioning (HVAC) systems, (12) Communication systems and (13) blow-out prevention systems (HSE, 2009). For the listed safety-critical systems, recognized and accepted by Health & Safety Executive (HSE) UK, it is not necessary to do, *for e.g.*, an RCM, RBI or FMECA to determine whether the system is critical or not.

Production-critical equipment: They are equipment that have the potential to cause loss of production time or reduction in production availability, *e.g.,* separators, pumps, turbine, compressors etc.

Quality-*critical systems:* They are systems in which certain deviations would lead to non-conformance to specifications - a quality issue that may become tied to loss of reputation, legislative implications or legal actions. Such systems may be software systems integrated with all types of computer systems used in manufacturing such as, Programmable Logic Controllers (PLCs), Personal Computers (PCs), Process Computers and networked systems (Margetts, 1991). The systems may be involved in the control of variables in continuous processes, batch processes or materials handling operations (Margetts, 1991).

Step 4: Data Collection and Analysis

This step involves gathering and analyzing information and data for further qualitative and quantitative analysis. The qualitative analysis covers relevant failure modes and failure causes, while the quantitative analysis encompasses reliability quantities such as MTTF, ageing parameter, PF intervals etc. The data needed for RCM analysis may be classified as follows (Rausand & Vatn, 2008):

1. *Design data:* This includes (i) information on system boundaries description with respect to main functions fulfillment, (ii) decomposition of systems to form a technical hierarchy, (iii) technical detailing (e.g., subsystem structure, capacity, functions etc.) of all subsystems, (iv) requirements for system performance (e.g., operational and environmental requirements), (v) requirements for system maintenance/testing (e.g., as contained in rules, regulations and instructions accompanying manufacturers manuals).
2. *Operational and failure data:* This includes (i) operating profile (e.g., operating temperature and continuous or intermittent operations) (ii) environmental conditions (iii) maintainability (iv) control philosophy (e.g. manual or automatic and remote or local), (v) calendar time and accumulated operating time for preventive

maintenance, (vi) Maintenance and downtime cost, (vii) Performance requirements, (viii) failure information (e.g., failure rates, failure causes and failure consequences), (ix) recommended maintenance for individual analysis items based on manufacturers advice, industrial best-practice or internally prescribed practice.

3. *Reliability data:* These may be obtained from the operational and failure data with the help of statistical analysis. Further analysis with tools such as the exponential model, the weibull model etc. gives the failure probability that may be combined with the quantified failure consequence to give a picture of the criticality. The criticality is used as a basis for prioritization and optimization of maintenance. Reliability data also contribute to maintenance optimization in terms of maintenance interval optimization by being applicable mathematically in failure process modeling.

Step 5: Failure Modes, Effects and Criticality Analysis (FMECA)

This step serves as an input to step 6 in which RCM decision logic will be used to select appropriate maintenance actions.

Step 5 aims to: (i) Identify significant failure modes of the MSIs treated in step 3, (ii) Analyze the effects of the failures on the system and (iii) Recommend measures to eliminate the failures or reasonably reduce their effects on the system.
According to (MIL-STD-1629A, 1980), *Failure Mode and Effects Analysis (FMEA)* is "a procedure by which each potential failure mode in a system is analyzed to determine the results or effects thereof on the system and to classify each potential failure mode according to its severity" while *Criticality Analysis (CA)* is "a procedure by which each potential failure mode is ranked according to the combined influence of severity and probability of occurrence." *Failure Mode, Effects and Criticality Analysis (FMECA)* is hence the combination of *FMEA* and *Criticality Analysis* (MIL-STD-1629A, 1980).

An FMECA worksheet, customized and intended to serve as a source of information for the RCM decision logic and maintenance interval optimization, is shown in Table 6 below.

Table 6: FMECA worksheet

System: *Performed by:*
Ref. Drawing No: *Date:* *Page:*
of:

Description of units			Description of failure			Failure Effect		Failure Rate	Repair Rate	α	Criticality				Risk Reduc-ing Measure
Ref No.	Func-tion	Opera-tional mode	Failure Mode	Failure Cause	Detection of failure	On sub-system	On system function				HSE	Prodtn Volume	Qual-ity	Maint Cost	

A recommendation by (SAE JA1012, 2002), advises that "failure modes should be described in enough detail for it to be possible to select an appropriate failure management policy, but not in so much detail that excessive amounts of time are wasted on the analysis process itself."

Criticality analysis may be used to prioritize risks by virtue of *Risk Priority Number (RPN)*. The *RPN* is the product of detectability (D), severity (S) and occurrence (O). Each quantity is usually on a scale of 1 to 10. Hence, the highest *RPN* of 1000 (i.e. 10 x 10 x 10) means that the failure is not detectable by inspection, very severe and the occurrence is almost certain. If the occurrence is very unlikely, then O = 1 and the *RPN* would be reduced to 100. In summary, the aim of the analysis here is to reduce the RPN as much as possible for a safer operation.

Alternatively, Criticality analysis may enable prioritization of risks with the aid of a risk matrix. The risk matrix charts the frequency/probability of the failure mode against the consequences of the failure as shown in Table 7 below.

Table 7: Risk matrix used for classification and decisions

	Consequences				**Frequencies**				
					1	**2**	**3**	**4**	**5**
Severity	**HSE**	**Production Volume**	**Quality**	**Maintenance Cost**	**Very Unlikely**	**Remote**	**Occasional**	**Probable**	**Frequent**
5	Disastrous Impact	Disastrous Impact	Disastrous Impact	Disastrous Impact	**M**	**H**	**H**	**H**	**H**
4	Critical Impact	Critical Impact	Critical Impact	Critical Impact	**L**	**M**	**M**	**H**	**H**
3	Major Impact	Major Impact	Major Impact	Major Impact	**L**	**L**	**M**	**M**	**H**
2	Minor Impact	Minor Impact	Minor Impact	Minor Impact	**L**	**L**	**L**	**M**	**M**
1	Slight Impact	Slight Impact	Slight Impact	Slight Impact	**L**	**L**	**L**	**L**	**L**
0	No Impact	No Impact	No Impact	No Impact	**VL**	**VL**	**VL**	**VL**	**VL**

The risk scale (very low-VL, low-L, medium-M and high-H) or the corresponding color coding (green, blue, yellow and red) implicitly establishes risk acceptance criteria. The consequences are described in details in Table 8 below.

Table 8: Consequence classes description

Consequence	**Description**
Disastrous impact	Impact that leads to more than 3 fatalities/continuous extreme environmental degradation that will lead to economic loss over a wide area/sudden and total loss of production/extreme quality reduction in large quantity of products/maintenance cost in excess of 10 million NOKs.
Critical impact	Impact that leads to permanent total disability, or 1 to 3 fatalities/extreme environmental degradation that will require extensive measures for remediation/up to two weeks shutdown/substantial quality reduction in large quantity of products/maintenance cost between1 to 10 million NOKs.
Major impact	Impact that leads to long-term disabilities or chronic health impairment /substantial environmental degradation that will persist and require clean-up/up to one week shutdown/substantial quality reduction

	in substantial quantity of products/maintenance cost between 100,000 to 1 million NOKs.
Minor impact	Impact that leads to lost work days up to 5 days/minor environmental degradation with transient effect/partial shutdown/minor quality reduction in products/maintenance cost between 10,000 and 100,000 NOKs.
Slight impact	Impact that leads to first aid cases and medical treatment cases /slight environmental degradation that is contained within immediate location/brief stops or disruptions/insignificant quality reduction in products/maintenance cost below 10,000 NOKs.
No impact	No injury or health impairment/ no environmental impact/ no production stop/no quality reduction/no maintenance cost

The RPN or risk matrix is necessary to provide the input for the criticality column in an FMECA worksheet.

3.4.2 RCM Decision Logic Tree Analysis

This is step 6 of the RCM process outlined above and is intended to guide an RCM analyst through a query and answer process in which significant failure modes (from a prior FMECA - step 5) decide between the suitability of a preventive maintenance task and an intentional run-to-failure (RTF) for corrective maintenance (Rausand & Vatn, 2008).

It is advisable to enter the dominant failure modes and their corresponding failure mechanisms into the decision logic in order to obtain the most appropriate maintenance tasks from among the following (Rausand & Vatn, 2008):

- Redundancy deployment (RED) *(adapted)*
- Continuous on-condition task (CCT)
- Scheduled on-condition task (SCT)
- Scheduled overhaul (SOH)
- Scheduled replacement (SRP)
- Scheduled function test (SFT)
- Run to failure (RTF)

Redundancy deployment (RED) is the installation of active shared-load or stand-by redundant system in a situation of mission-critical assets for which no other approach is acceptable (Troyer, 1999). According to Wikipedia, "The term ***mission critical*** (or *mission-critical*) refers to any factor (equipment, process, procedure, software, etc.) which is essential to the core function of an organization. That is, it is critical to the organization's *mission*." The definition of degrees of redundancy could vary from one organization to another. An example of degrees of redundancy is shown in Table 9 below.

According to (Draft NORSOK Standard Z-008, 2009), in the case of safety systems or protective functions with redundancy due to functional reliability or regulatory requirements, the redundancy effect should not be accounted for. The standard also stipulates that compensating operational actions used to temporarily maintain a function can be described as redundancy and used for priority of operational actions.

Table 9: Example of degrees of redundancy definitions

Redundancy Class	Redundancy Description
A	No redundancy i.e. the probability of loss of function is required to be very low in the system.
B	Partial redundancy i.e. there is possibility of partial fulfillment of function in event of system failure
C	Full redundancy i.e. there is possibility of full fulfillment of function in event of system failure

Continuous on-condition task (CCT) is a continuous monitoring of an item to detect any potential failures. An on-condition task is applicable where it is possible to establish measurable quantities that are indicative of reduced failure resistance for a particular failure mode (Rausand & Vatn, 2008).

Scheduled on-condition task (SCT) is a periodic monitoring of an item to detect any potential failures. A scheduled on-condition task is applicable if the following three criteria are fulfilled (Rausand & Vatn, 2008):

1. Reduced failure resistance must be detectable for a particular failure mode.
2. A potential failure condition, detectable by an explicit task, should be definable.
3. The age interval between the time of potential failure and the time of failure must be reasonable and consistent.

Scheduled overhaul (SOH) is a scheduled repair of an item at or before some specified age limit. A scheduled overhaul is applicable if the following three criteria are fulfilled (Rausand & Vatn, 2008):

1. There exists an identifiable age at which the item shows a rapid increase in its failure rate function.
2. A considerable number of the units must survive to that age.
3. The original failure resistance of the item must be restorable.

Scheduled replacement (SRP) is a scheduled substitution of an item (or a part of an item) with another of integrity at or before some specified age limit. A scheduled replacement is applicable only if the following conditions exist (Rausand & Vatn, 2008):

1. The item must be prone to a critical failure.
2. Test data must indicate that no failures are expected to occur below the specified age limit.
3. The item must be prone to a failure of great economic (but not safety) consequences.
4. There exists an identifiable age at which the item shows a rapid increase in its failure rate function.
5. A considerable number of the units must survive to that age.

