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Reliability centered maintenance on the Norwegian continental shelf

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Preface

This master thesis has been written at the Norwegian University of Science and Technology, NTNU, Department of Marine Technology. The work corresponds to 30 credit points.

The aim of this thesis has been to unveil the challenges of RCM as an analysis method for assets on the Norwegian continental shelf. Writing the thesis has been exceedingly interesting and provided a lot of learning on how maintenance is managed on the Norwegian continental shelf, and in particular with respect to RCM. I have found much joy with the research and would love to do this again, if I had the opportunity. However, knew adventures are ahead of me in the industry where I will get to work more with maintenance.

There have also been challenges to overcome during the work with my thesis. I am thinking especially about my brother, Håvard, who tragically died after been involved in a motorcycle accident. It has been a long and tough process that has demanded a lot of my attention. I would like to thank the University for understanding the difficult situation I have been through, when extending the deadline for delivery. I would also like thank my supervisor Professor Ingrid Bouwer Utne for letting me write a thesis on a topic that I wanted. All the meetings and feedback I've gotten have been meaningful, motivational and helped me keeping a steady progress. Thank you very much, Ingrid. I truly appreciate your educational skills and kindliness.

To all my friends and family who have stayed close with me through all the times, I cannot express how grateful I am for you just being around me. I must mention my nephew Anders for all the long conversations and for helping me with editing figures and Andreas Nilsen for being helpful with programming. Thank you!

Last, but not least, a special thanks goes to my fiancée Line. Now we'll finally get more time to be together.

Trondheim, April 8th 2014

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Sverre Wattum

Summary

The main objective of this thesis is to unveil the challenges of RCM as an analysis method for assets on the Norwegian continental shelf. A mixed research method have been used, also known as a semi-quantitative method, with gathering of both quantitative and qualitative data from RCM facilitators with relevant experience. A secondary goal with this thesis has been to develop a systematic approach to those who participate in RCM processes, to evaluate their own processes and RCM tools towards applicable standards to generate increased awareness.

The primary motivation for maintenance on the Norwegian continental shelf is risk centered, rather than reliability centered. Nevertheless, it is called for RCM, but not all the capacities of RCM to ensure reliability are utilized. There were found several reasons for why this is so.

RCM is by many viewed as a resource consuming method. This have led to many attempts in streamlining the process, which often entails crosscuts that threatens the quality of the analysis.

Another reason is the lack of data to perform mathematical and statistical evaluations, which implies that nearly all decisions made in the analysis are based on qualitative experiences rather than neutral data. This is a challenge which is hard to overcome when maintenance concepts, assets and processes to analyze are dynamic and will always be subject for change. That should be a good reason for performing living programs, so that the analysis keep track with the changes. However, this is not the case, which means that data will not be gathered either. There is simply no culture for taking use of mathematical and statistical formulae in order to optimize maintenance.

RCM depends to a large degree on the humans performing the analysis. This involves personal knowledge of the RCM methodology, software skills, insight and understanding of the assets and systems under review, and an ability to cooperate in a group while carrying out the analysis.

The large tag structures on the Norwegian continental shelf that are analyzed with RCM are complex structures that are challenging to keep overview of when performing the analysis. With such large tag structure, it is hard to take notice if an item has changed its identification because such changes are not necessarily updated with the RCM software. This puts the analysis in risk of omitting certain items for the analysis. Also, it is hard to estimate how long it will take to perform an analysis for large tag structures.

A method for self-evaluation of RCM processes have been developed for RCM participants in order to ensure increased awareness on important aspects of the RCM methodology and software in use.

The work from this thesis can be continued by testing out the survey which has been developed, in order to make this a tool for RCM participants to increase awareness in the processes and the tools they use when performing the analyses.

Relevant research could also be done within the standardization of methods and criterions for execution of RCM analysis.

Future attention should be put on how one can collect data from maintenance for use in mathematical and statistical formulae to ensure living programs for RCM analyses.

Sammendrag

Formålet med denne masteroppgaven har vært å avdekke hvilke utfordringer som er knyttet til RCM-analyse av store tag-strukturer på norsk sokkel. En semi-kvantitativ metode er benyttet, der bade kvantitative og kvalitative data har blitt innhentet fra RCM-fasilitatorer med relevant erfaring. I tillegg har det vært et mål å utvikle en systematisk metode til deltakere i RCM-prosesser som gjør at de kan evaluere egne prosesser og verktøy opp i mot relevante standarder for å skape økt bevissthet.

Hovedgrunnlaget for alt vedlikehold som gjøres på norsk sokkel er basert på tilnærminger innen risiko fremfor pålitelighet. Likevel er RCM både en anbefalt og etterspurt metodikk, uten at alle dens egenskaper kommer til sin fulle rett i å ivareta pålitelighet. Det ble påpekt flere grunner til hvorfor dette er slik.

RCM er av mange oppfattet som en ressurskrevende prosess. Dette har ført til mange forsøk på strømlinjeformede RCM-prosesser, hvilket har lett for å innebære snarveier i analysen som igjen medfører en trussel på kvaliteten som analysen leverer.

Andre årsaker er manglende datagrunnlag for å gjøre matematiske beregninger med tall, hvilket innebærer at så å si alle beslutninger som tas i en RCM-prosess er basert på kvalitative erfaringer fremfor et nøytralt datagrunnlag. Denne utfordringen er vanskelig å håndtere på grunn av at vedlikeholdskonsepter, utstyr og prosesser som analyseres er dynamiske og derfor hele tiden i endring. Det i seg selv burde være en god grunn til å implementere levende program som ivaretar endringer i forhold til analysen. Dette er likevel ikke tilfellet, hvilket betyr at et datagrunnlag heller ikke vil bli samlet inn. Et annet tilfelle som gjør dette vanskelig er at det heller ikke finnes en kultur for å benytte seg av matematiske metoder for å optimere vedlikeholdet.

RCM avhenger i stor grad av de menneskene som utfører analysen. Dette involverer menneskelig kompetanse på RCM-metodikken, datatekniske ferdigheter, innsikt og forståelse i utstyret og systemene som analyseres, og evne til å samarbeide i gruppe i utarbeidelsen av analysen.

De store tag-strukturene som analyseres med RCM på norsk sokkel er komplekse og utfordrende å holde oversikt over underveis i analysen. Det er også vanskelig å fange opp endringer i id-nummereringen av utstyr, fordi slike oppdateringer ikke nødvendigvis oppdateres automatisk i RCM-verktøyet som benyttes i analysen. Dette medfører at analysen

står i fare for å overse enkeltkomponenter. Det er dessuten vanskelig å estimere hvor lang tid en analyse med store tag-strukturer vil vare.

Det er utviklet en metode for selv-evaluering av RCM-prosesser for alle RCM-deltagere. Hensikten med dette er å skape økt bevissthet omkring viktige aspekter i RCM-metodikken og RCM-verktøy.

Arbeidet I denne masteroppgaven kan videreføres ved å teste ut selv-evalueringen som har blitt utviklet, slik at denne kan bli et verktøy deltagere i RCM-prosesser kan benytte seg av for å oppnå økt bevissthet omkring prosessene de deltar i og verktøyene de bruker.

Videre relevant forskning kan også rettes mot standardisering av metoder og kriterier for gjennomføringen av RCM-analyser.

Det bør også vies oppmerksomhet i hvordan man kan samle inn data til bruk i matematiske modeller for optimering av vedlikehold og sikre at RCM-analysen holdes levende gjennom et utstyrs levetid.

Abbreviations

A-RCM	Accelerated Reliability Centered Maintenance
CMMS	Computerized Maintenance Management Systems
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Mode, Effects, and Criticality Analysis
FRRM	Fault Recovery Management Mechanism
GMC	Generic Maintenance Concept
HES	Health, Environment and Safety
ILS	Integrated Logistic Support
LCC	Life Cycle Cost
NPD	Norwegian Petroleum Directorate
PM	Preventive Maintenance
PMO	Preventive Maintenance Optimization
PSA	Petroleum Safety Authority
QFD	Quality Function Deployment
RBI	Risk-Based Inspection
RCFA	Root Cause Failure Analysis
RCM	Reliability Centered Maintenance
RCOM	Reliability Centered Operation and Maintenance
RRCM	Reliability and Risk Centered Maintenance
SIL	Safety Integrity Level

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Introduction

Background

During the 1990s the petroleum activity on the Norwegian continental shelf was marked by development of new technology and increased competency, which in turn led to prolonged and increased production. The physical development and high activity also led to an increased number of technical and maintenance related challenges.

RCM has been introduced and much used in the industry as a method to identify and select failure management policies to efficiently and effectively achieve the required safety, availability and economy of operation, in accordance with NEK IEC 60300-3-11 (2009).

Initially developed by the commercial aviation industry, RCM has been, and still is, the focal point in discussions with respect to its practicability to the petroleum industry on the Norwegian continental shelf. As an established and highly acknowledged method, it has also been exposed to several attempts of development. Various suggestions have been proposed in adapting, adjusting or automating the RCM process.

However, less research is done to identify the specific problems that are related to RCM for assets on the Norwegian continental shelf. A systemized approach in understanding these would be an appropriate starting point for defining solutions to application of RCM. In turn, that would hopefully lead to improved management of maintenance on the Norwegian continental shelf as well.

Objective

The main objective of this thesis is to unveil the challenges of RCM as an analysis method for assets on the Norwegian continental shelf.

In order to achieve this, the thesis will view RCM as part of a whole on the Norwegian continental shelf, and also drill down in to details of the RCM method. Both of these aspects are considered necessary to cover, in order to understand what the challenges really are with RCM in this context.

A secondary goal with this thesis is to develop a systematic approach to those who participate in RCM processes, to evaluate their own processes and RCM tools towards applicable standards. The intention of this is to contribute to increased awareness and a common understanding of RCM. The desired effect is a better and common understanding among RCM participants, as a basis for learning and improvement.

This thesis will provide an overview of RCM for the Norwegian continental shelf, which should be of special interest for everyone directly involved in these processes. It should be of general interest for everyone working with maintenance management in this area, and who are indirectly affected and wants to gain more insight into the methodology and its suitability. Since RCM is used worldwide, this thesis may also be of interest for RCM developers and researchers throughout the world who debates RCM and wants to improve the method.

Scope and limitations

This thesis is limited to investigate the issues of applying RCM on assets operating on the Norwegian continental shelf, which applies to large tag structures such as oil platforms and drilling rigs with thousands of tags.

The matter of risk will be discussed, but this thesis is not an evaluation of risk or risk assessment as such. Rather, risk will be discussed along with maintenance to gain a better understanding of RCM.

Software has become an unavoidable part of today's RCM analysis, and will therefore be subject for analysis and discussion in this thesis. However, this thesis will not go further in detail of what makes good software or how RCM should be programmed into software. What concerns software, this thesis is limited to superficial software functionality and how these may affect the RCM process itself.

The thesis is not intended to provide a course in RCM, but the method and its context must be explained to give answer to the problem addressed. If one finds interest in the literature brought up in this thesis, one is suggested to look up the references to read more.

Since RCM is a globally acknowledged process the reader may find parts of this thesis relevant for own interest. Therefore, it is worth emphasizing that the thesis is intentionally meant for large tag structures on assets operating on the Norwegian shelf. This means that the results in this thesis are especially related for this purpose.