Scheduled function test (SFT) is a scheduled inspection of a hidden function to detect any failure. A scheduled function test is applicable in the following circumstances (Rausand & Vatn, 2008):

1. The item must be prone to a functional failure that is hidden to the operating crew during routines.
2. No applicable and effective alternative task is available for the item.

Run to failure (RTF) is an intentional decision to use an item without maintenance until it fails either because it is not maintainable or it is uneconomical to maintain it (Rausand & Vatn, 2008).

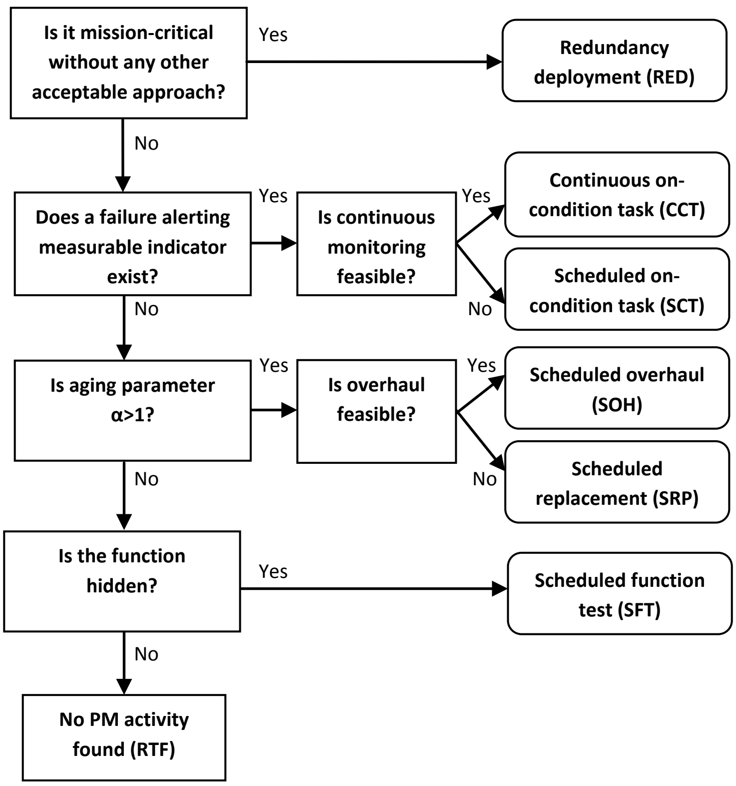

Figure 14: Maintenance task assignment/decision logic (Rausand & Vatn, 2008) ***(adapted)***

3.5 How Criticality Based on NORSOK Z-008 and RCM Logic Can Be Applied In a Maintenance Concept

Draft NORSOK Z-008:2009 recommends the use of a *system risk decision matrix* in maintenance and inspection, planning, classification and prioritization of work orders. It advises however that the risk matrix used for maintenance purposes should be harmonized with risk matrices used for risk evaluation in other areas of operation within an organization.

Draft NORSOK Z-008:2009 also recommends *maintenance interval optimization* consistent with MTTF, in addition to a *spare parts risk decision matrix* for *spare parts strategy optimization*.

These recommendations of Draft NORSOK Z-008:2009 are being integrated with RCM decision logic and other essential features to create a maintenance concept system called MCDS.

3.5.1 MCDS Maintenance Management Model

The MCDS maintenance management model is presented in figure 15 below.

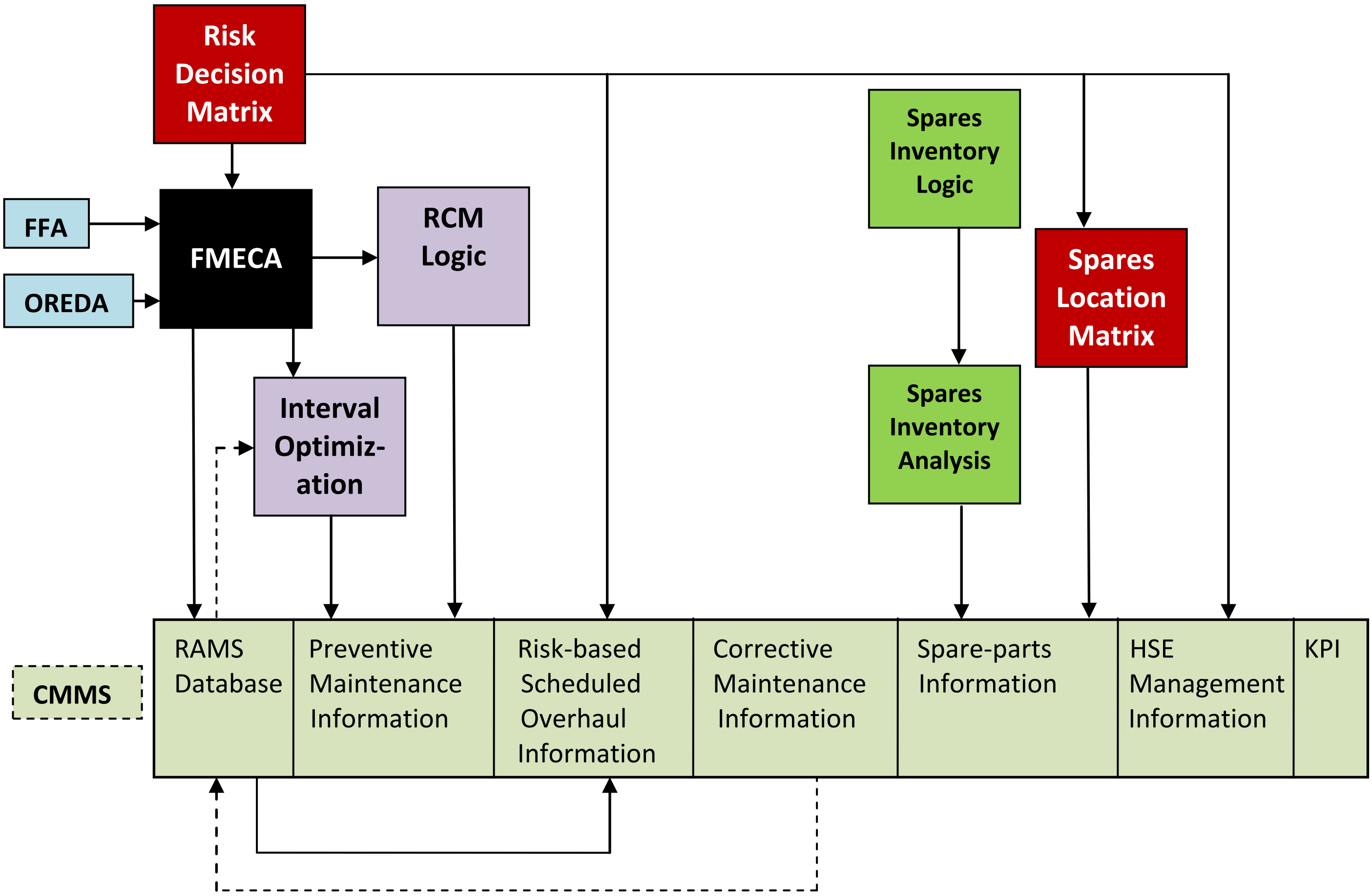

Figure 15: MCDS maintenance management model

Maintenance management, according to (Schjølberg, 1999), is "the management responsibility, the organisational and managerial tasks linked to establishment (objectives and strategies), implementation (action plans), monitoring (control) and planning of maintenance activities." Maintenance management, according to (Schjølberg, 1999), is also defined as "all systematic actions a company can implement in order to obtain and maintain maintenance standard in keeping with the company's objectives." In other words, maintenance management is the utilization and coordination of resources such as capital, plant, materials, and labour to attain/maintain maintenance standards while striving to realize set objectives (Slater, 2010).

The MCDS maintenance management model shown in Figure 15 above consists of an analytical section and a CMMS section. The activities of both sections are described as follows:

MCDS analytical section:

The functional failures from the FFA serve as the starting point in the FMECA, as failure mode at equipment class level (Rausand & Vatn, 2008). Some reliability data from OREDA (or other database) such as failure rate and repair rate serve as input for some columns of the FMECA. The risk decision matrix provides information for the criticality part of the FMECA. Reliability data such as failure rate and aging parameter from the FMECA serve as inputs for maintenance interval optimization. The dominant failure modes from the FMECA serve as inputs to the RCM Logic (Rausand & Vatn, 2008). Information from the risk decision matrix also serves as input for the spare-parts location matrix. Meanwhile, spare-parts analyses are performed by spare-parts inventory logic and spare-parts inventory analysis.

MCDS CMMS section:

The outputs from the analytical section of MCDS are fed into appropriate parts of the CMMS. Information from the RAMS database part of the CMMS is fed into the risk-based scheduled overhaul part of the CMMS which also receives information from the risk decision matrix. The dotted arrows represent feedback from the corrective maintenance part of the CMMS to update the RAMS database part of the CMMS and further from the RAMS database part of the CMMS to update the interval optimization part of the analytical section.

3.5.2 MCDS Modules of Concepts

MODULE 1- *Criticality Analysis (CA):* The system risk matrix (Table 7 of subsection 3.4.1) is employed to aid maintenance management by prioritizing the failure modes to be described in the FMECA worksheet (Table 6 of subsection 3.4.1).

MODULE 2- *RCM Logic Analysis (RLA):* The failure modes (from the FMECA worksheet), that are responsible for the risk levels shown on the system risk decision matrix, are entered into the RCM decision logic tree (Figure 14 of subsection 3.4.2) to select an appropriate preventive maintenance task.

MODULE 3- *Maintenance Interval Optimization (MIO):* Select a suitable approach for maintenance interval optimization, for e.g. age-based maintenance models (Weibull standard PM model and ARP model), shock model and PF model as described in the next chapter.

MODULE 4- *Risk based maintenance (RBM):* The RBM methodology is based on (i) risk analysis, consisting of the description of unwanted events, their probabilities/frequencies and consequences (ii) risk evaluation, consisting of risk aversion and risk acceptance analysis (iii) maintenance planning (encompassing the plans for inspections, repair, and replacement) based on the risk factors (Allahkaram & Others, 2005).

A simple approach will be to apply **Risk-based scheduled overhaul prioritization (RSO)** shown below (in Table 10), which is based on the system risk matrix (Table 7 of subsection 3.4.1), for decision making and prioritization of overhauls.

Table 10: Example of risk based scheduled overhaul plan

Risk Level	MTBF (Year)	Prioritized time to overhaul
H	0-1	*e.g.* 1 week
M	1-4	*e.g.* 4 weeks
L	4-20	*e.g.* 24 weeks
VL	>20	*e.g.* 52 weeks

> *The time to overhaul should be some fraction of the MTBF. For example, if the MTBF is expected to be 3 years, the time to repair could be, say 13 months for high risk and, say 27 months for medium risk* (Draft NORSOK Standard Z-008, 2009).

The risk scale and color coding are as defined in the system risk matrix in Table 7.

MODULE 5- *Spare Parts Strategy Optimization (SSO):* The objectives are to optimize the location (i.e. accessibility) of spare parts (Draft NORSOK Standard Z-008, 2009) and the sum of (i) cost of running out of stock (which includes production loss due to interruptions, cost of lease, etc. (ii) cost of replenishing stock (which partly depends on the quantity ordered) and (iii) cost of holding stock (which includes interest on capital, depreciation, insurance, obsolescence, storage, etc.) (Kelly, 2007).

Spare parts inventory control analysis (SICA): This involves different suitable approaches for controlling the inventory of (i) fast-moving spares (> 3 demands per year) (ii) slow-moving spares (< 3 demands per year) and rotables (repairable equipment).

TYPE A PARTS: ***Fast-moving spares (> 3 demands per year) inventory control analysis (FSICA)***

Fast movers have two basic types of control policy, namely (Kelly, 2007):

- Re-order level: replenishment is triggered by stock falling to a preset re-order level.
- Re-order cycle: replenishment decided at regular intervals based on stock review.

Re-order level policy (RLP): Adopting this policy requires that we establish a re-order level (M) to which the stock on-hand (S_{OH}) [i.e. stock held (S_H) plus stock on order (S_{OO})] must be equal. If the latter is less than the former, then a re-order quantity (q) is calculated to replenish the stock. Hence (Kelly, 2007):

$$M = DL + k\sigma_D L^{1/2}$$

Where:

D	= Mean demand for the part per unit time
L	= Mean lead time
σ_D	= The standard deviation of demand per unit time
k	= Standard normal variate such that: **F (k) = 1 – X** Where, X = level of service Thus, if the desired level of service is say, 96%, then F (k) will be 4% or 0.04 Then k from the standard normal probability density function table is 1.75
F(k)	= the probability that demand will not be met during a lead-time, i.e. a stockout will occur.

The desired level of service, *X*, is an acceptable value of the likelihood that demand will be met within any given lead time (Kelly, 2007), and typical values are chosen from 90-99%.

$$q = \sqrt{\frac{2DC_O}{C_H}}$$

Where:

C_O	= Cost of the replenishment order
C_H	= Cost of holding the spare part per unit time

These parameters can be incorporated into Microsoft Excel to make life easier as shown:

Table 11: Illustration of Excel worksheet for fast-moving spares inventory control analysis (FSICA)

Item #	D	L	σ_D	X	k =NORMSINV(X)	M	S_H	S_{OO}	S_{OH}	C_O	C_H	q
1.	12	0.17	3	0.96	1.75	4.14				40	60	4
2.												

<u>TYPE B PARTS:</u> ***Slow-moving spares (< 3 demands per year) inventory control analysis (SSICA)***

A suggestion by (Nahmias, 1993) for the modeling slow-moving spares is the Laplace distribution, given as:

$$f(x) = \frac{1}{2\theta} e^{-\frac{|x-\mu|}{\theta}}$$

$$for -\infty < x < +\infty$$

Where:

μ = mean of demand over lead-time
$2\theta^2$ = variance of demand over lead-time = $(\sigma_\mu)^2$

Note: The detailed mathematical process is omitted here.

Hence:

$$q = \theta + \sqrt{\frac{2AC_O}{C_H} + \theta^2}$$

Where:

A = Annual demand

q is finally chosen after rounding off to the nearest integer.

The *reorder point (R)* suggested by (Nahmias, 1993) is given by:

$$R = \mu + k\sigma_\mu$$

Where:

σ_μ = Standard deviation of demand over lead-time

These parameters can be incorporated into Microsoft Excel to make life easier as shown:

Table 12: Illustration of Excel worksheet for slow-moving spares inventory control analysis (SSICA)

Item #	μ	σ_μ	X	k =NORMSINV(X)	R	θ	A	C_O	C_H	q
1.										
2.										

The level of service described under type A parts can also be applied for type B parts.

<u>TYPE C PARTS:</u> ***Rotables (repairable equipment) inventory control analysis (RICA)***

For a rotable (repairable equipment), the re-order quantity is given by (Harper, 1998):

$$q = EAD \cdot (1 - \%REC) \cdot YP + ELTD + Z \cdot \sqrt{ELTD}$$

Where:

EAD = Expected Annual Demand
% REC = The percentage of parts recoverable or repairable (from service statistics or expert judgement.
YP = The number of years to be planned for
ELTD = Expected Lead-Time Demand
Z = Safety factor or standardized variate

The standardized variate (safety factor) used in this model is obtained by virtue of a newsboy model (Nahmias, 1993), in which the model parameters are used to determine overage and underage cost (Harper, 1998). The idea behind this is that more critical parts have higher underage cost and cheaper parts have lower overage cost (Harper, 1998).

Underage cost implies the cost of a spare part being used before the time expected of it to begin service. According to (Inderfurth & Mukherjee, 2008):

Underage cost (C_U) = Shortage cost of rotables spare parts per unit per time period (C_S)

Overage cost ($C_{OV)}$ implies the cost of a spare part being retained in a store beyond the expected period of its use. According to (Inderfurth & Mukherjee, 2008), overage cost is a function of the holding cost (C_H) and run-out time (t) such that:

$$C_{OV} = C_H \cdot t$$

According to (Harper, 1998), a criticality ratio (CR) may be defined as:

$$CR = \frac{C_U}{C_U + C_{OV}} = \frac{C_S}{C_S + C_H \cdot t}$$

The value of CR from the normal distribution table results in the standardized variate (Z)

These parameters can be incorporated into Microsoft Excel to make life easier as shown:

Table 13: Illustration of Excel worksheet for rotable inventory control analysis (RICA)

Item #	EAD	% REC	YP	C_S	C_H	t	CR	ELTD	Z =NORMSINV(CR)	q
1.										
2.										

A simple spare-parts decision logic, which enables the selection of an appropriate method of inventory analysis, is shown as follows.

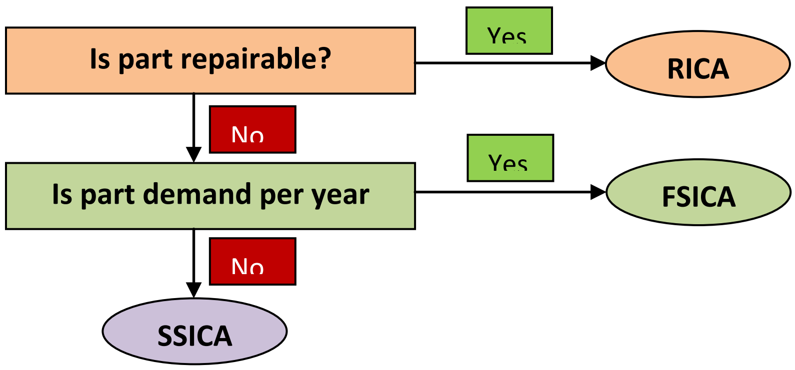

Figure 16: Spare parts inventory control decision logic

Spare parts location analysis (SLA): A risk matrix for spare parts recommended by NORSOK-Z008 is established to determine the optimum location for spare parts.

Table 14: Example of spare parts location matrix (Draft NORSOK Standard Z-008, 2009)

Consequence Demand rate	Low Impact	Medium Impact	High Impact
First line spare parts. Frequently used.	Minimum stock at site **M**	Minimum stock at site, and any additional spare parts at central warehouse.	Adequate stock at site. **H**
Not frequently used.	No stock **L**	Central warehouse, no stock at site.	Central warehouse. Minimum stock at site if convenient.
Insurance spare parts. Seldom never used.	No stock **L**	No stock **L**	Holding optimized by use of risk assessment case by case.

The consequence classes could be defined as follows:

Table 15: Spare parts consequence classes description (Draft NORSOK Standard Z-008, 2009) ***(adapted)***

Consequence	Description
High	Equipment of a system that must operate in order to maintain operational capability in terms of HSE, production and quality
Medium	Equipment of a system that has installed redundancy, of which either the system or its installed spare must operate in order to maintain operational capability in terms of HSE, production and quality
Low	No consequence for HSE, production or quality.

MODULE 6- *Manpower Strategy Optimization (MSO):* The outcomes of activities 1 to 5 are entered into a CMMS, which also receives other necessary information from other sources, *for e.g.,* OREDA. According to Draft NORSOK Z-008:2009, the reporting of maintenance data should be based on ISO 14224, which lists a minimum of maintenance-related information to be reported, as shown.

Table 16: Minimum required maintenance data reportage (ISO 14224, 2006)

Corrective maintenance	**Preventive maintenance**
Failure mode Failure cause and mechanisms Equipment outage time Spare parts used Man-hours for activity Start and finish time	Condition of equipment before PM work Man-hours for activity Spare parts used Start and finish time

The contents of the ISO 14224 table are augmented with the following extra features for use in a CMMS to enhance workforce efficiency.

- Work order generation (scheduling jobs, assigning personnel, reserving materials, recording costs etc.) and prioritization by criticality.
- Filtering and tracking of all work orders history by equipment, date, responsible person, etc.
- Hosting of maintenance procedures, reliability data and warranty information by component.
- Real-time on-going work status reports.
- Spare parts locations.
- Spare parts, tools and materials inventory control with automated reorder capability.
- Management of permit-to-work (PTW), lockout-tagout (LOTO) and other safety requirements.
- Key Performance Indicators (KPI)

3.6 MCDS: A Promising Maintenance Database Solution

A maintenance programme focused only on CMMS is unoptimizable. CMMS dwells on maintenance efficiency improvement, while the link between CMMS and some sound maintenance concepts could focus on maintenance effectiveness. Efficiency is about doing things rightly and effectiveness is about doing the right things; and when the right things are being done rightly, it could lead to optimization.

Ruth Olzweski, President of CMMS Data Group Inc., in (Olszewski, 2008) establishes a relationship between CMMS and RCM. She stated that CMMS contributes critically to RCM analysis by providing equipment data and history. She reiterated that in order for RCM to be successful, CMMS data must be complete and accurate. She concluded that CMMS also allows for action to be taken based on the result of an RCM analysis; and that, in tandem, successful RCM analyses and successful CMMS systems will ensure that a company optimizes its return on assets.

Yet, it is apparent that there is still a need for further optimization. According to Prof. Jørn Vatn, the standard RCM methodology does not prescribe ways of optimizing maintenance intervals, although it could be restructured in such a way that it becomes compatible with existing maintenance optimization models (Vatn, 2007). Further to this, Prof. Jørn Vatn states that the results of a qualitative RCM analysis could be used as a basis for interval optimization with additional assessments e.g. failure rates, ageing parameters, PF intervals, failure progression speeds, cost of maintenance and cost of failure (Vatn, Welcome to Phd Seminar: Maintenance and Renewal Optimization, 2009). The standard RCM methodology also does not recommend ways of optimizing spare parts strategy and manpower strategy.