Review of the Literature

The concept of maintenance on the Norwegian continental shelf is first reviewed to legitimate the role of RCM in this context. Then a presentation of the RCM methodology, relevant literature and research on RCM are following in this chapter.

Maintenance on the Norwegian continental shelf

Many of the facilities on the Norwegian continental shelf were older than what they were designed for (Meland et al. 2008:6) which would lead to consequences for the management of maintenance (Øien and Schjølberg 2009:52):

1. Increased scope of maintenance
2. Increased time consumption for performing maintenance on ageing facilities
3. An increasing need for updating analyses
4. An increasing need for modifications and replacements
5. A stronger focus on continuous improvement and maintenance efficiency

Maintenance baseline study

In 1996 the NPD initiated a project called "The maintenance baseline study". The objective was to develop a method for systematic and comprehensive assessment of the companies own maintenance management system (NPD 1998:3). The desired effect was to contribute to a general improvement of the quality of the operator's system for managing safety-related maintenance and provide better predictability for the operators, in terms of the NPD's expectations and requirements within this area (NPD 1998:3).

As a result, the study presented a model named the maintenance management model, based on the structure of a quality system (NPD 1998:8). The model is presented in figure 1. It claims to be viewed as an overall process description of safety related maintenance management with the purpose of producing safety and availability. It contains a number of elements which are supposed to illustrate a continuous improvement process. In this process problems are incessantly identified, solved, and decent solutions are standardized.

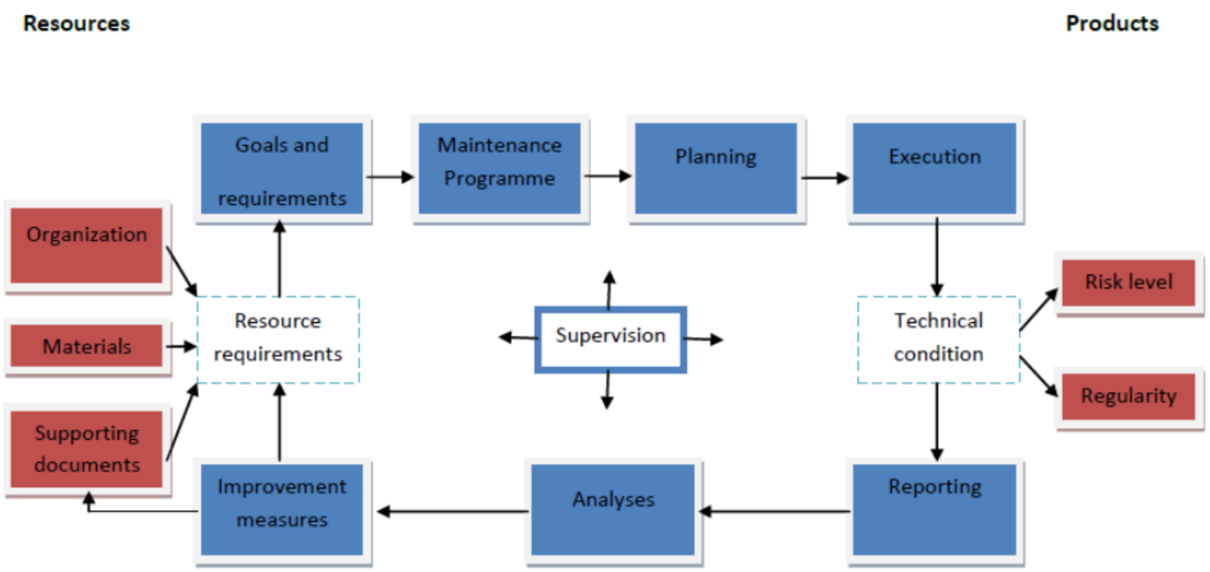

Figure 1: Maintenance management model.

The operating companies were invited to relate themselves to the model by answering questions from each of the elements in it. In this way, the questions were meant to facilitate the companies to generate new ideas and increase awareness on predictability and safety-related maintenance.

Petroleum Safety Authority

On the 14th of December in 2001 a white paper (St.meld. no.7, 2001-2002) was recommended by the coalition Government and approved by the Parliament in Norway. The paper expressed concern with the development of the petroleum activity on the Norwegian continental shelf. It suggested more attention on HSE and stated that it was necessary to invest adequately of resources in maintenance to reach desired results with regard to HSE, operation regularity and efficiency (St.meld. no.7 2001-2002:51).

In the paper, authorities suggested co-operation with the operating companies to fortify the quality of maintenance on the Norwegian continental shelf by using the maintenance baseline study as a foundation (St.meld. no.7 2001-2002:52). Also, the paper suggested that the NPD should be supplied with new duties as well as it should prioritize or expand its attention to particular areas (St.meld. no.7 2001-2002:90). A direct result was more money granted to the NPD to ensure its supervision with HSE.

During the late 2002 the government resolved that the NPD would be divided by allocating responsibility for supervising safety to a separate regulator entitled the PSA, which were given the following duties from the government (PTIL 2014):

1. Ensure that the petroleum industry and related activities are supervised in a coherent manner through PSA's own audits and in cooperation with other health, safety and environmental (HSE) regulators.
2. Supply information and advice to the players in the industry, establish appropriate collaboration with other HSE regulators nationally and internationally, and to contribute actively to conveying knowledge about HSE to society in general.
3. Provide input to the supervising ministry on matters being dealt with by the latter, and support with issues on request.

As a result, PSA developed regulations and supervisory systems to help enhance the companies' awareness on responsible and acceptable operations. As with the baseline study, companies were free to generate new ideas and solutions, but PSA would execute system-oriented and risk-based supervision at relevant parts of a company's management system in the form of audits and verifications.

In the Activity Regulation (2014) which was enforced by PSA, the Norwegian Environment Agency and the health authorities; maintenance was officially defined as a petroleum activity. Chapter IX in this regulation, which is titled "Maintenance", is instructive for maintenance on the Norwegian continental shelf. It is quoted in its entirety in appendix A. Briefly summed up, this chapter may be said to focus on classification of failure modes that constitute HSE risk, as a basis for maintenance. To satisfy these classification requirements, the NORSOK Z-008 standard should be used in the area of health, working environment and safety (Activity Regulation 2014, section 46).

NORSOK Z-008: Risk based maintenance and consequence classification

Z-008 is a NORSOK standard developed with broad petroleum industry participation by interested parties in the Norwegian petroleum industry and is owned by the Norwegian petroleum industry represented by The Norwegian Oil Industry Association and The Federation of Norwegian Industry (Z-008:1). It is supposed to provide requirements and guidelines in the preparation and optimization of maintenance activities, and cover all types of failure modes and failure mechanisms.

Primarily, the standard states that risk assessment shall be used as the guiding principle for maintenance decisions (Z-008:11). The key elements of the methodology for risk based maintenance management are summed up (Z-008:12):

a) Consequence classification of functional failure.
b) Use of GMC in combination with classical RCM methods. The GMCs are developed by RCM analysis including plant experience. The GMCs will implicit express the probability of failure via the maintenance tasks and the maintenance interval assigned. It is recommended that the GMCs are adjusted to the local conditions via a cost-benefit assessment and including other local conditions.
c) In case no GMC are applicable or the purpose of the study requires more in-depth evaluations, an FMECA/RCM/RBI analysis should be carried out. Identification of relevant failure modes and estimation of failure probability should primarily be based on operational experience of the actual equipment. Alternatively generic failure data from similar operations may be used with sufficiently reliable data qualification in accordance with ISO 20815, Annex E.2.
d) The application of the consequence classification and additional risk factors for decision making related to corrective maintenance and handling of spare parts.

The maintenance management process in Z-008 is a development of the maintenance management model from the maintenance baseline study, which is already presented in figure 1. There are only minor adjustments and the principles are equivalent for both models.

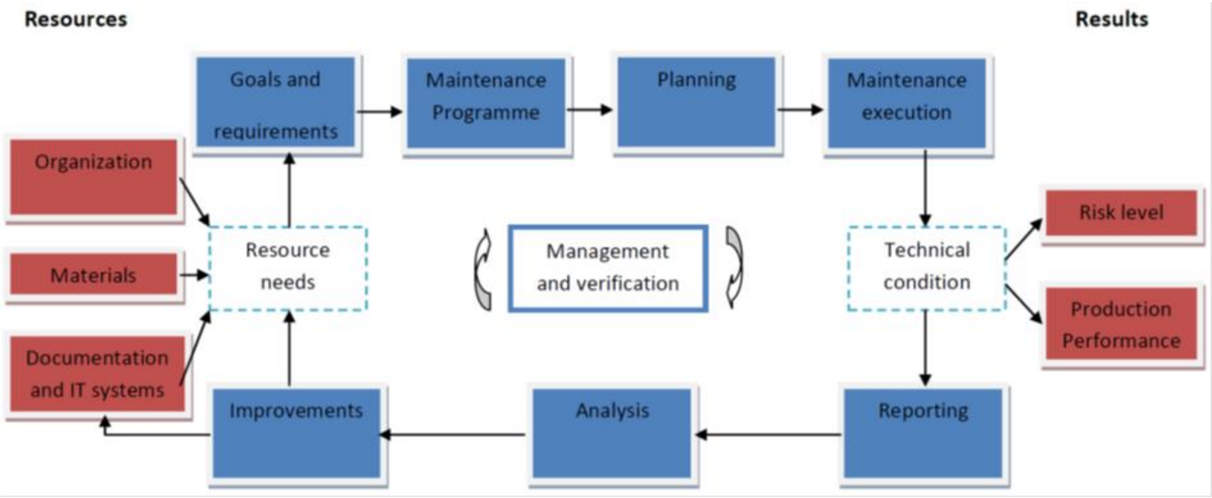

Figure 2: Maintenance management process.

RCM belongs to the element named “Maintenance Programme” in this model. This is where failure modes, failure mechanisms and failure causes that can have a significant effect on safety and production shall be identified and risk determined in order to establish a maintenance programme (Z-008:14). This is also where consequence classifications for functions belong.

Maintenance programme

The purpose of a maintenance programme is to control all risks associated with degradation of equipment (Z-008:20). This starts with a consequence classification to identify critical equipment for HSE, production and cost (Z-008:17). The consequence classification process in Z-008 is illustrated in figure 3.