Taking cognizance of the inability of RCM to offer full optimization, the maintenance interval and spare parts optimization models were considered among other modules developed in the previous section for the integrated maintenance concepts solution called Maintenance Concept Database Solution (MCDS).

Figure 17 below, is an illustration of the hierarchical structure of Maintenance Concept Database Solution (MCDS).

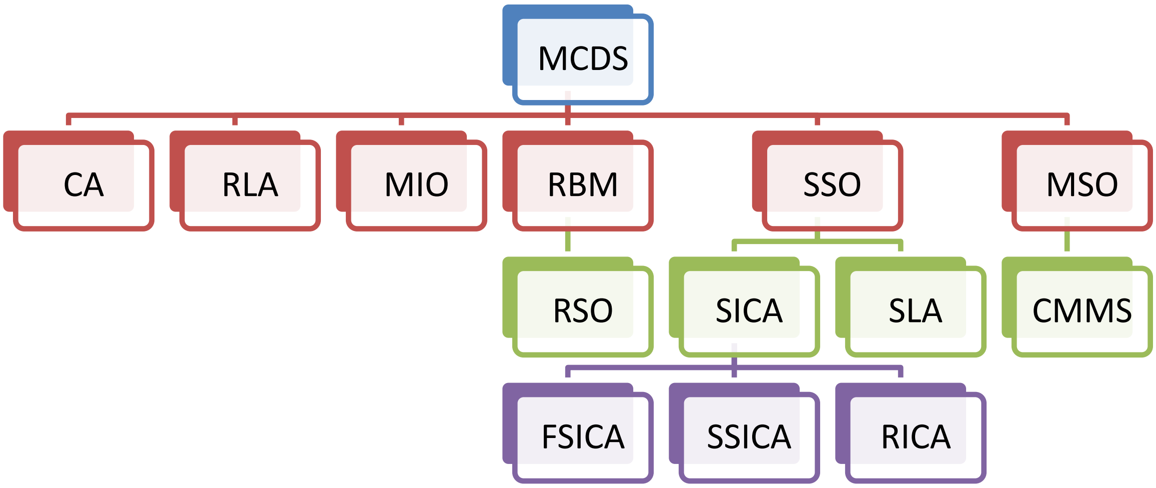

Figure 17: MCDS hierarchical structure

In Figure 17 above, MCDS exists at the blue level, which represents a state of complete maintenance optimization. The red level represents the main aspects of maintenance optimization: Strategy optimization, interval optimization, spare-parts optimization and manpower optimization. The green level is the component level of some of the elements of the red level. The purple level is a subcomponent level for the Spare-parts Inventory Control Analysis (SICA) component on the green level.

Meaning of Abbreviations

MCDS = Maintenance Concept Database Solution

CA = Criticality Analysis

RLA = RCM Logic Analysis

MIO = Maintenance Interval Optimization

RBM = Risk Based Maintenance

SSO = Spare-parts Strategy Optimization

MSO = Manpower Strategy Optimization

PIO = PM-Interval Optimization

RSO = Risk-based Scheduled Overhaul

SICA = Spare-parts Inventory Control Analysis

SLA = Spare-parts Location Analysis

CMMS = Computerized Maintenance Management System

FSICA = Fast-moving Spares Inventory Control Analysis

SICA = Slow-moving Spares Inventory Control Analysis

RICA = Rotables Inventory Control Analysis

3.7 Conclusion

In this chapter, I have succeeded in using Draft NORSOK Z-008:2009 and RCM Logic as basis for integrating different maintenance concepts bordering on maintenance strategy optimization, maintenance interval optimization, maintenance spare-parts optimization and maintenance manpower optimization , with the objective of achieving maintenance optimization in one whole package called MCDS.

4. ADAPTABILITY OF THE MAINTENANCE CONCEPT ACCORDING TO CLIENTS REQUIREMENTS

4.1 Background

This chapter intends to suggest ways in which this system of maintenance concepts (Maintenance Concept Database Solution) can be made flexible and versatile to be able to satisfy other clients' needs. The idea is to have a concept with several versions based on criticality, availability, safety, punctuality, failure progression etc.

4.2 Adaptability of MCDS to Divers Industrial Applications

Maintenance Concept Database Solution (MCDS) is applicable to other different industries by virtue of the use of appropriate concepts and models which may include criticality, safety, unavailability, punctuality, age-based maintenance models (for non-observable failure progression, *for e.g.* Weibull standard PM model and Age replacement model), PFD-model (for shocks) and PF-model (for observable "sudden" failure progression) (NTNU & SINTEF, 2009).

The objective is to achieve maintenance optimization. Optimization is realizable via the consideration of (Vatn, Hva er RAMS, og hvordan bruke RAMSmetodikk i vedlikeholdsplanlegging?, 2008):

(i) Cost models
(ii) Component (effective-failure-rate) models *e.g.* PF-model
(iii) System (component performance - system performance) models *e.g.* Markov model
(iv) Criticality *(adapted)*
(v) Spare-parts reorder quantity models *(adapted)* [*See previous chapter for details*]

Criticality analysis can optimize cost via the prioritization of equipment for the apportionment of appropriate strategies of maintenance. Spare-parts reorder quantity models can optimize cost by minimizing holding cost, system unavailability cost etc. The so-called cost model, component (effective-failure-rate) model (*e.g.* PF-model) and system model (*e.g.* Markov model) are used to optimize maintenance interval which in turn influences the total maintenance cost (Vatn, Hva er RAMS, og hvordan bruke RAMSmetodikk i vedlikeholdsplanlegging?, 2008).

The models mentioned in paragraph 1 (above) can be expressed in terms of cost models or component models as may be appropriate.

The cost model approach entails establishing an object function (*for e.g.* total cost per unit time, $C(\tau)$) and then determining the maintenance interval that gives the best performance according to the object function – a benefits/disadvantages balance for maintenance. The total cost per unit time, $C(\tau)$, may be set as a function of the costs associated with all the relevant parameters that have influence on maintenance in a given industrial application (Vatn, Hva er RAMS, og hvordan bruke RAMSmetodikk i vedlikeholdsplanlegging?, 2008).

In a component (effective-failure rate) model, the effective failure rate is established as a function of the maintenance interval (Vatn, Hva er RAMS, og hvordan bruke RAMSmetodikk i vedlikeholdsplanlegging?, 2008).

4.2.1 Criticality

Criticality analysis is helpful in prioritizing equipment, which are matched against effective maintenance strategies, thus eliminating unnecessary maintenance actions and hence optimizing maintenance cost by reducing maintenance-induced cost of performance loss in key business segments (HSE, production, quality, maintenance etc.) of an organization. Ineffective or wrong maintenance can incur HSE cost (*for e.g.* cost of injuries, impaired health or fatality and cost of environmental degradation), production-loss cost (*for e.g.* cost of economic loss and cost of manpower redundancy), quality-loss cost (*for e.g.* cost of loss of reputation and cost of litigation) and increased maintenance cost (*for e.g.* additional cost due to maintenance task re-assignment).

4.2.2 Safety

The concept of safety is applied in terms of "safety cost" in some of the models presented below. The safety cost may include the cost of maintaining safety barriers and cost of accident given barrier failure.

Safety, according to (MIL-STD-882D, 2000), is defined as "Freedom from those conditions that can cause death, injury, occupational illness, or damage to or loss of equipment or property."

Safety, is yet defined in words of (DEF-STD 00-56, 1996), as "The expectation that a system does not, under defined conditions, lead to a state in which human life is endangered."

The military standard definition has resulted in a lot of controversies, based on the argument of some experts that freedom from unwanted events in not realistic, since most activities involve one kind of risk or the other. Hence, alternative definitions, most of which view safety as an "acceptable level of risk" have been equally proposed (Rausand & Høyland, 2004).

Also with reference to the contentious phrase "freedom from", "freedom from unacceptable risk" is considered appropriate in (Vatn, Hva er RAMS, og hvordan bruke RAMSmetodikk i vedlikeholdsplanlegging?, 2008).

4.2.3 Unavailability

The concept of unavailability (the reverse of availability) is applied in terms of "unavailability cost" in some of the models presented below. The unavailability cost may include cost of substitute equipment leasing and cost of production loss.

Availability, according to (BS 4778), is defined as "The ability of an item (under combined aspects of its reliability, maintainability and maintenance support) to perform its required function at a stated instant of time or over a stated period of time."

Unavailability could be defined, by coining the BS 4778 definition, as "The inability of an item (under combined aspects of its reliability, maintainability and maintenance support) to perform its required function at a stated instant of time or over a stated period of time."

Mathematically, unavailability, U, is denoted as (Vatn, 2007):

$$\boldsymbol{U = \frac{MDT}{MTTF + MDT} \approx \lambda \cdot MDT = \frac{\lambda}{\mu}}$$

Where (Vatn, 2007):

λ = 1/MTTF = failure rate (assume constant failure rate)

μ = 1/MDT = repair rate (assume constant repair rate)

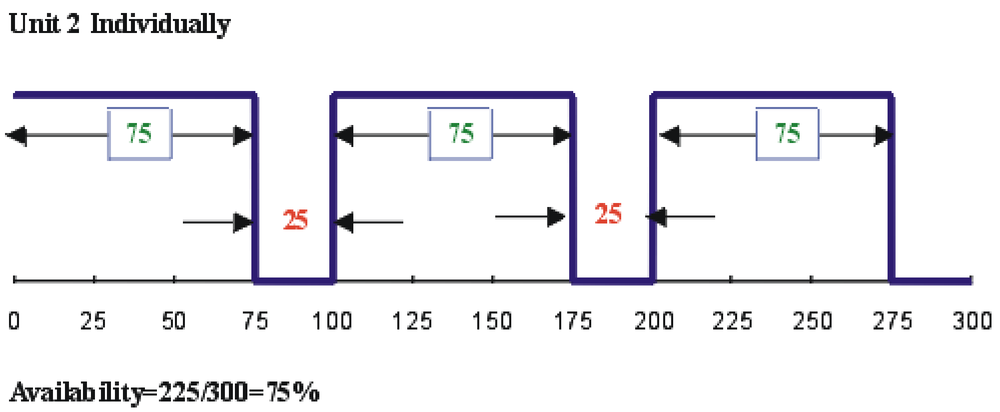

Figure 18: Illustration of availability (copied from www.reliasoft.com/newsletter/3q2002/availabilities.htm)

4.2.4 Punctuality

The cost of punctuality could be considered as one of the parameters of the total maintenance cost per unit time in addition to cost of safety and other costs according to (Vatn, 2007):

$$\boldsymbol{C(\tau) = C_S(\tau) + C_P(\tau) + C_{PM}(\tau) + C_{CM}(\tau)}$$

$$\boldsymbol{= C_S(\tau) + C_P(\tau) + C_{PM}/\tau + C_{CM} \cdot f_c}$$

Where:

C_P	= Total punctuality cost
C_S	= Total safety cost
C_{PM}	= Cost per preventive maintenance action
C_{CM}	= Cost per corrective maintenance action
f_c	= Component failure frequency
τ	= Optimized maintenance interval

An example of a maintenance optimization model incorporating the concept of punctuality is shown in the Excel worksheet in Table 17 below.