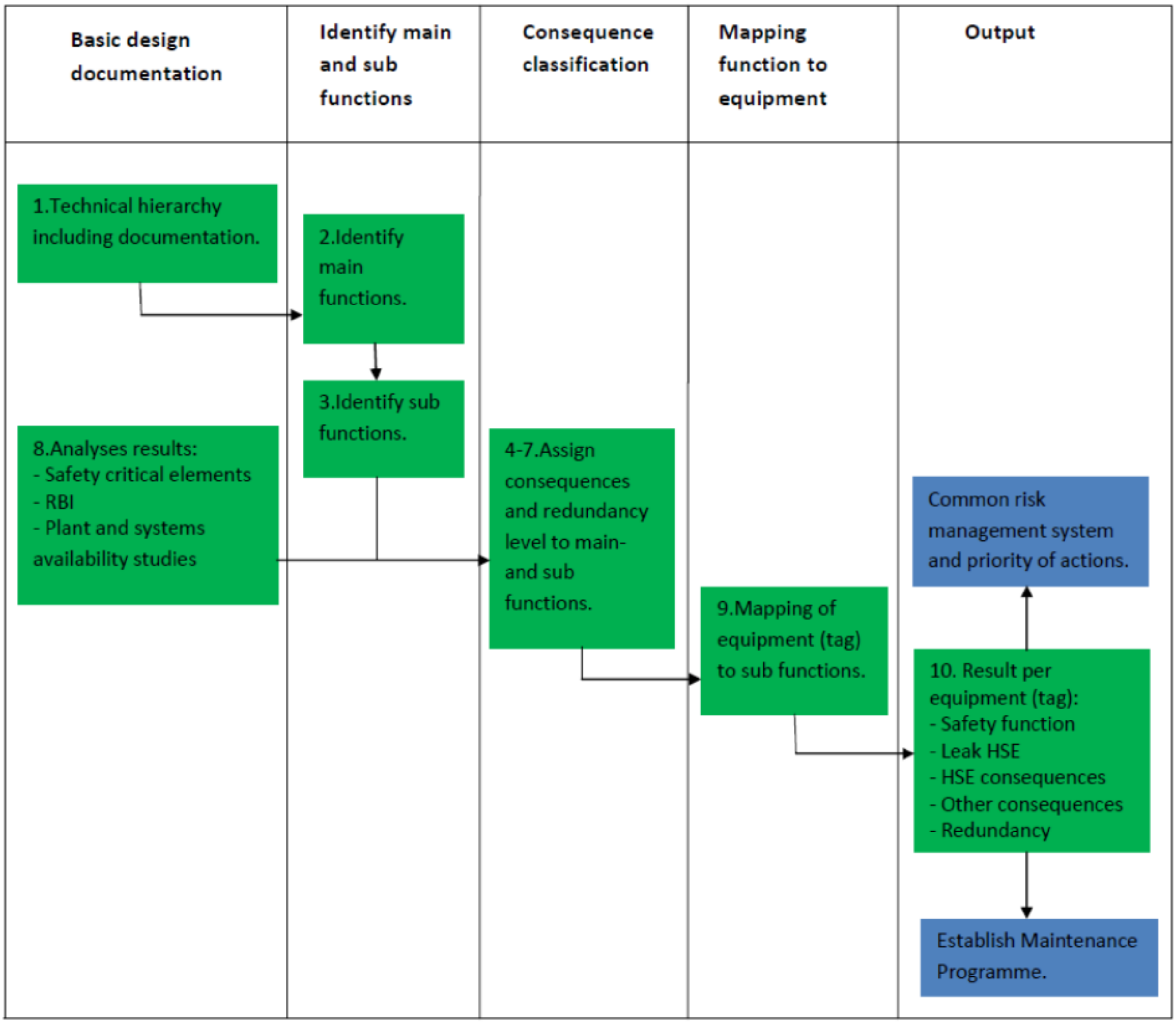

Figure 3: Consequence classification process.

In the consequence classification process, tag structure is first established as a technical hierarchy before components are broken down into functions for analysis. A consequence classification together with other key information and parameters gives input to the following activities and processes (Z-008:17):

1. Selection of equipment where detailed RCM/RBI/FMECA analysis is recommended
2. Establish PM programme
3. Preparation and optimisation of GMCs
4. Design evaluations
5. Prioritisation of work orders
6. Spare part evaluations

Z-008 further promotes GMC in combination with detailed RCM methods to establish a maintenance programme. A GMC 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 (Z-008:22). The process of establishing a maintenance programme in accordance with Z-008 is illustrated in figure 4.

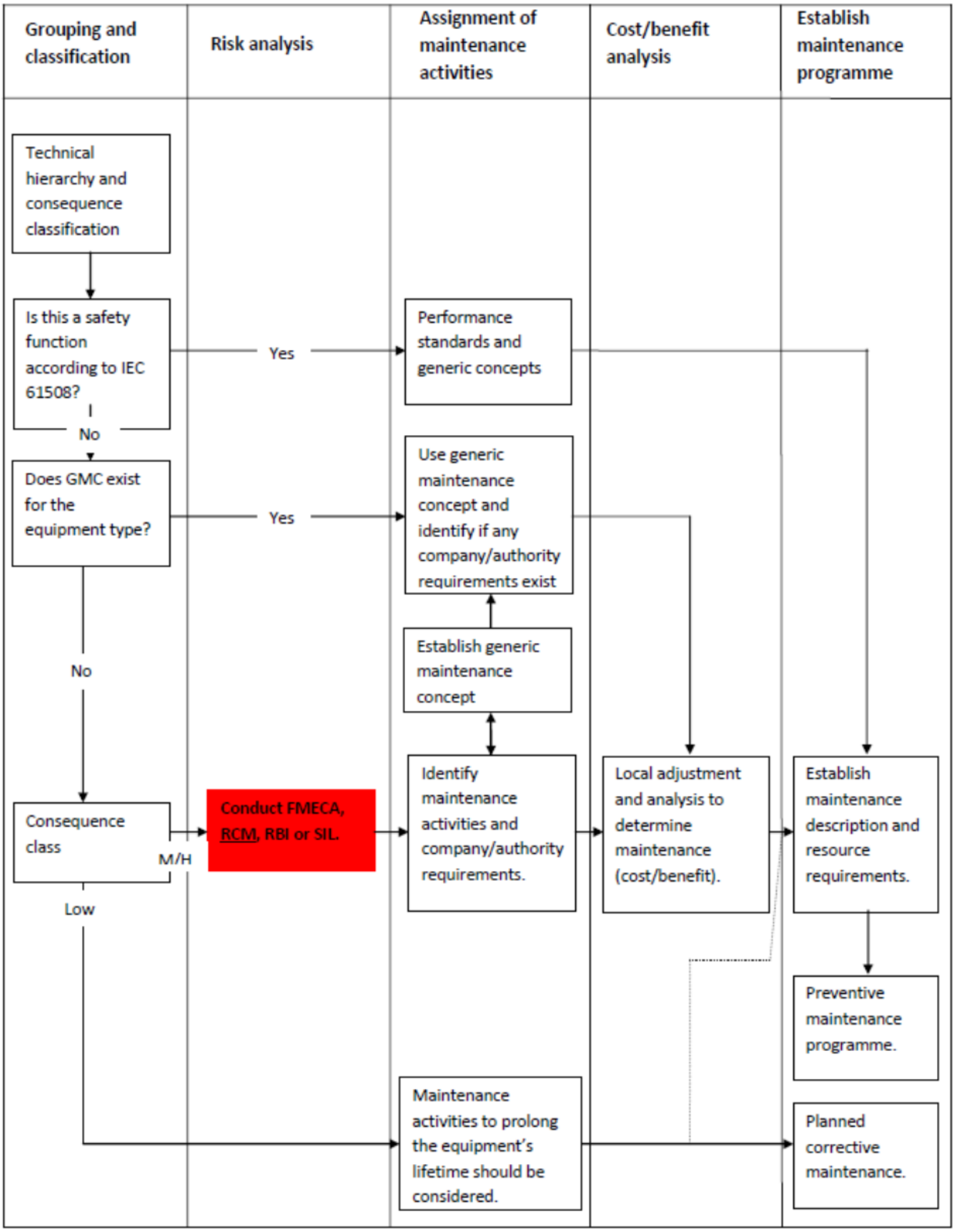

Figure 4: The process of establishing a maintenance programme according to Z-008.

The maintenance programme starts with a consequence classification, as already presented, to identify safety functions. If there happen to be a GMC for the equipment, its applicability and relevance should be considered and adjusted as a basis for establishing maintenance description and resource requirements for a preventive maintenance program. In case no GMC is applicable or the purpose of the study requires more in-depth evaluations, it is recommended that an FMECA/RCM/RBI/SIL analysis is carried out according to IEC 60300-3-11 and DNV RP-G-101 (Z-008:20).

Application guide RCM

IEC 60300-3-11 provides guidelines for the development of failure management policies for equipment and structures using RCM analysis techniques (60300-3-11:7). The standard describes RCM as a part of a maintenance policy where the objectives of an effective preventive maintenance programme are (60300-3-11:12):

a) To maintain the function of an item at the required dependability performance level within the given operating context.
b) To obtain the information necessary for design improvement or addition of redundancy for those items whose reliability proves inadequate.
c) To accomplish these goals at a minimum total LCC, including maintenance costs and the costs of residual failures.
d) To obtain the information necessary for the ongoing maintenance programme which improves upon the initial programme, and its revisions, by systematically assessing the effectiveness of previously defined maintenance tasks. Monitoring the condition of specific safety, critical or costly components play an important role in the development of a programme.

RCM is in this standard understood as a process with preliminary activities, analysis, and follow-on activities constituted of five elements, illustrated in figure 5 and further explained.

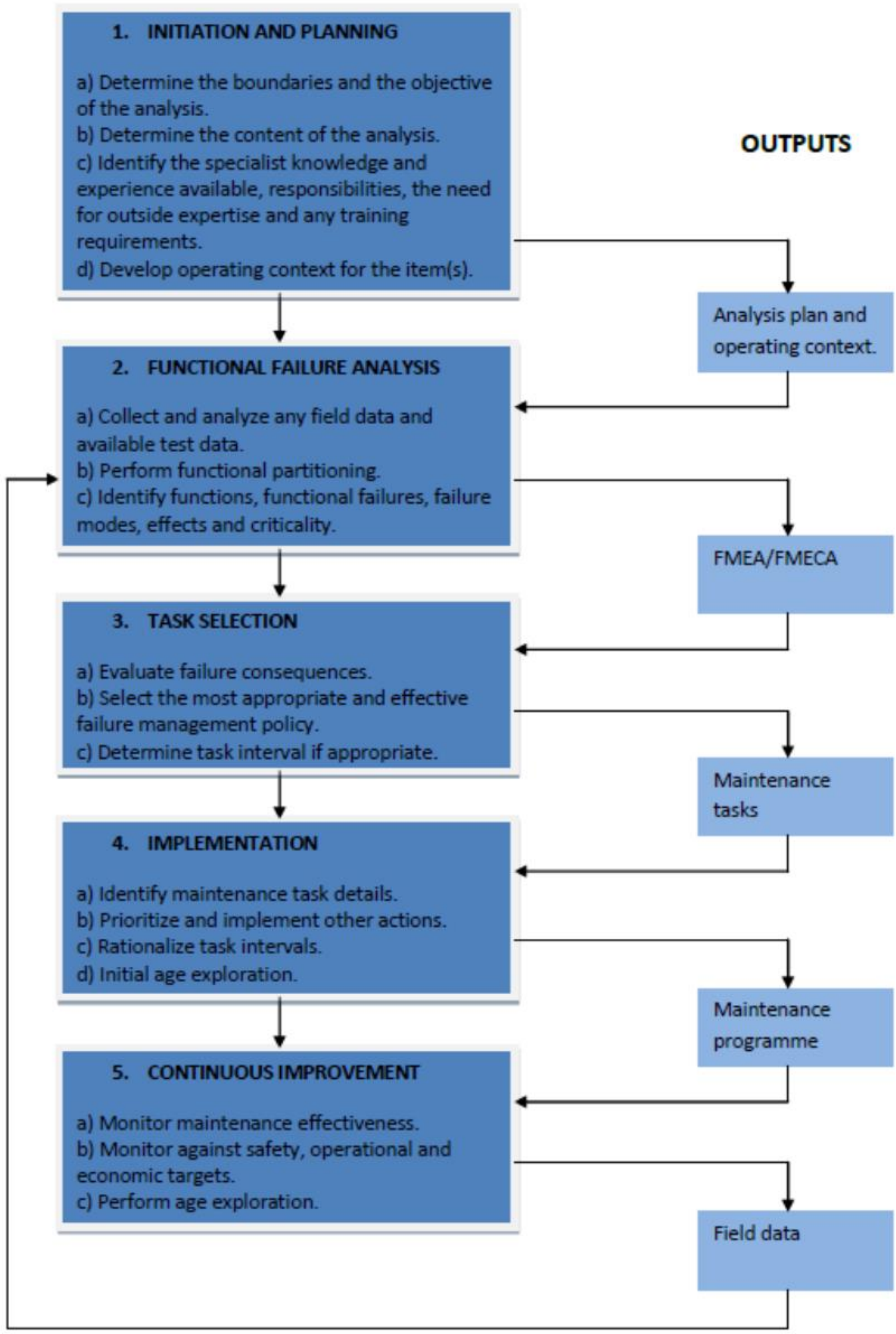

Figure 5: Overview of the RCM process in accordance with IEC 60300-3-11.