Table 17: Maintenance Optimization (involving punctuality) Excel worksheet (Vatn, ProM@in EXCEL files, 2001)

General parameters		⇒ Enter numeric value
MTTF	10	⇒ Enter code
Maintenan	1	⇒ Enter maintenance interval
Ageing para	3	Safety
PF-Mean	3	Punctuality
PF-SD	0.4	Maintenance
Insp Succes	0.9	Total cost
Demand ra	1	
Maintenan	9	
TOP Safety	1	Derailment

The concept of punctuality is of paramount importance in the transport industry. Maintenance has significant influence on the punctuality of vehicles; lack of maintenance or inadequate maintenance could result in, *for e.g.*, slow speeds, full stops etc., which could in turn result in delays. The cost of punctuality may include the cost of loss of reputation among others.

Punctuality is defined by (Glycee, 1994) as "the ability to achieve a safe arrival at a destination to an advertised timetable."

According to (Rudnicki, 1997), punctuality is "a feature consisting in that a predefined vehicle arrives, departs or passes at a predefined point at a predefined time."

Punctuality, in other words, is a measure of acceptable deviation from a vehicle's timetable. The acceptability is established with reference to a predefined level of acceptable deviation. So, a vehicle that runs within the acceptable deviation from its timetable is punctual, otherwise it is not.

4.2.5 Weibull Standard PM Model

The Weibull standard PM model is an age-based maintenance model (for non-observable-failure-progression) in which the total cost per unit time is given as a function of the optimized maintenance interval, i.e. $C(\tau)$ (NTNU & SINTEF, 2009).

$C(\tau) = C_{PM} / \tau + \lambda_E(\tau) [C_{CM} + C_{EU} + C_{ES}]$

$= C_{PM} / \tau + [\Gamma(1+1/\alpha)/MTTF_{wo}]^{\alpha} \tau^{\alpha-1} [C_{CM} + C_{EU} + C_{ES}]$

$\partial C(\tau) / \partial \tau = 0$ such that:

$$\tau = \frac{\mathbf{MTTF_{wo}}}{\Gamma(1+1/\alpha)} \left[\frac{C_{PM}}{(C_{CM} + C_{EU} + C_{ES})}\right]^{1/\alpha}$$

Where:

$MTTF_{WO}$	= Mean Time To Failure Without Maintenance
α	= Aging parameter
C_{PM}	= Cost per preventive maintenance action
C_{CM}	= Cost per corrective maintenance action
C_{EU}	= Expected total unavailability cost given a component failure
C_{ES}	= Expected total safety cost given a component failure
τ	= Optimized maintenance interval

These parameters can be entered into an excel sheet as shown in Table 18 below.

Table 18: Illustration of PM interval optimization Excel worksheet (Vatn, 2007) ***(adapted)***

Item #	MTTF	α	C_{PM}	C_{CM}	C_{EU}	C_{ES}	τ
1	175	3	7000	35000	10000	1000	10
2							

The Weibull standard PM-model is applicable in situations of non-observable-failure progressions illustrated in Figure 19 below.

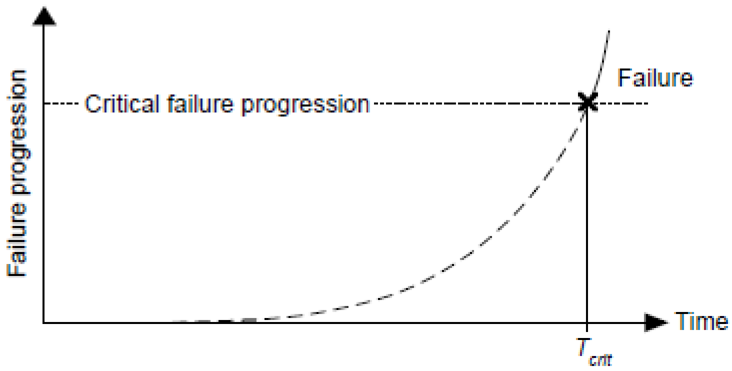

Figure 19: Non-observable failure progression (SINTEF & NTNU, 2009)

4.2.6 ARP Model

Age Replacement Policy (ARP) model is a classical age-based maintenance optimization model that can be used to express the total maintenance cost per unit time as follows (NTNU & SINTEF, 2009):

$$C(\tau) = C_{PM}\left[\frac{1}{E(T_{MC})} - \lambda_E(\tau)\right] + \lambda_E(\tau)[C_{CM} + C_{EU} + C_{ES}]$$

Where:

$$E(T_{MC}) = \int_0^\tau t f_T\,(t)dt + \tau P_r(T > \tau) = \int_0^\tau \big(1 - F_T(t)\big)dt$$

$$\lambda_E(\tau) = \frac{F_T(\tau)}{\int_0^\tau (1 - F_T(t))dt}$$

C_{PM}	= Cost per preventive maintenance action
C_{CM}	= Cost per corrective maintenance action
C_{EU}	= Expected total unavailability cost given a component failure
C_{ES}	= Expected total safety cost given a component failure
τ	= Optimized maintenance interval
$\lambda_E(\tau)$	= Effective failure rate
T_{MC}	= Length of maintenance cycle
$1/E(T_{MC}) - \lambda_E(\tau)$	= Rate of PM actions

The following are the age replacement policy (ARP) description and assumptions (NTNU & SINTEF, 2009):

- The component is replaced periodically when it reaches a fixed age
- If the component fails within a maintenance interval, the component is replaced, and the "maintenance clock" is reset
- Usually the component is replaced after a service time of τ
- Assume all components are as good as new after a repair or a replacement
- Usually we assume Weibull distributed failure times
- Repair time could be ignored with respect to length of a maintenance cycle
- The length of a maintenance cycle (T_{MC}) is a random quantity
- Sometimes, the component may fail in the maintenance interval denoted by T_1 and T_2 as shown in Figure 20 below.

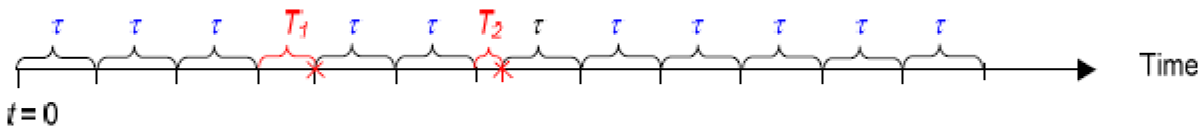

Figure 20: Illustration of age replacement policy (NTNU & SINTEF, 2009)

4.2.7 PF-Model

The PF-model (for observable-"sudden"-failure-progression) is suitable for condition monitoring situations and is applicable in the form of effective failure rate as a function of maintenance interval, as shown (Vatn, 2007):

$$\lambda_{PF}(\tau) = f_P \cdot Q_I(\tau)$$

Where,

$$Q_I(\tau) = Q_{PF}(\tau, E_{PF}, SD_{PF}, P_I) + (1 - P_C)$$

Q_I = the probability that inspection is an efficient barrier

E_{PF} = Mean PF-interval length

SD_{PF} = Standard deviation in PF-interval length

P_I = Probability that an existing crack (or another warning situation) will be detected by a inspection (given that it is possible to detect the crack by condition monitoring method)

P_C = Coverage of the inspection method, i.e. percentage of cracks that could be detected

τ = interval length of inspections

f_P = Frequency of potential failures

Q_{PF} = Probability that failure progression is not detected in due time

The objective of the PF model is to obtain the probability, Q_{PF}, of not detecting the crack in due time as a function of the inspection interval, τ (SINTEF & NTNU, 2009).

Q_{PF} (τ, E_{PF}, SD_{PF}, P_I) could be determined by using the Q_{PF} (τ) chart in Figure 21 below (Vatn, 2007):

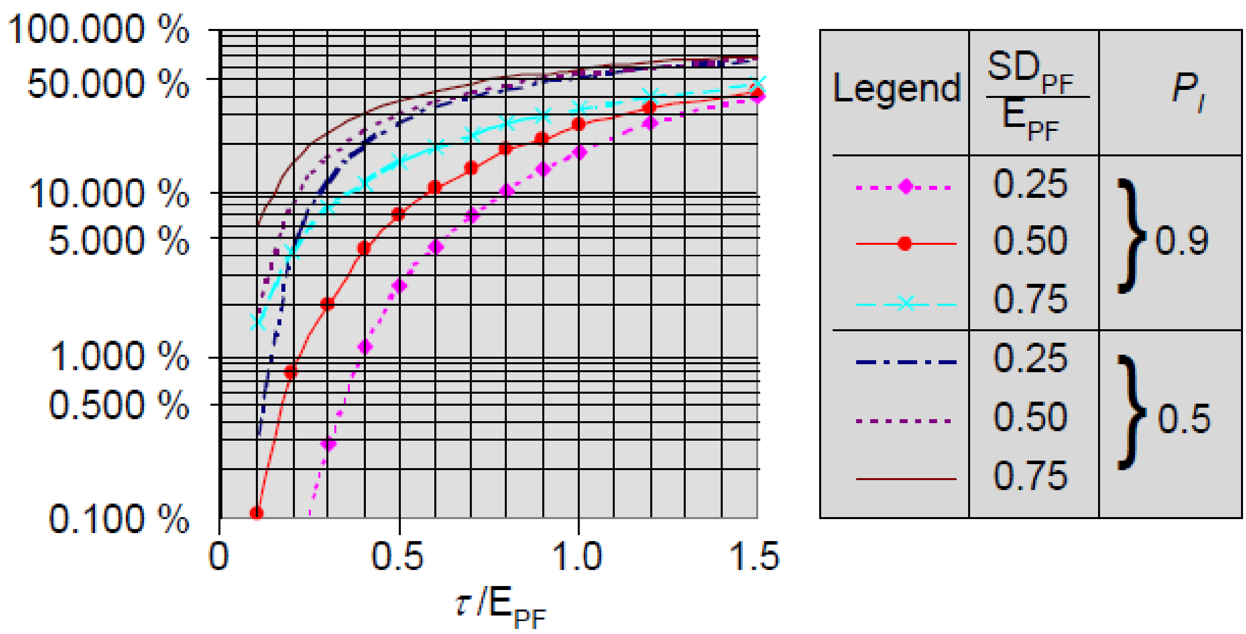

Figure 21: Q_{PF}(τ) for different combination of SD_{PF}/E_{PF} and P_I (Vatn, 2007)

The length of the PF interval is assumed to be a time-dependent variable, which also depends on influencing factors such as load, temperature, structure quality, corrosive environment etc. Fast-propagating cracks pose the highest risk of not being detected by ultrasonic inspection (SINTEF & NTNU, 2009). An illustration of this variation is shown in Figure 22 below.