Initiation and planning

The first phase of the RCM process, as described in IEC 60300-3-11, is to determine the need and extent of the study (60300-3-11:15), based on the organization's programme of continuous maintenance improvement.

Secondly, an RCM analysis should only be implemented when there is confidence that it can be cost effective or when direct commercial cost considerations are overridden by other critical objects, such as requirements for safety and the environment (60300-3-11:16). The analysis requires (60300-3-11:17):

a) Knowledge of and experience with the RCM process.
b) Detailed knowledge of the item and the appropriate design features.
c) Knowledge of the items' operating context.
d) Knowledge of the condition of the item (when analyzing existing equipment).
e) Understanding of the failure modes and their effects.
f) Specialist knowledge of constraints, such as safety and environmental legislation, regulation.
g) Knowledge of the maintenance techniques and tools.
h) Knowledge of costs.

Prior to conducting an RCM analysis, it is essential that an operating context statement is developed (60300-3-11:17). This is supported by the need for knowledge of the environment that the item is operating in, which affects the desired performance from the item. Also, the context may change with time resulting in various requirements for performance, which further supports the need for defining the different operating contexts for an asset. Redundancy is another argument directly affecting reliability and availability of a system, which gives another reason for careful development of the operating context.

As part of any RCM analysis effort, a set of guidelines and assumptions should be made to help direct the analysis process (60300-3-11:18). This is for instance prevailing regulations or procedures, risk analyses, reliability block diagrams or other data sources aiding in establishing a consistent approach with the RCM. Actual or generic failure data used in isolation has limited value without understanding failure mechanisms and the operating context (60300-3-11:19). The use of system experts along with all obtainable failure data is therefore suggested when performing RCM.

The output from performing initiation and planning is a plan for the analysis.

Functional failure analysis

When undertaking the analysis of a complex item, it may be necessary to break down the total functionality into more manageable blocks (60300-3-11:20). A functionally based equipment hierarchy may serve this purpose, which is relevant when performing RCM for large tag structures.

All functions of the item should be identified together with a performance standard, which is quantified whenever possible (60300-3-11:20). The performance standard is the level of performance required of the item to fulfil the stated function of the system in the given operating context, which should be stated quantitatively and/or unambiguously to ensure a meaningful analysis (60300-3-11:21). An item may serve several functions and each function may operate under various contexts, which is why these relations should be documented together with a performance standard.

All the functional failures associated with each of the defined functions should be identified (60300-3-11:21). When this is done the process is prepared for identification of failure modes. A failure mode is defined as a manner in which the inability of an item to perform a required function occurs (13306:9). The failure mode should include the identification of the physical item that has failed and a description of the failure mechanism (60300-3-11:21). The matter of risk assessment could come in handy when defining what failure modes to include or not, in terms of identifying those that are "reasonably likely" to cause functional failures. It is suggested that the owner of the asset defines what is "reasonably likely".

The effects of functional failure should be identified (60300-3-11:22). This is typically done after the failure modes have been identified. The importance of describing effects properly is to make clear what a failure mode would result in, making it easier to enable an accurate assessment of the consequences that come with them.

Not all failure modes are necessarily critical and therefore might not be cost effective to evaluate further (50300-3-11:22). IEC 60300-3-11 suggests a criticality analysis of the failure modes, combining severity and rate of occurrence to derive a criticality value representing the level of risk associated with a failure mode (2009:22). For failures where no analysis is required, it is often the case that the failures will be allowed to occur and no active preventive maintenance policy used; however, this decision is dependent upon the organization and its objectives (60300-3-11:22).

Task selection

IEC 60300-3-11 suggest a decision diagram (2009:25) to guide the analysis process when evaluating possible failure management policies for a preventive maintenance programme. Corrective maintenance tasks may result from the decision not to perform a preventive task, from the findings of a condition-based task, or an unanticipated failure mode (60300-3-11:23).

The objective of RCM task selection is to select a failure management policy that avoids or mitigates the consequences of each identified failure mode, the criticality of which renders it worthy of consideration (60300-3-11:23).

The decision logic is used to classify the consequences of the failure mode and then ascertain if there is an applicable and effective maintenance task that will prevent or mitigate it (60300-3-11:24). The diagram is presented in figure 6.

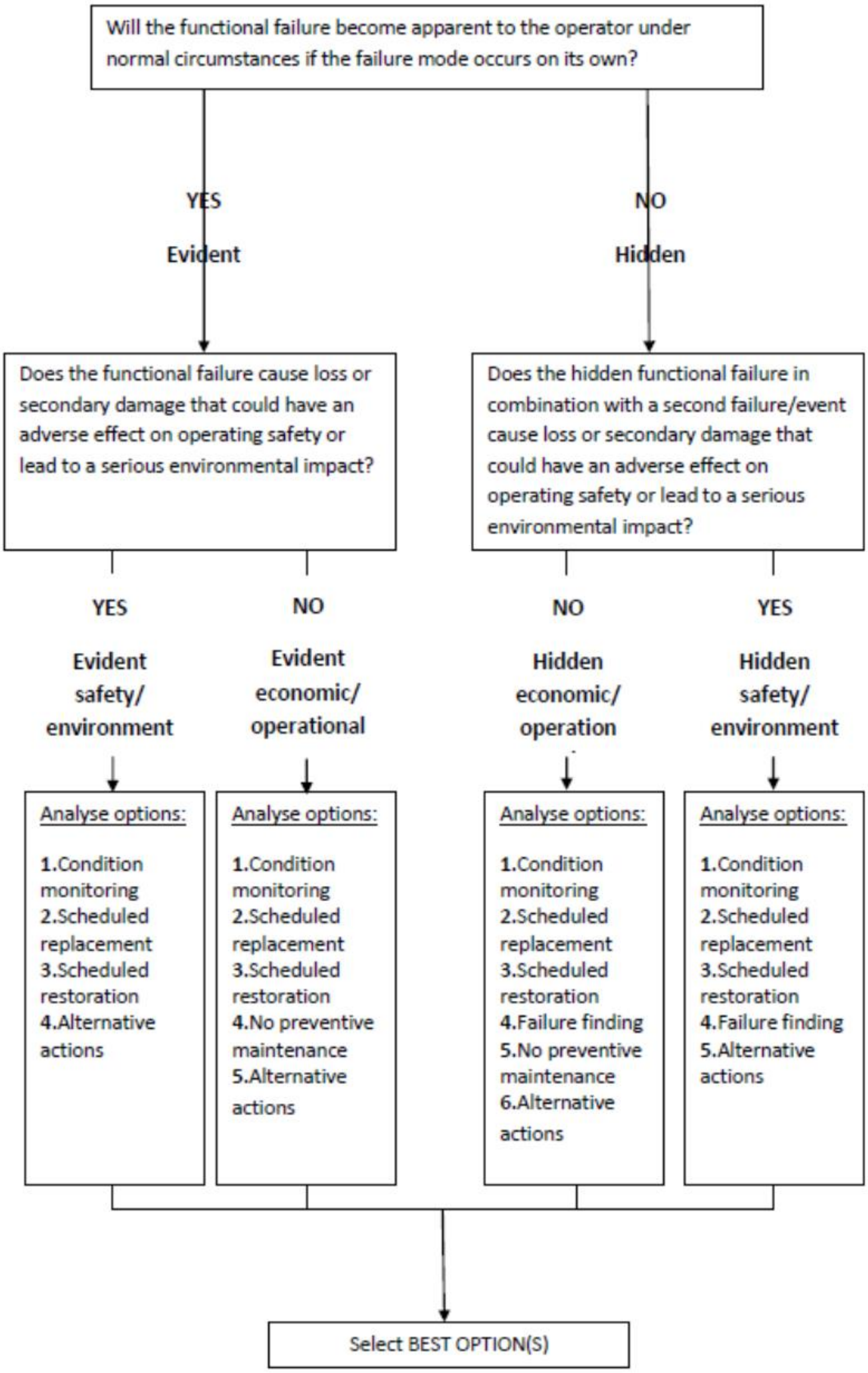

Figure 6: The decision logic in accordance with IEC 60300-3-11.

In the decision logic, failure modes are processed to be classified in terms of the consequences of functional failure. There are four different classes that a failure mode may be allocated to, according to the logic:

1. Hidden functional failure with safety/environmental consequences
2. Hidden functional failure with economic/operational consequences
3. Evident functional failure with safety/environmental consequences
4. Evident functional failure with economic/operational consequences

For each of these classes, there are a set of suggested analyze options that are meant to aid in the selection of an appropriate failure management policy for each failure mode. These options are, according to IEC 60300-3-11:

1. Condition monitoring
2. Scheduled restoration
3. Scheduled replacement
4. Failure-finding
5. No preventive maintenance
6. Alternative actions
    a. Redesign
    b. Modifications
    c. Changes in operating procedures
    d. Changes in maintenance procedures
    e. Pre-use or after-use checks
    f. Modification of spare supply strategy
    g. Training of operators or maintenance personnel

The best option will be determined by the cost of executing that solution and the operational consequences that option will have on the programme's maintenance operations (60300-3-11:27).

To set a task frequency or interval, it is necessary to determine the characteristics of the failure mode that suggest a cost-effective interval for task accomplishment (60300-3-11). This may be done by gathering information from people with relevant experience, reliability data, life cycle costs, or predictions based on failure attributes.

Implementation

A task found from the decision logic might need additional details before it can be implemented, such as time consumption, procedure and description, the risk involved, or logistic issues connected with execution of the task (60300-3-11:30).

Maximum benefit can be obtained from an RCM analysis if it is conducted at the design stage so that feedback from the analysis can influence design (60300-3-11:30). Redesign is most economic if the system is not already built or put into operation.

The failure identification process and RCM analysis enable the whole range of expected maintenance tasks to be identified and hence permit support planning to be initiated (60300-3-11:31). Support planning could involve activities such as spare management, desired competency among the maintenance personnel, and the need for facilities to ensure the maintenance concept. At this stage ILS comes to interest in merging support activities which redeems customer requirements and the asset owner's needs. IEC 60300-3-12 describes the concept of ILS further.

Every effort should be made at the beginning of the development of a maintenance programme to institute a procedure for documenting electronically the results of the RCM analysis and all in-service modifications (60300-3-11:34). The standard encourages use of software in the RCM process, meaning that documentation and implementation of decisions becomes easier to manage when the analysis is performed electronically.

When an item's maintenance task is implemented, the standard suggests an age exploration of the item to determine the optimum maintenance task interval. Age exploration needs data, which can be generated in two ways according to IEC 60300-3-11 (2009:34):

1. Lead concept: The first items entering service are used extensively. This allows the early identification of dominant failure modes as well as wear-out patterns. It identifies design problems quickly.
2. Sample data collection: A sample of a population system is closely monitored.

Continuous improvement

Selected tasks need to be scheduled into a plan and allocated to the right maintenance personnel so that they can be carried out. At some point, one may experience that adjustments of intervals can be necessary in order to make the entire plan run smoothly, which is why a continuous improvement cycle is introduced in IEC 60300-3-11 (2009:35). The "RCM continuous improvement cycle" is illustrated in figure 7.

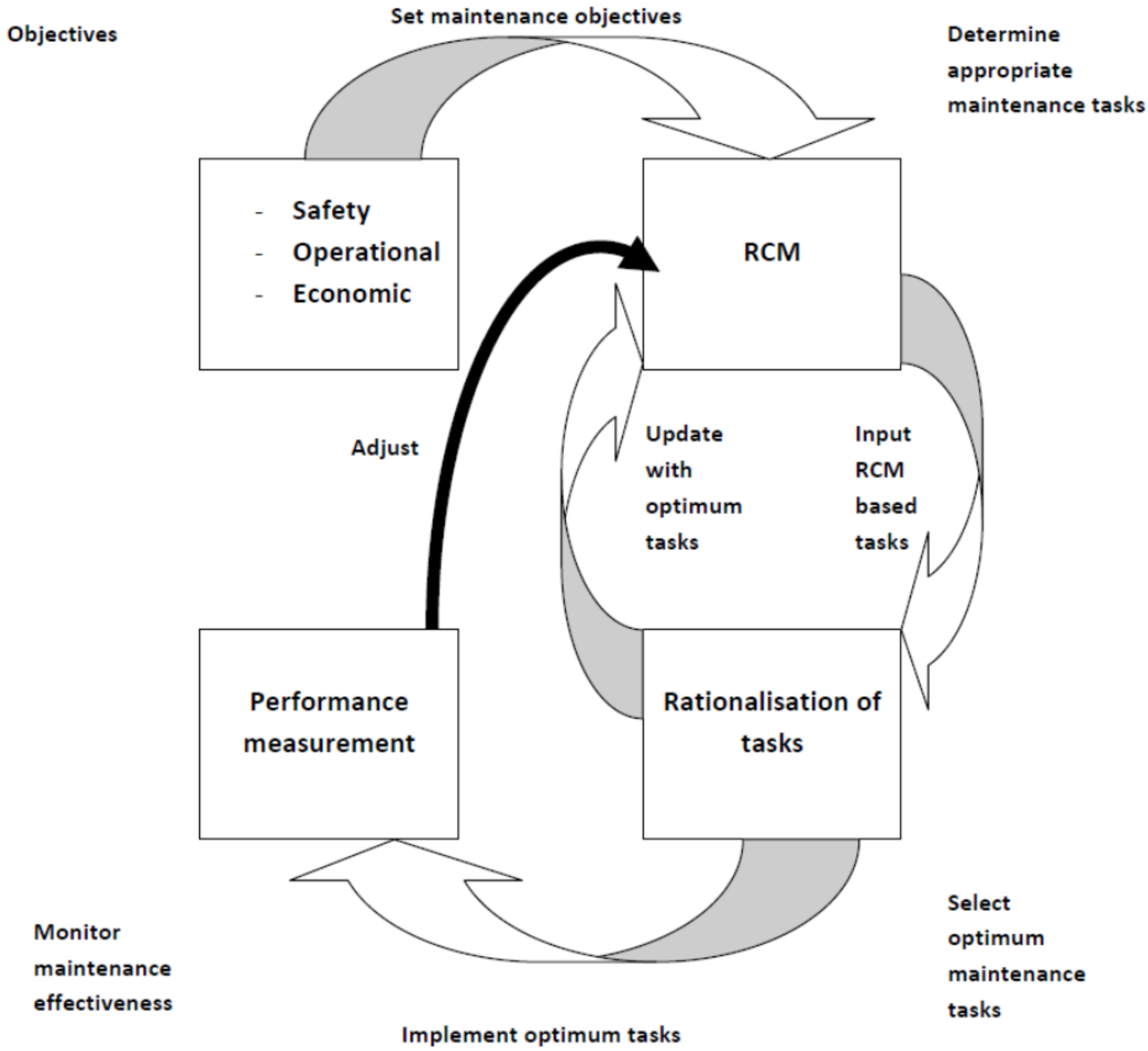

Figure 7: RCM continuous improvement cycle in accordance with IEC 60300-3-11.

The model has safety, operational and economic objectives as a basis. In order to ensure these objective, maintenance is needed. This calls for RCM to address the appropriate maintenance tasks. These tasks should be further rationalized and optimized. Monitoring of these tasks after implementation will provide further information for adjustment of the tasks selected in the RCM. Repeating this process makes the RCM continuous improvement cycle.

The operating context and assumption statements should be considered as living documents and be maintained throughout the item's life (60300-3-11:35). This substantiates the importance of defining the operating context in RCM, and also making it clear that it is a dynamic aspect which needs to be monitored. Not only does the asset itself need monitoring, but also the surroundings which also is capable of affecting maintenance tasks for changes.

Evaluation criteria for RCM processes

The following documents describe the minimum criteria that any process must comply with to be called "RCM":

1. SAE JA1011 – Evaluation Criteria for Reliability-Centered Maintenance Processes.
    a. There has been a growing international demand for a standard that sets out the criteria that any process must comply with in order to be called "RCM". This document meets that need. (SAE JA1011, foreword)
2. SAE JA1012 - A guide to the Reliability-Centered Maintenance Standard.
    a. SAE JA1011 presupposes a high degree of familiarity with the concepts and terminology of RCM. This Guide amplifies, and where necessary clarifies, those key concepts and terms, especially those that are unique to RCM. (SAE JA1012, foreword).
3. Reliability-centered Maintenance, second edition – Book written by John Moubray.
    a. The book is intended for maintenance, production and operations managers who wish to learn what RCM is, what it achieves and how it is applied (Moubray 1997:xiii).

SAE JA1011 is the main document providing the standard RCM evaluation criteria's. SAE JA1012 is a supplementary document to SAE JA1011 and the book "Reliability-centered Maintenance, second edition" is based on these two documents.

RCM is a process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating context (Moubray 1997:7). The process entails seven basic questions about the asset or system under review (SAE JA1011):

1. What are the functions and associated desired standards of performance of the asset in its present operating context (functions)?

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)?

Step 1

"What are the functions and associated desired standards of performance of the asset in its present operating context (functions)?"

The operating context of the asset shall be defined (SAE JA 1011, section 5.1.1), which typically includes a brief overall description of how it is to be used, where it is to be used, overall performance criteria governing issues such as output, throughput, safety, environmental integrity, and so on (SAE JA1012, section 6.1). Everyone involved in the development of a maintenance program must have a crystal clear understanding of the operating context of the asset (Moubray 1997:29).

All the functions of the asset/system shall be identified (SAE JA1011, section 5.1.2), and all function statements shall contain a verb, an object and a performance standard (SAE JA1011, section 5.1.3). In the figure below, the function of a pump is illustrated and may be described as "pump shall deliver no less than 500 liters per minute from tank A to tank B".

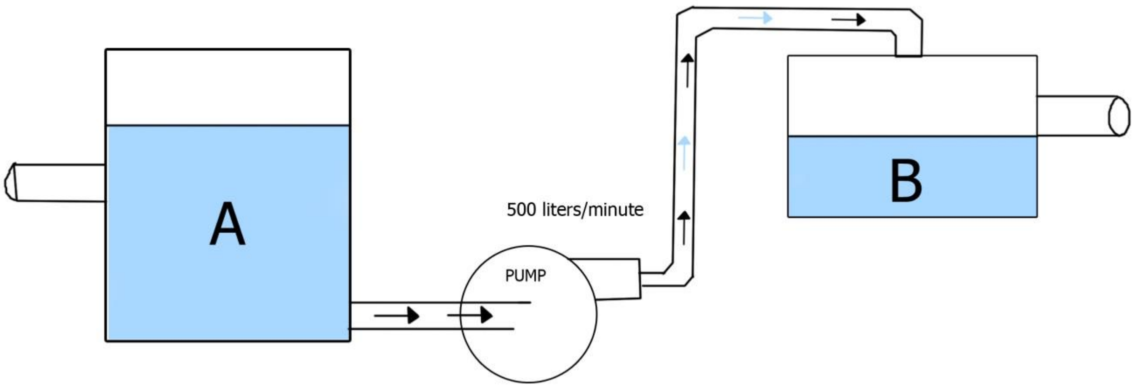

Figure 8: Function "Pump shall deliver no less than 500 liters per minute from tank A to tank B".

Functions may be systemized to distinguish their different qualities from each other by dividing them into two categories: primary and secondary functions (SAE JA1012, section 6.2). Primary functions are the “main” reasons why the asset is acquired (Moubray 1997:35) and secondary functions are additional to the primary function (Moubray 1997:37).

Performance standards incorporated in function statements shall be the level of performance desired by the owner or user of the asset/system in its operating context (SAE JA1011, section 5.1.4). Performance can be defined in two ways (Moubray 1997:23):

1. *Desired performance (what the user wants the asset to do)*
2. *Built-in capability (what it can do)*

This can also be illustrated, as in the figure below.

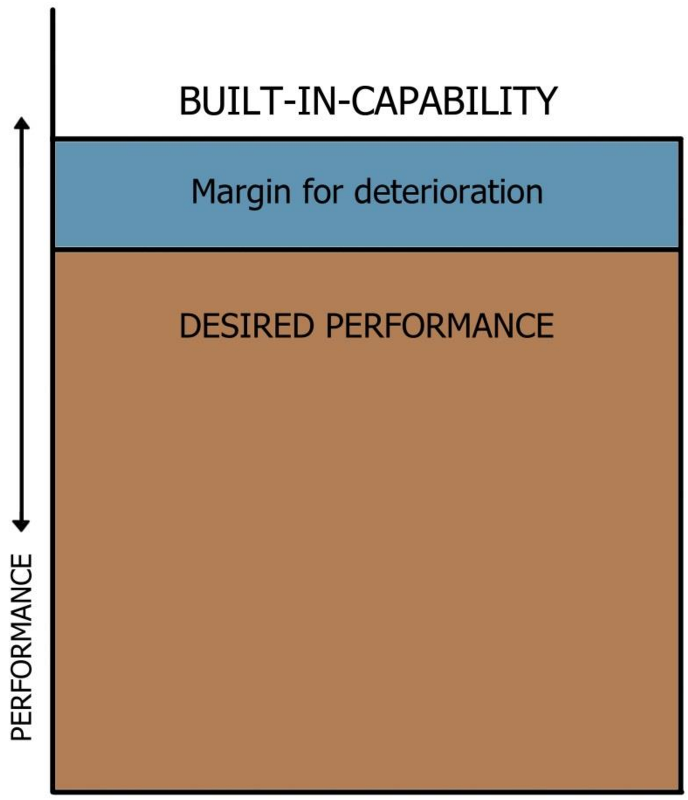

Figure 9: Illustration of a performance standard.