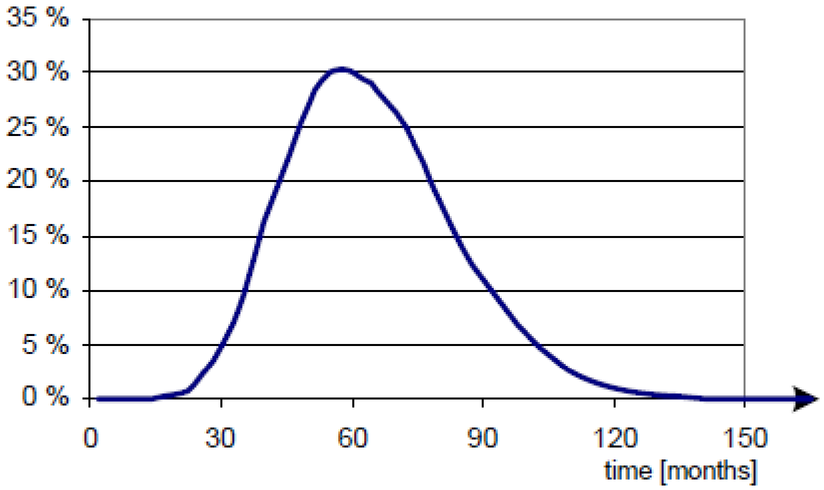

Figure 22: Variation in PF-interval (Vatn, 2007)

Q_{PF} (τ, E_{PF}, SD_{PF}, P_I) may also be determined from an Excel worksheet as shown in Table 19.

Table 19: P-F Interval Excel Worksheet (Vatn, ProM@in EXCEL files, 2001)

Average PF	50000			Note: Edit only entries with blue background		
Inspection	30000					
Inspection	0.2					
Total failur	0.14826					
		From	To	Prob	AvP-F	LowNum
	0.15	0	7500	1.00%	3750	0
	0.3	7500	15000	2.00%	11250	0
	0.45	15000	22500	5.00%	18750	0
	0.6	22500	30000	10.00%	26250	0
	0.75	30000	37500	15.00%	33750	1

What drives on-condition tasks is not whether the equipment is critical or not, but the *lead time between failure detection and failure itself* called the *PF-Interval.*

According to (Vatn, 2007), "PF-interval is time from a potential failure (P) is detected until a failure (F) occurs." The objective of the inspection under that PF-model is to uncover *for e.g.*, a crack in a train's wheel (i.e. a potential failure) before it culminates in a breakage – a critical failure (SINTEF & NTNU, 2009).

An ultrasonic inspection is carried out at regular time interval of τ to detect potential failures. The inspection intervals must not exceed the average PF-interval in length. In fact, to be on a much safer side, it is advisable to keep the inspection interval reasonably shorter than the average PF-interval, because the PF-interval varies from time to time and there exists the probability that a potential failure is unrevealed during an inspection. Prior to applying the PF-interval concept in maintenance planning, one must consider the possibility of establishing early-warning systems which can be triggered by deviations from preset magnitudes of failure-indicating variables. Typical examples of such variables are: vibration, cracks, increased temperature etc (vatn, 2007).

Figure 23 below illustrates an observable "sudden" failure progression, whereby the point "P" exists at the level of *potential failure* while the point "F" exists at the level of *functional failure*. The point "P" is the point when potential failure is detectable (or the limit of failure undetectability) while "F" is the breakage point (or the limit of functional relevance).

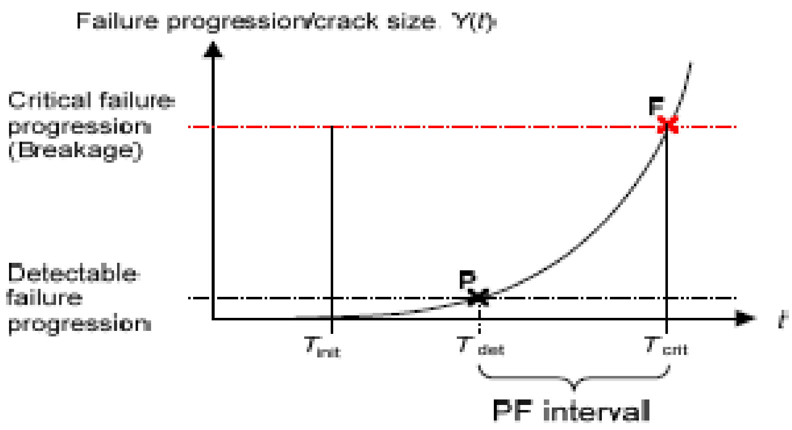

Figure 23: Observable "sudden" failure progression (SINTEF & NTNU, 2009)

The knowledge of PF-Interval enables us to avoid unnecessary holding cost incurred by keeping certain spares in stock. If the PF-Interval is enough for us to get a component to site, plan it and replace a defective one, then there is no need to hold it in the stores at all. But if you have a PF-Interval of, *for e.g*. three weeks and a spare delivery lead time of, *for e.g*. five weeks, then it would be wise to hold a spare in stock.

4.2.8 PFD-Model

A PFD-model (a shock model) could be considered for safety instrumented systems, in which the cost of hazard is applied where a hidden function is demanded and the component is in a fault state (NTNU & SINTEF, 2009).

This situation is synonymous with a shock model, where the PF-interval is so short that there is no possible inspection techniques that are able to reveal a potential failure in due time. Hence, the time to failure (TTF) is approximately an exponential distribution (Vatn, 2007).

Figure 24 below illustrates the failure progression in a shock model.

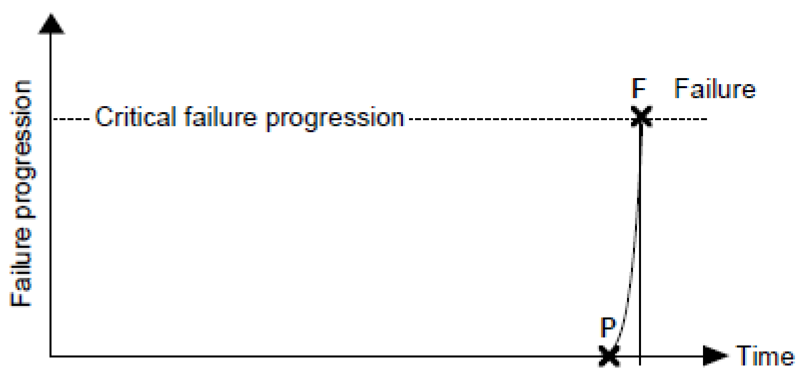

Figure 24: Shock model (SINTEF & NTNU, 2009)

Here, we consider that a component fails due to external shocks and consider the following (NTNU & SINTEF, 2009):

- Assumption of exponentially distributed failure rate, λ
- Assumption that function is hidden
- PFD (for one component) = $\lambda\tau/2$
- Demand rate of function = f_d

Hence, we can establish a cost model, such that the average cost per unit time is given as a function of the maintenance (inspection) interval as follows (NTNU & SINTEF, 2009):

$$C(\tau) \approx \frac{C_I}{\tau} + C_R\left(\tau - \frac{\lambda^2\tau}{2}\right) + f_D C_H \lambda\tau/2$$

Where:

C_I = cost of inspection
C_R = cost of repair/replacement upon revealing a failure during inspection
C_H = cost of hazard, i.e., if the hidden function is demanded, and the component is in a fault state

For a K out of N (KooN) voting configuration, the $\lambda\tau/2$ term above should be replaced with (NTNU & SINTEF, 2009):

$$PFD_{KooN} \approx \binom{n}{n-k+1}\frac{(\lambda\tau)^{n-k+1}}{n-k+2}$$

If there is a common cause failure, we add $\beta\lambda\tau/2$ to the expression for PFD to account for the common cause failure. β is the fraction of failure that is due to common cause (NTNU & SINTEF, 2009).

Unavailability of a safety item (commonly called Probability of Failure on Demand – PFD), could be defined as "The probability that a safety item will fail to respond adequately to a demand at a given time." (Rausand & Høyland, 2004).

According to (Vatn, 2007), PFD is "the average time a failure of a hidden function is not detected." Sometimes the acronym MFDT (Mean Fractional Dead Time) is used instead of PFD (Vatn, 2007).

Mathematically, PFD is given by (Vatn, 2007):

$$U = \frac{MDT}{MTTF + MDT} = \frac{\tau/2}{MTTF + \tau/2} \approx \frac{\lambda \cdot \tau}{2} = PFD$$

This is the expression for a single component.

For multiple components in series, the PFD of the system is the algebraic sum of the individual PFDs.

For multiple identical and independent *n* components in parallel with constant failure rate and common test interval, the PFD of the system is given as (Rausand & Høyland, 2004):

$$PFD = \frac{(\lambda\tau)^n}{n+1}$$

The interval for function tests necessary to reveal hidden failures is illustrated in Figure 25.

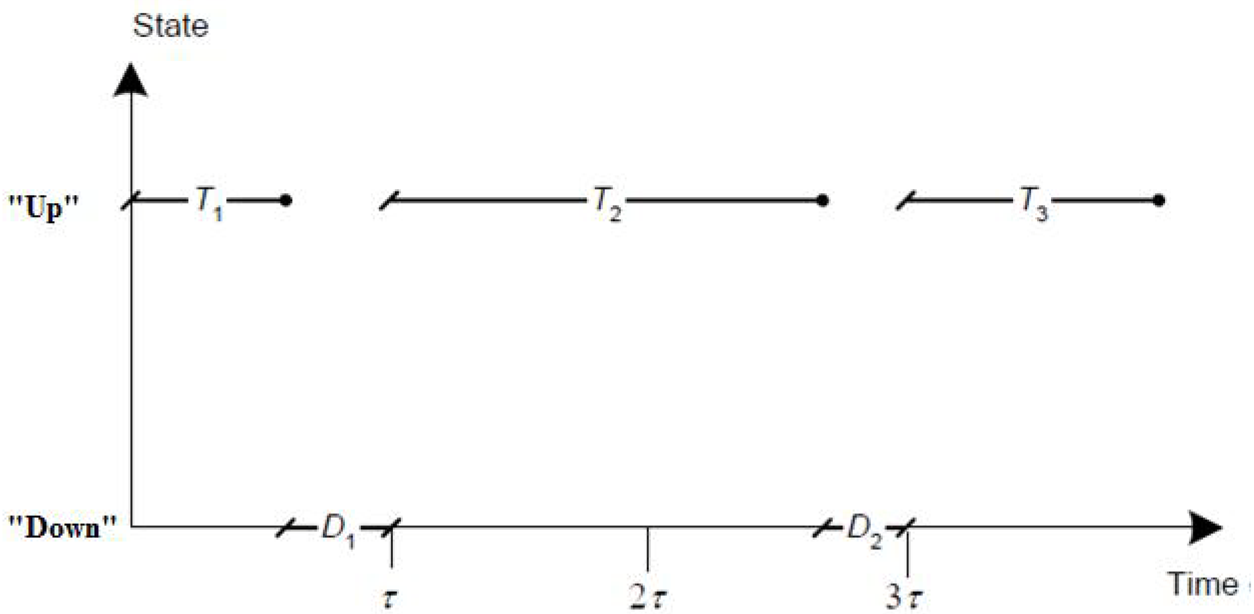

Figure 25: Function test with interval length, τ (Vatn, 2007)

4.3 How to transform one MCDS version to another

The MCDS version applicable to a given industry or industrial application could be transformed to another version of MCDS for use in another industry or industrial application by:

1. Substituting the existing external maintenance database link (if necessary) with a suitable one: For example, substituting OREDA with RAC (Reliability Analysis Centre) /DSC (Data Sharing Consortium), INSC (International Nuclear Safety Centre), RAM/SHIPNET (Reliability, Availability, and Maintainability Information Management for the New Millennium, REMAIN Data Base, or Navy Maintenance Data Base (UPM & Adepa, 2000).

2. Substituting the existing maintenance interval optimization model (if necessary) with a suitable one: For example, substituting the standard Weibull PM model with ARP model, PF-model, or PFD-model.

3. Adjustment of data/information of other variables as may be necessary.

Table 20: Examples of possible data sources for transformation of MCDS versions

Database	Custodian	Data type
OREDA	Consortium of BP, Shell, Eni, Total, ExxonMobil, Gassco and ConocoPhillips.	Offshore (Oil and gas) industry reliability data
RAC/DSC	Reliability Analysis Centre (RAC) under sponsorship of U.S. Department of Defense (DoD).	General industrial data pertaining to reliability and quality of components and systems.
INSC	International Nuclear Safety Centre under the guidance of U.S. Department of Energy (DOE).	Nuclear plant-specific information, material properties for safety and risk analyses and project-specific reactor safety bibliographies.
RAM/SHIPNET	Network of worldwide maritime organizations: owners/operators, government organizations and regulatory agencies.	Information pertaining to the improvement of the safety, reliability, and cost-effectiveness of marine machinery used onboard vessels.
REMAIN	Project of the Commission of European Communities.	Information pertaining to the management of *reliability* and *maintainability* in European Railway systems.
Navy maintenance database	Network of world Navies.	Information related to dependability management in marine systems.

Table 21: Recommended concepts for different industries

Concept / Industry	Criticality	Safety	Unavailability	Punctuality	Weibull Std. PM Model	ARP Model	P-F Model	PFD Model
Geophysical	√	√	√			√		√
FPSO	√	√	√		√	√	√	√
Drilling	√	√	√		√	√	√	√
Process	√	√	√		√	√	√	√
Production / Manufacturing	√	√	√		√	√	√	√
Pipeline Transport	√	√	√	*(regularity)*		√	√	√
Road Transport	√	√	√	√	√	√	√	√
Railways	√	√	√	√	√	√	√	√
Aviation	√	√	√	√	√	√	√	√
Marine/Maritime	√	√	√	√	√	√	√	√
Mining	√	√	√		√	√	√	√
Machinery systems	√	√	√		√	√	√	√
Civil/steel works & building services	√	√	√			√	√	√
Defense	√	√	√		√	√	√	√
Aerospace	√	√	√		√	√	√	√
Electrotechnical	√	√	√			√		√
Fossil-fuel Power	√	√	√		√	√	√	√
Nuclear Power	√	√	√		√	√	√	√
Hydropower	√	√	√		√	√	√	√
Wind Power	√	√	√		√	√	√	√
Solar Power	√	√	√		√	√	√	√
Geothermal Power	√	√	√		√	√	√	√
Biopower	√	√	√		√	√	√	√
Instrumented medical system	√	√	√			√		√

4.4 Conclusion

In this chapter, I have achieved a means of creating different versions/variations of MCDS in order to be able to meet the needs of virtually all industries which show concern for World Class Maintenance. The main idea dwells on the use of appropriate maintenance interval optimization models and external maintenance databases.

5. EVALUATION OF THE MARKET POTENTIALS OF THE MAINTENANCE CONCEPT AND WAYS OF OFFERING IT TO THE MARKET

5.1 Background

This chapter intends to present ideas peculiar to technology-based business development and aims to prepare a framework for the successful commercialization of Maintenance Concept Database Solution (MCDS) in future.

5.2 SWOT Analysis of MCDS

A SWOT (**S**trengths, **W**eaknesses, **O**pportunities and **T**hreats) analysis of MCDS is shown as follows.

STRENGTHS

Comprehensive maintenance optimization:

Unlike many existing products, MCDS offers comprehensive maintenance optimization, integrating maintenance interval optimization, spare optimization and manpower optimization.

Consolidated maintenance strategy optimization:

RCM and RBM concepts integrated into MCDS.

Product differentiation capability:

MCDS is adaptable to maintainable equipment of all industries.

Self-funding capability:

AGR FO has adequate resources to sustain the continuous development of the software.

WEAKNESSES

No Protection:

MCDS is not protected as yet against possible infringements.

OPPORTUNITIES

Existing growing market:

The software market is the fastest growing and most dynamic.

Existing framework for networking:

AGR FO can leverage on the network already created with KAMFER (own existing maintenance software) to market MCDS.

Partnership with maintenance software companies:

There is the possibility of partnering with maintenance software companies seeking product differentiation. AGR FO can license MCDS for certain fees.

Partnership with industries into operation:

AGR FO can partner with several industries that are keen on MCDS and willing to outsource the maintenance of their equipment.

THREATS

Copycats:

MCDS can be copied if it is not protected.

Competitors:

AGR FO may have a better product now, but there is always the possibility of the competitors improving their products. So, AGR FO has to benchmark its competitors continuously.

5.3 Key issues for technology-driven innovation

Some essential issues in technology-driven innovation include the following (Klingsheim, 2010):

- **WHO** – *Market analyses*:
  – Is the market sufficiently large?
  – Who is your first customer? What's his financial status?
  – What are the dominant trends? Who are the players?

- **WHY** – *Value proposition*:
  – Simpler or cheaper than the competition?
  – How does the customer survive until he gets your product?
  – Customer needs Vs product features?
    - Customers' Vs vendors' perspective
    - Technology driven innovation?

  – Is it "nice to have" or "need to have"?
  – Do you promise top-line growth or bottom-line savings? By how many Kroner?
  – Compelling reasons to buy?

- **HOW** – *Go-to-market*:
  – How do I get in?
  – Business concept/model to adopt
  – Channels, distributors, OEM, VAR, marketing, sales, etc

- **WHEN –** *Technical/internal analyses*:
  – Time and effort required before invoices?

– Funding requirements and investors?

5.4 Marketing and sales

Marketing and sales are very crucial to business development. Their characteristics are outlined in the following (Klingsheim, 2010):

- Marketing is all about fighting for turf, i.e.:
  – Outwitting, outfighting and outflanking the competition
  – Conquering and defending positions in the market place
  – The price is a favorable position in the minds of customers
  – I.e. marketing is all about fighting a WAR!

- Sales is all about customer satisfaction, i.e.:
  – Provide true value to customers' business
  – Instill a sense of "I cannot live without" with customers
  – Form eternal, win-win relationships with recurring revenue
  – I.e. sales is all about forging PEACE!

- Marketing is the function that "creates customers"

- Sales is the function that "creates invoices"

- Common objectives:
  – Make your product/service appear attractive
  – and deliver the best product and/or service in the world
  – to your targeted customers
  – so that lots are sold
  – repeatedly

5.5 Recommended strategies for established businesses

Established businesses like AGR FO usually subscribe to the following business strategies (Klingsheim, 2010):

- Strategies based on market share or dominance of an industry:
  – Leader
  – Challenger
  – Follower

- Generic strategies (e.g. M.Porter) based on strategic scope (market penetration) and strategic strength (sustainable competitive advantage):
  – Cost leadership
  – Product differentiation
  – Market segmentation

- Innovation strategies (product- and/or business model innovation):
  – Pioneers

– Close followers
– Late followers

- Growth strategies, choosing between:
  – Horizontal integration
  – Vertical integration
  – Diversification
  – Intensification

5.6 Recommended Business Model/Strategies for AGR FO

A *strategy* is a long-term action plan intended for the realization of a desired goal. Strategies are mapped-out to gain benefits or advantages. In the case of business, a primary advantage is *competitive advantage* which maximizes a company's return on investment (ROI).

I strongly advise AGR FO against licensing MCDS for a fee, because this will amount to getting a smaller "piece of the pie." AGR FO should seek to maximize return on investment (ROI). There is absolutely no basis for a business exit strategy now, since AGR FO has the capacity to pursue the continuous development of the software and the distribution of its services.

It is a sound idea to adopt the *delta model* in which AGR FO will strive to stand in the "total customer solutions" position. AGR FO should seek for business deals with clients that are interested in outsourcing their maintenance. The MCDS package should be web-based, such that it is hosted by AGR FO (the company selling the product) on its server, while the companies which have outsourced their maintenance to AGR FO are connected from their various locations.

5.6.1 The Delta Model

The delta model is a new scheme of strategy that positions the customer at the middle of management. It examines the foremost options available to establish customer bonding and it recommends how to connect strategy to execution through the alignment of adaptive processes (Hax & Wilde, 2003).

The three distinct strategic options in the delta model are shown in fig. 26 below.

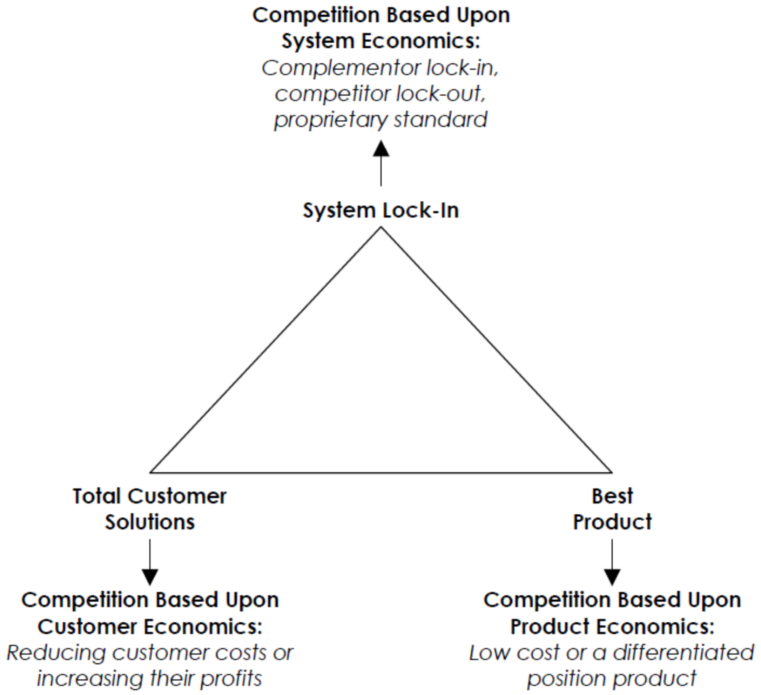

Figure 26: Business Model-Three distinct strategic options (Hax & Wilde, 2002)

These three main strategic options yet have several other sub-options for strategic positioning as shown in fig. 27 below.