The laws of physics tell us that any organized system which is exposed to the real world will deteriorate (Moubray 1997:22). If so, the figure above illustrates how deterioration must be accounted for in relation to the built-in-capability and the minimum standard of performance as desired by the user. This means that one must make sure that any performance standard incorporated in a function statement must not exceed the built-in-capability of the asset. Therefore, both the built-in-capability of the asset and the desired performance must be known at step 1.

Step 2

"In what ways can it fail to fulfill its functions (functional failures)?"

All the failed states associated with each function shall be identified (SAE JA1011, section 5.2).

A functional failure is defined as the inability of any asset to fulfill a function to a standard of performance which is acceptable to the user (Moubray 1997:47). Since a function may suffer from several functional failures, it is suggested that functional failures are listed with their associated function.

Step 3

"What causes each functional failure?"

The cause of a functional failure is known as a *failure mode* (Moubray 1997:53). All failure modes reasonably likely to cause each functional failure shall be identified (SAE JA1011, section 5.3.1).

A failure mode should be described with a noun and a verb, and be concise enough so that the optimal failure management strategy can be selected (Moubray 1997:54). Particularly the selection of verb should be done with care, and specific verbs should be preferred in advantage of general verbs like "fails", "breaks" or "malfunctions". That is because general verbs provide little help in understanding what the specific failure is caused by, hence making it difficult to understand and find the appropriate way of handling the failure.

Failure modes can be classified into one of three groups (Moubray 1997:58):

1. Capability falls below desired performance.
    a. Deterioration, lubrication, dirt, disassembly, human errors which reduce capability.
2. Desired performance rises above initial capability.
    a. Sustained deliberate overloading, sustained unintended overloading, sudden unintentional overloading, incorrect process or packaging materials.
3. The asset is not capable of doing what is wanted from the outset.

The method used to decide what constitutes a "reasonably likely" failure mode shall be acceptable to the owner or user of the asset (SAE JA1011, section 5.3.2). "Reasonably likely" means a likelihood that meets the test of reasonableness, when applied by trained and knowledgeable people (SAE JA1012, section 8.2). Those failure modes that are reasonably likely to occur in the context in question are generally (Moubray 1997:70):

1. Failures which have occurred before on the same or similar assets.
    a. Information may be gathered from people who know the asset well, such as employees, vendors or other users of the same equipment.
2. Failure modes which are already the subject of proactive maintenance routines.
    a. Information may be gathered from existing maintenance schedules.
3. Any other failure modes which have not yet occurred, but which are considered to be real possibilities.

This is compliant to SAE JA1011 section 5.3.4: "Lists of failure modes shall include failure modes that have happened before, failure modes that are currently being prevented by existing maintenance programs and failure modes that have not yet happened but that are thought to be reasonably likely (credible) in the operating context."

Failure modes shall be identified at a level of causation that makes it possible to identify an appropriate failure management policy (SAE JA1011, section 5.3.3). A failure management policy is defined as a generic term that encompasses on-condition tasks, scheduled restoration, scheduled discard, failure-finding, run-to-failure, and one-time changes (SAE JA1012, section 3.11). This paper will get back to failure management policy in step 6. In order to identify an appropriate failure management policy, one should be aware the level of detail and the number of failure modes listed. That is because too little information could lead to misassumptions or surmising, and too much information could be considered time consuming and irrelevant in the RCM process.

A suggested method to judge whether or not a failure mode should be listed in the analysis is to look at the probability of occurrence and the consequences of a failure mode. Different failure modes occur at different frequencies (Moubray 1997:70) and if the consequences are likely to be very severe indeed, then less likely failure possibilities *should* be listed and subjected to further analysis (Moubray 1997:71).

Great care should be taken to ensure that the operating context is identical before applying an FMEA developed in one set of circumstances to an asset which is used in another (Moubray 1997:73). This is highly relevant for RCM applied to large tag structures. Once each failure mode has been identified, it is natural to start assessing the consequences of the functional failures, which is done in step 4. The process of step 3 and step 4 are closely attached to each other and is widely known as FMEA.

Step 4

"What happens when each failure occurs (failure effects)?"

The fourth step in the RCM process entails listing failure effects, which describe what happens when a failure mode occurs (Moubray 1997:73). Failure effects shall describe what would happen if no specific task is done to anticipate, prevent, or detect the failure (SAE JA1011, section 5.4.1).

Failure effects shall include all the information needed to support the evaluation of the consequences of the failure (SAE JA1011, section 5.4.2). The average description of a failure effect usually amounts to between twenty and sixty words (Moubray 1997:74). Attention should be given to the differences between failure *effects* (what happens) and failure *consequences* (how does it matter). Failure consequence will be further explained at step 5.

Step 5

"In what way does each failure matter (failure consequences)?"

There are mainly two requirements to the categorization of failure consequences, which shall be formally categorized by means of the following (SAE JA1011, section 5.5.1):

1. The consequence categorization process shall separate hidden failure modes from evident failure modes.

2. The consequence categorization process shall clearly distinguish events (failure modes and multiple failures) that have safety and/or environmental consequences from those that only have economic consequences (operational and non-operational consequences).

The assessment of failure consequences shall be carried out as if no specific task is currently being done to anticipate, prevent or detect the failure (SAE JA 1011, section 5.5.2). That is because such checks are a form of scheduled maintenance, and the whole purpose of the analysis is to find out whether such maintenance is necessary (SAE JA 1012, section 10.1.1.2).

An evident function is one whose failure will on its own eventually and inevitably become evident to the operating crew under normal circumstances (Moubray 1997:92). A hidden function is one whose failure will not become evident to the operating crew under normal circumstances if it occurs on its own (Moubray 1997:93). Evident failures are classified into three categories in descending order of importance, as follows (Moubray 1997:93):

1. Safety and environmental consequences
2. Operational consequences
3. Non-operational consequences

A failure has safety consequences if there is an intolerable probability that it could kill or injure a human being (SAE JA 1012, section 10.1.2.1). A failure has environmental consequences if there is an intolerable probability that it could breach any known environmental standard or regulation (SAE JA 1012, section 10.1.2.2).

The phrase “intolerable probability” emerges on the issue of safety and environmental consequences, which leads to risk assessment in order to evaluate the safety and environmental consequences properly. According to Moubray (1997:95):

Risk assessment consists of three elements. The first asks what could happen if the event under consideration did occur. The second asks how likely it is for the event to occur at all. The combination of these two elements provides a measure of the degree of risk. The third – and often the most contentious element – asks whether this risk is tolerable.

The frequency and the consequence can be found from step 3 and step 4; the failure modes and their failure effects. Whether or not the risk is tolerable is more difficult to define during this aspect of managing safety. A wide variety of factors influence these beliefs, by far the most dominant of which is the degree of control which any individual thinks he or she has over the situation (Moubray 1997:98). Other relevant factors are individual values, industry values, the effect on "future generations" and knowledge (Moubray 1997:100).

Some organizations may already have established levels of risk ready for use that are considered to be tolerable by all parties involved. If not, then the risk should be evaluated by a group representing of (SAE JA 1012, section 12.1.4):

1. People who are likely to have a clear understanding of the failure mechanism, the failure effects (especially the nature of any hazards), the likelihood of the failure mode occurring and what possible measures can be taken to anticipate or prevent it.
2. People who have a legitimate view on the tolerability or otherwise of the risks. This might include representatives of:
    a. The likely victims (operators or maintainers in the case of direct hazards, and the community in general in the case of environmental hazards).
    b. Those who have to deal with the consequences if someone is injured or killed or if an environmental standard is breached (such as management).

A failure has operational consequences if it affects production or operations (Moubray 1997:93). Evident failures in this category affect neither safety nor production, so they involve only the direct cost of repair (Moubray 1997:93).

Step 5 categorizes the consequences for each failure mode recorded in step 3. In an attempt to eliminate (or at least reduce) these consequences, increasing use is being made of automatic protective devices (Moubray 1997:41). The existence of such systems creates two main sets of failure possibilities, depending on whether the protective device is fail-safe or not (Moubray 1997:111). The failure possibilities are fail-safe and not fail-safe.

Fail-safe protective devices are connected to evident failure modes because, in this context, fail-safe means that the failure of the device on its own will become evident to the operating crew under normal circumstances (Moubray 1997:111).

There are three failure possibilities of a fail-safe protective device (Moubray 1997:112):

1. Neither device fails.
    a. Everything proceeds normally.

2. The protected function fails before the protective device.
    a. *The protective device carries out its intended function and reduces or eliminates the consequences of failure.*
3. The protective device fails before the protected function.
    a. *Evident, because the device is fail-safe.*

The consequences of the failure of a fail-safe protective device usually fall into the “operational” or “non-operational” categories (Moubray 1997:112).

Protective devices which are not fail-safe are connected to hidden failure modes because the fact that the device is unable to fulfil its intended function is *not* evident under normal circumstances (Moubray 1997:112). This creates four failure possibilities in any given period, two of which are the same as those which apply to a fail-safe device (Moubray 1997:112):

1. Neither device fails.
    a. *Everything proceeds normally.*
2. The protected function fails before the protective device.
    a. *The protective device carries out its intended function reducing or eliminating the consequences of failure.*
3. The protective device fails while the protected function is still working.
    a. *A hidden function.*
4. The protective device fails, and then the protected function fails while the protective device is in a failed state.
    a. *Multiple failure.*

The only direct consequence of a hidden failure is increased exposure to the risk of a multiple failure (Moubray 1997:115), which is relevant for those systems that are protected by devices that are not fail-safe. The probability of a multiple failure in any period must be given by the probability that the protected function will fail while the protective device is in a failed state during the same period (Moubray 1997:116). This can be mathematically expressed:

$$P\begin{pmatrix} multiple \\ failure \end{pmatrix} = P\begin{pmatrix} failure\ of \\ protected\ function \end{pmatrix} \times \begin{pmatrix} Average\ unavailability \\ of\ the\ protective\ device \end{pmatrix}$$

The tolerable probability of multiply failure must be defined by the user, and the probability of failure of the protected function is usually given. This leads to an opportunity of defining what can be allowed for of unavailability of the protective device by rearranging the formula:

$$Allowed\ unavailability\ of\ the\ protected\ device = \frac{P(multiple\ failure)}{P(failure\ of\ protected\ function)}$$

Step 6

"What should be done to predict or prevent each failure (proactive tasks and task intervals)?"

Proactive tasks embrace what is traditionally known as "predictive" and "preventive" maintenance. RCM uses the terms *scheduled restoration, scheduled discard* and *on-condition maintenance* (Moubray 1997:129). In order to choose appropriate proactive tasks, four minimum criterions are established in the SAE JA1011 section 5.6 concerning failure management policy selection:

1. The relationship between age and failure.
2. Technically feasible and worth doing.
3. Cost effectiveness.
4. Failure management policy selection.

These criterions are further explained in SAE JA1011 (section 5.6.1):

The failure management selection process shall take account of the fact that the conditional probability of some failure modes will increase with age (or exposure to stress), that the conditional probability of others will not change with age, and the conditional probability of yet others will decrease with age.

There are six sets of ways in which the conditional probability of failure varies as an item gets older (SAE JA1012, section 11.1), as shown in figure 10.

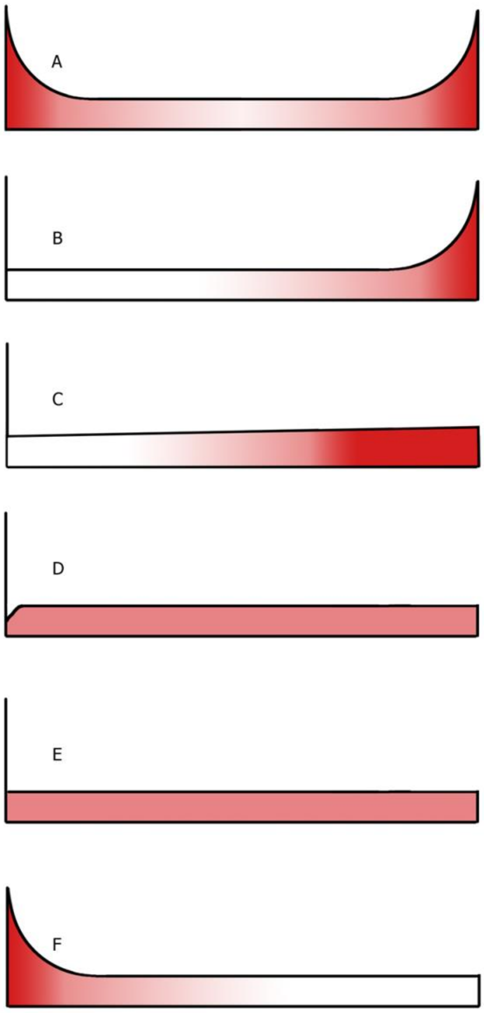

Figure 10: Six patterns of failure.

Pattern A is popularly nicknamed the “bathtub curve”, displaying a high probability of failure in the beginning (often referred to as an infant mortality period) before stabilizing at a safer level until it reaches a “wear-out zone” in the end of an asset’s lifetime. Pattern B has a similar “wear-out zone”, but is not suffering from high probability of failure in the beginning. The remaining patterns have no “wear-out zone”. Pattern C has a slight increase in probability of failure. Pattern D displays the probability of failure for an asset with low conditional probability of failure when brand new, but suffers from a rapid increase before stabilizing at a constant level probability of failure. Pattern E represents those assets suffering from random failure at all ages. Pattern F is reversed with pattern B, displaying an infant mortality period before stabilizing at a constant decreasing probability of failure.

All scheduled tasks shall be technically feasible and worth doing (applicable and effective), and the means by which this requirement will be satisfied are set out in 5.7 (SAE JA1011, section 5.6.2).

Any scheduled task is only worth doing if it reduces (avoids, eliminates or minimizes) the consequences of the failure mode to an extent that justifies the direct and indirect costs of doing the task (SAE JA1012, section 11.2).

Section 5.7 in the SAE JA1011 describes failure management policies for scheduled tasks. It describes in general what all scheduled tasks shall comply with (5.7.1), and in special what on-condition tasks (5.7.2), scheduled discard tasks (5.7.3), scheduled restoration tasks (5.7.4) and failure-finding tasks (5.7.5) must comply with. These will be explained in more detail .

If two or more proposed failure management policies are technically feasible and worth doing (applicable and effective), the policy that is most cost-effective shall be selected (SAE JA 1011, section 5.6.3). When more than one failure management policy option is technically appropriate, correctly-applied RCM always strives to select the policy that deals satisfactorily with the consequences of the failure mode in the most economical fashion, rather than always selecting the policy with the greatest technical sophistication (SAE JA1012, section 11.3).

The selection of failure management policies shall be carried out as if no specific task is currently being done to anticipate, prevent or detect the failure (SAE JA1011, section 5.6.4). In order to start from a true zero base, it is essential to assume that the failure mode does in fact cause the associated functional failure (SAE JA1012, section 9.1).

All scheduled tasks shall comply with the following criteria (SAE JA1011, section 5.7.1):

1. In the case of an evident failure mode that has safety or environmental consequences, the task shall reduce the probability of the failure mode to a level that is tolerable to the owner or user of the asset (SAE JA1011, section 5.7.1.1).
2. In the case of a hidden failure where the associated multiple failure has safety or environmental consequences, the task shall reduce the probability of the hidden failure mode to an extent which reduces the probability of the associated multiple failure to a level that is tolerable to the owner or user of the asset (SAE JA1011, section 5.7.1.2).
3. In the case of an evident failure mode that does not have safety or environmental consequences, the direct and indirect costs of doing the task shall be less than the

direct and indirect costs of the failure mode when measured over comparable periods of time (SAE JA1011, section 5.7.1.3)

4. In the case of a hidden failure mode where the associated multiple failure does not have safety or environmental consequences, the direct and indirect costs of doing the task shall be less than the direct and indirect costs of the multiple failure plus the cost of repairing the hidden failure mode when measured over comparable periods of time (SAE JA1011, section 5.7.1.4).

Predictive maintenance tries to predict whether – and possibly when – an item is going to fail on the basis of its present behavior. This may also be called condition-based maintenance because the need for corrective or consequence-avoiding action is based on assessment of the condition of the item (Moubray 1997:145).

On-condition tasks entail checking for potential failures, so that action can be taken to prevent the functional failure or to avoid the consequences of the functional failure (Moubray:145). Any on-condition task that is selected shall satisfy the following additional criteria (SAE JA1011, section 5.7.2):

1. There shall exist a clearly defined potential failure (SAE JA1011, section 5.7.2.1).
2. There shall exist an identifiable P-F interval (or failure development period) (SAE JA1011, section 5.7.2.2).
3. The task interval shall be less than the shortest likely P-F interval (SAE JA1011, section 5.7.2.3).
4. The shortest time between the discovery of a potential failure and the occurrence of the functional failure (the P-F interval minus the task interval) shall be long enough for predetermined action to be taken to avoid, eliminate, or minimize the consequences of the failure mode (SAE JA1011, section 5.7.2.5).

The initiation of a failure, its deterioration and its final outcome may be presented graphically in a P-F curve.

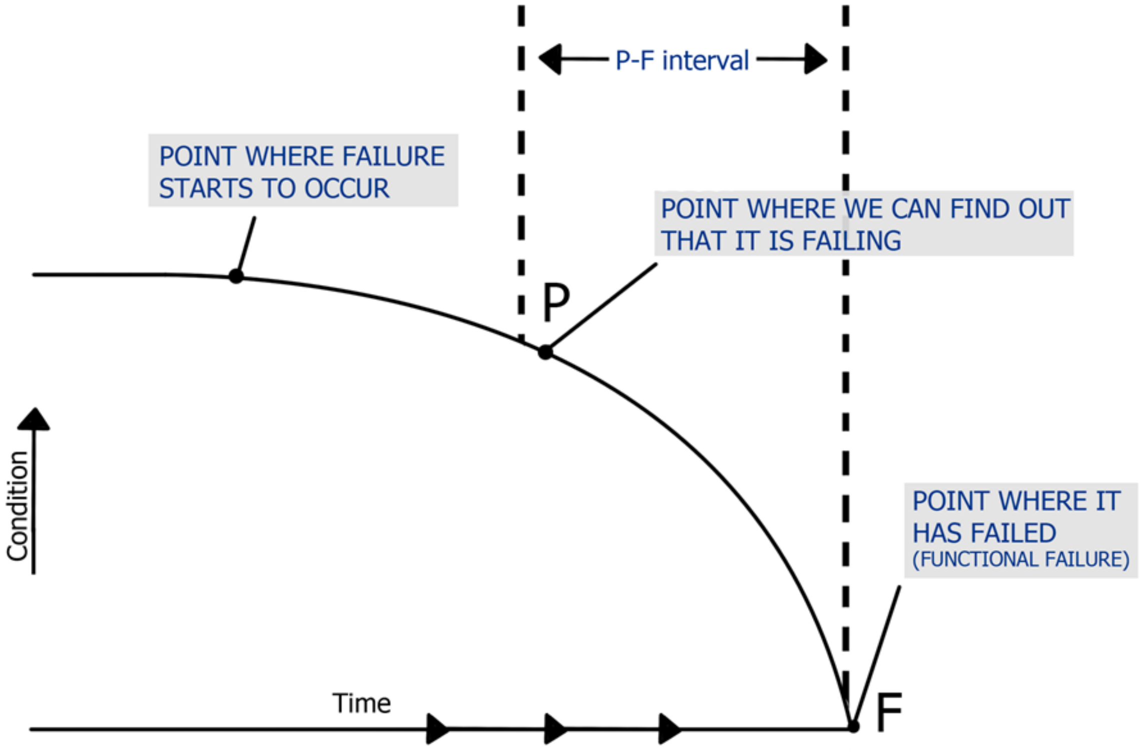

Figure 11: The P-F curve.

The point P in the figure identifies the occurrence of a potential failure; where it is possible to detect that a failure is about to occur. The point F in the figure indicates the point of functional failure. On this basis, the P-F interval arises as the interval between the occurrence of a potential failure and its decay into a functional failure (Moubray 1997:145).

On-condition tasks are considered first in the task selection process, for the following reasons (Moubray 1997:168):

1. They can nearly always be performed without moving the asset from its installed position and usually while it is in operation, so they seldom interfere with the production process. They are also easy to organize.
2. They identify specific potential failure conditions so corrective action can be clearly defined before work starts. This reduces the amount of repair work to be done, and enables it to be done more quickly.
3. By identifying equipment on the point of potential failure, they enable it to realize almost all of its useful life.

While predictive maintenance is focused on what happens once a failure has started to occur, preventive maintenance can be differed from predictive as more focused on the relationship between the age of the item under consideration and how likely the item is to fail. If there existed enough information about failures it would be possible to predict equipment life with great precision (Moubray 1997:131). Scheduled discard and scheduled restoration are considered as preventive tasks in the RCM.

Scheduled discard tasks entails discarding an item or component at or before a specified age limit, regardless of its condition at the time (Moubray 1997:135). Any scheduled discard task that is selected shall satisfy the following additional criteria (SAE JA1011, section 5.7.3):

1. There shall be a clearly defined (preferably a demonstrable) age at which there is an increase in the conditional probability of the failure mode under consideration (SAE JA1011, section 5.7.3.1).
2. A sufficiently large proportion of the occurrences of this failure mode shall occur after this age to reduce the probability of premature failure to a level that is tolerable to the owner or user of the asset (SAE JA1011, section 5.7.3.2).