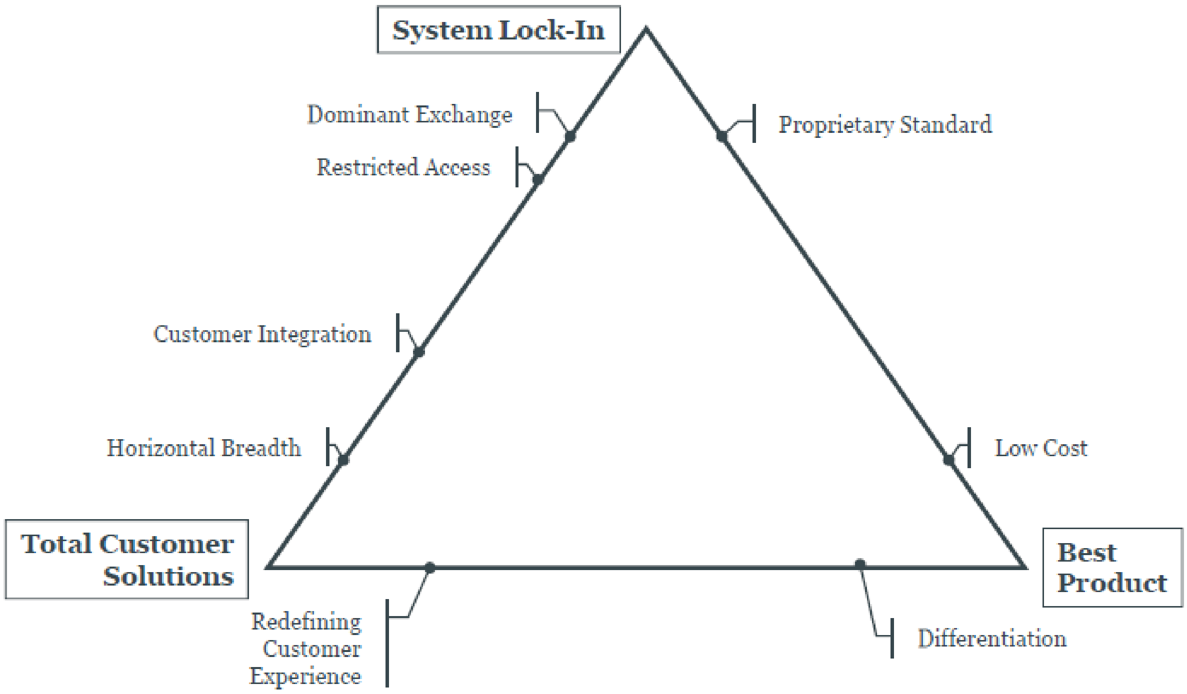

Figure 27: Options for strategic positioning (Investinor, 2010)

The various options for strategic positioning are described in detail in the following tables.

Table 22: "Best Product" Delta Strategy (Investinor, 2010)

Best Product	Centered on product economies	
Low cost	Focus on being the lowest cost provider in an undifferentiated product category.	Since there is only one lowest cost producer, this strategy leaves very little space as a competitive position. It also tends to standardize the product offering, commoditize the customer and intensify rivalry.
Differentiation	While maintaining effective prodiction economies focus on the key differentiation in the product features and functionalities such that the products ar unique desired and command price premiums.	The problem with this strategic position is that as soon as the differentiated product emerges, competitors tend to imitate them. A competitive advantage is therefore non-sustainable.

Table 23: "Total Customer Solutions" Delta Strategy (Investinor, 2010)

Total Customer Solutions	Oriented to customer economics	
Redefining the customer experience	A focus is placed on considering the full experience of the customer from the point of acquisition through to the complete lifecycle of ownership of the product.	This positioning is based upon an intimate knowledge of the customer base leading toward an effective customer segmentation and a differentiated treatment of the customer tiers.
Horizonal Breadth	A complete set of of product and service offerings that fulfill the entire customer needs are customized and provided. "One stop shopping for a unique solution".	We are seeking a dominant position in "share of the wallet of the customer."
Customer Integration	This strategy seeks to effectively substitute for or leverages activities currently performed by the customer. It is outsourcing in its extreme form and at least represents a complex web of connections with the customer that enhance their ability to do business and to use your product.	The firm is regarded as a bundle of competencies that will be brought to the customer to enhance the customer economics.

Table 24: "System Lock-in" Delta Strategy (Investinor, 2010)

System Lock-In	Focuses on complementor economics	
Restricted Access	Significant barriers are in place that make it difficult for competitors to even compete for the acquisition of customers.	This is a difficult position to achieve and to sustain. Regulatory prectices tend to be deployed to prevent it, has to be accomplished one customer at a time.
Dominant Exchange	With this strategy the company provides an interface between buyers and sellers that is very hard to displace once it achieves critical mass.	This is the most accessible of all of the systems lock-in options. The first mover advantage is critical.
Proprietary Standard	The customer is drawn to your product because of the extensive network of third party complementors that are designed to work with your product.	This option isn't available in most industries. If it can be achieved the rewards are enormous.

5.6.2 Delta Model Winning Steps

The following are delta model steps necessary and sufficient for success (Hax & Wilde, 2003).

Step 1: Customer Segmentation

"Concentrate on the customer. Start with a careful segmentation of your customer base and develop as much knowledge as possible of the customer economics. Remember that the primary objective is to seek customer bonding."

Step 2: Strategic Positioning

"Select the most appropriate strategic positioning among the three key options (Best Product, Total Customer Solutions, and System Lock-in) that will result in a customer value proposition with the highest possible bonding."

Step 3: Implementation of Strategic Option

"Define the strategic agenda that determines the action program to implement your desired strategic option. Assure the proper alignment with the three adaptive processes – Operational Effectiveness, Customer Targeting, and Innovation."

Step 4: Key Performance Indicators (KPI)

"Design the proper metrics and reward to facilitate the strategy development."

5.6.3 The Adaptive Processes: Linking Strategy with Execution

The adaptive processes (*Operational Effectiveness*, *Customer Targeting* and *Innovation*) are business processes that capture the essential tasks of execution. The adaptive processes are the tools expected to bring about a sound implementation of the strategic positioning (*Best Product*, *Total Customer Solutions* or *System Lock-in*).

The table below describes the synergy between adaptive process and strategic positioning.

Table 25: The Role of the Adaptive Processes in supporting the Strategic Options of the Triangle (Hax & Wilde, 2003)

	Best Product	Total Customer Solutions	System Lock-in
Operational Effectiveness	Best Product Cost Identify product cost drivers Improve stand along product cost	Best Customer Benefits Improve customer economics Improve horizontal linkages in the components of total solutions	Best System Performance Improve system performance drivers Integrate complementors in improving system performance
Customer Targeting	Target Distribution Channels Maximize coverage through multiple channels Obtain low cost distribution Identify and enhance the profitability of each product by channel	Target Customer Bundles Identify and exploit opportunities to add value to key customers by bundling solutions and customization Increase customer value and possible alliances to bundle solutions Select key vertical markets Examine channel ownership options	Target System Architecture Identify leading complementors in the system Consolidate a lock-in position with complementors Expand number and variety of complementors Whenever possible create ownership of direct distribution channels
Innovation	Product Innovation Develop family of products based on common platform First to market, or follow rapidly — stream of products	Customer Service Innovation Identify and exploit joint development linked to the customer value chain Expand your offer into the customer value chain to improve customer economics Integrate and innovate customer care functions Increase customer lock-in through customization and learning	System Innovation Create customer and system lock-in, and competitive lock-out Design proprietary standard within open architecture — Complex interfaces — Rapid evolution — Backward compatability

5.7 Conclusion

In this chapter, the path to maximum Return on Investment (ROI) in the course of commercializing MCDS was analyzed and the delta business model was recommended.

6. FINAL CONCLUSION AND FURTHER RECOMMENDATIONS

6.1 *Final Conclusion*

Maintenance optimization is a broad sector of industrial optimization that encompasses four major optimization categories, namely: maintenance strategy optimization, maintenance interval optimization, manpower strategy optimization and spare-part strategy optimization.

Maintenance strategy optimization entails the application of the most cost-effective technique or method to a given maintenance program. This is achievable by using an RCM Logic Tree.

Maintenance interval optimization involves the determination of the most cost-effective frequency for the application of a maintenance strategy on a given maintenance program since both under-maintenance and over-maintenance are undesirable. This is realizable with the aid of cost, component and system performance models, namely: Weibull PM model, ARP model, PF model, PFD model, etc.

Manpower strategy optimization is about the improvement of the efficiency of maintenance workers. This is attainable with the deployment of CMMS, which is a revolutionized departure from the paper-based maintenance system of old.

Spare-parts strategy optimization ensures that just-enough number of spares are kept at a vantage locations, thus minimizing holding costs and maintenance lead-time. This is feasible via spare-parts inventory control analysis and spare parts location matrix.

Return on Investment (ROI) in a maintenance organization can be maximized through the proper combination of these four classes of maintenance optimization.

This thesis has offered a total maintenance optimization solution in an integrated package, a synergy of all the aforementioned aspects of maintenance optimization. The product is Maintenance Concept Database Solution (MCDS).

6.2 *Further Recommendations/Further Work*

The following are some important points to be considered for the future:

6.2.1 Recommendations for the Short Term (1-3 years)

- Creation of necessary links/interfaces for data/information transfer within the MCDS package.
- Engagement of the services of an aggressive Business Development Manager to present proposals on the product to companies in Norway and the entire Nordic region.
- Participation in different trade fairs to showcase the product.
- Presentation of the new product to companies which currently use KAMFER (an existing maintenance management tool) and/or other software from the portfolio of

AGR FO.

- Advertise in technical magazines, for e.g., *Teknisk Ukeblad.*

6.2.2 Recommendations for the Long Term (>3 years)

- Modification of MCDS to improve turnaround and shutdown preparedness and performance (Thorstensen, Finbak, & Thuestad, 2010)
- Modification of MCDS to optimize turnaround and shutdown frequency and duration for a single installation (Thorstensen, Finbak, & Thuestad, 2010)
- Modification of MCDS to optimize turnaround frequency and duration across interdependent installations (Thorstensen, Finbak, & Thuestad, 2010)

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