A scheduled discard task is of interest if scheduled restoration is impossible or more costly than replacing the item.

Scheduled restoration entails restoring the initial capability of an existing item or component at or before a specified age limit, regardless of its apparent condition at the time (Moubray 1997:134). Any scheduled restoration task that is selected shall satisfy the following additional criteria (SAE JA1011, section 5.7.4):

1. There shall be a clearly defined (preferably a demonstrable) age at which there is an increase in the conditional probability of the failure mode under consideration (SAE JA1011, section 5.7.4.1).
2. A sufficiently large proportion of the occurrences of this failure mode shall occur after this age to reduce the probability of premature failure to a level that is tolerable to the owner or user of the asset (SAE JA1011, section 5.7.4.2).
3. The task shall restore the resistance to failure (condition) of the component to a level that is tolerable to the owner or user of the asset (SAE JA1011, section 5.7.4.3).

Scheduled restoration tasks include overhauls or turnarounds that are performed at preset intervals in order to prevent specific age-related failure modes (Moubray 1997:135).

In general, scheduled restoration and scheduled discard tasks are preferred if a suitable on-condition task cannot be found, because on-condition tasks are nearly always more cost-effective (Moubray 1997:168). Scheduled restoration and scheduled discard tasks have much in common, but scheduled restoration is usually considered before scheduled discard because it is inherently more conservative to restore things instead of throwing them away (Moubray 1997:169). The disadvantages of scheduled restoration and scheduled discard tasks are (Moubray 1997:168):

1. They can only be done when items are stopped and (usually) sent to the workshop, so the tasks nearly always affect operations in some way.
2. The age limits apply to all items, so many items or components which might have survived to higher ages will be removed.
3. Restoration tasks involve work shop, so they generate a much higher workload than on-condition tasks.

Step 7

"What should be done if a suitable proactive task cannot be found (default actions)?"

If a proactive task cannot be found which is both technically feasible and worth doing, then a default action must be taken (Moubray 1997:170). There are three options for default action, which are *failure-finding*, *one-time changes* (redesign) and *run-to-failure* (no scheduled maintenance).

Failure-finding is the initial default action if a suitable proactive task cannot be found for a *hidden failure* (Moubray 1997:187). Scheduled failure-finding entails checking a hidden function at regular intervals to find out whether it has failed (Moubray 1997:173).

Any failure-finding task that is selected shall satisfy the following additional criteria (failure-finding does not apply to evident failure modes) (SAE JA1011, section 5.7.5):

1. The basis upon which the task interval is selected shall take into account the need to reduce the probability of the multiple failure of the associated protected system to a level that is tolerable to the owner or user of the asset (SAE JA1011, section 5.7.5.1).
2. The task shall conform that all components covered by the failure mode description are functional (SAE JA1011, section 5.7.5.2).

3. The failure-finding task and associated interval selection process should take into account any probability that the task itself might leave the hidden function in a failed state (SAE JA1011, section 5.7.5.3).
4. It shall be physically possible to do the task at the specified intervals (SAE JA1011, section 5.7.5.4).

Failure-finding is worth doing if it reduces the probability of the associated multiple failure to a tolerable level (Moubray 1997:185).

One-time changes (redesign) refers to any change to the specification of any item of equipment, which means any once-off change to a process or procedure which affects the operation of the plant (Moubray 1997:188). A one-time change is to look at all possible maneuvers such as modification of equipment, change of operating procedures, or even lowering of expectations. These are beyond maintenance when no appropriate maintenance task could be found.

However, the RCM process shall endeavor to extract the desired performance of the system as it is currently configured and operated by applying appropriate scheduled tasks (SAE JA1011, section 5.8.1.1). In cases where such tasks cannot be found, one-time changes to the asset or system may be necessary, subject to the following criteria (SAE JA1011, section 5.8.1.2):

1. In cases where the failure is hidden, and the associated multiple failure has safety or environmental consequences, a one-time change that reduces the probability of the multiple failure to a level tolerable to the owner or user of the asset is compulsory (SAE JA1011, section 5.8.1.2.1).
2. In cases where the failure mode is evident and has safety or environmental consequences, a one-time change that reduces the probability of the failure mode to a level tolerable to the owner or user of the asset is compulsory (SAE JA1011, section 5.8.1.2.2).
3. In cases where the failure mode is hidden, and the associated multiple failure does not have safety or environmental consequences, any one-time change must be cost-effective in the opinion of the owner or user of the asset (SAE JA1011, section 5.8.1.2.3).
4. In cases where the failure mode is evident and does not have safety or environmental consequences, any one-time change must be cost-effective in the opinion of the owner or user of the asset (SAE JA1011, section 5.8.1.2.4).

If the failure is evident and it does not affect safety or the environment, or if it is hidden and the multiple failure does not affect safety or the environment, the initial default decision is to do *no scheduled maintenance* (Moubray 1997:187).

Any run-to-failure policy that is selected shall satisfy the appropriate criterion as follows (SAE JA1011, section 5.8.2):

1. In cases where the failure is hidden and there is no appropriate scheduled task, the associated multiple failure shall not have safety or environmental consequences (SAE JA1011, section 5.8.2.1).
2. In cases where the failure is evident and there is no appropriate scheduled task, the associated failure mode shall not have safety or environmental consequences (SAE JA1011, section 5.8.2.2).

The requirement for doing no scheduled maintenance is that there is no safety or environmental consequences related to the failure mode. This implies that allowance of the failure mode involves lower costs than applying a task to avoid the failure.

A living program

Under the headline "A living program" the SAE JA1011 states the following in section 5.9.1 and 5.9.2:

This document recognizes that (a) much of the data used in the initial analysis are inherently imprecise, and that more precise data will become available in time, (b) the way in which the asset is used, together with associated performance expectations, will also change with time, and (c) maintenance technology continues to evolve. Thus a periodic review is necessary if the RCM-derived asset management program is to ensure that the assets continue to fulfill the current funcitonal expectations of their owners and users.

Therefore any RCM process shall provide for a periodic review of both the information used to support the decisions and the decisions themselves. The process used to conduct such a review shall ensure that all seven questions in Section 5 continue to be answered satisfactorily and in a manner consistent with the criteria set out in 5.1 through 5.8.

In order to ensure that the seven questions of SAE JA1011 "continue to be answered satisfactorily and in a manner consistent with the criteria set out" in the document, specific questions that should be answered include the following (SAE JA1012, section 16):

a. Operating context: Has the operating context of the equipment changed enough to change any of the information recorded or decisions made during the initial analysis? (For example, a change from single shift/5-day operation to 24-hour/7-day operation, or vice-versa.)
b. Performance expectations: Have any performance expectations changed enough to make it necessary to revise the performance standards that were defined during the initial analysis?
c. Failure modes: Since the previous analysis, has it transpired that any existing failure modes were incorrectly recorded, or have any unanticipated failure modes occurred that should be recorded?
d. Failure effects: Should anything be added to or changed in the descriptions of failure effects? (This applies especially to the evidence of failure and estimates downtime.)
e. Failure consequences: Has anything happened to cause anyone to believe that failure consequences should be assessed differently? (Possibilities here includes changes to environmental regulations, and changed perceptions about tolerable levels of risk.)
f. Failure management policies: Is there any reason to believe that any of the failure management policies selected initially is no longer appropriate?
g. Scheduled tasks: Has anyone become aware of a method of performing a scheduled task that could be superior to one of those selected previously? (In most cases, "superior" means "more cost effective", but it could also mean technically superior.)
h. Task intervals: Is there any evidence suggesting that the frequency of any task should be changed?
i. Task execution: Is there any reason to suggest that a task or tasks should be done by someone other than the type of person selected originally?
j. Asset modifications: Has the asset been modified in a way that adds or subtracts any functions or failure modes, or that changes the appropriateness of

any failure management policy? (Special attention should be paid to control systems and protection.)

Meetings that are held to reappraise and when necessary update the analysis should be held at intervals of nine to twelve months, and ideally should be facilitated by the original facilitator (Moubray 1997:277).

Mathematical and statistical formulae

Any mathematical and statistical formulae that are used in the application of the process (especially those used to compute the intervals of any task) shall be logically robust, and shall be available to and approved by the owner or user of the asset (SAE JA1011, section 5.10.1).

RCM development

RCM was first documented by Nowlan and Heap (1978) to improve safety and reliability of equipment for the commercial aviation industry. It proved to be a success which motivated for further research and several attempts in exploiting the method to make the most out of it. In this way, RCM has proven to a method of many aspects.

During the mid-90s, streamlining of RCM emerged as a method to evaluate existing maintenance performance; proposed by Rotton (1994) and Johnson (1995). Streamlined RCM, in the shape of PMO, would assure that the right PM activities were being performed on the right equipment for the right reasons (Johnson 1995). This was also what RCM was supposed to do, but it was claimed by Johnson that PMO was a much faster method which provided pretty much the same results. The problem with RCM, as described by Johnson (1995), was that it proved to be a very cumbersome process due to the detail required and the excessive documentation that was produced as a result of the rigid process steps. PMO differed from RCM by reviewing existing tasks to identify the failure they were intended to prevent, and then collect relevant data to decide what the appropriate activity should be. Moubray (2000) named this approach "retroactive", in that it started at the end of the RCM process and only moved three steps back before working forward again to identify failure management policies. Moubray (2000) described the problems with this approach in a following manner:

1. It assumes that existing maintenance programs have covered all failure modes that are reasonably likely to occur, which is not a reasonable assumption.
2. It was difficult to identify exactly what failure cause motivated the selection of a particular task. Either inordinate amounts of time were wasted trying to establish real connection, or sweeping assumptions were made that very often proved to be wrong.
3. Functions were neglected in this approach, which is necessary in re-assessing the consequences of a failure mode. In fact, it is generally accepted by all the proponents of true RCM that in terms of improved plant performance, by far the greatest benefits of true RCM flow from the extent to which the function definition step transforms general levels of understanding of how the equipment is supposed to work. Cutting out this step costs far more in terms of benefits foregone than it saves in reduced analysis time.
4. Retroactive approaches were especially weak on specifying appropriate maintenance for protective devices. Most of the protective devices in maintenance programs have a tendency to be overseen. So if one uses a retroactive approach to RCM, in most cases a great many protective devices will continue to receive no attention in the future because no tasks were specified for them in the past. Given the enormity of the risks associated with unmaintained protective devices, this weakness of retroactive RCM alone makes it completely indefensible.
5. Retroactive approaches focus on maintenance workload reductions rather than plant performance improvements (which are the primary goal of function-oriented true RCM).

When Johnson (1995) stated that RCM was a cumbersome process with an excessive amount of details and documentation, he probably spoke on behalf of many others. The Pareto's 80-20-principle is another proposal which suggested that only 20% of failures which causes 80% of the risk should be analyzed; motivated by the amount of resources it might take to perform a complete RCM (Mokashi et al., 2002). Deepak Prabhakar P. and Dr. Jagathy Raj V. P. (2013) developed a similar methodology of RCM known as A-RCM, which focuses on identifying and analyzing only critical equipment.

According to Moubray (2000), analyzing only “critical” functions had two main flaws:

1. Assumptions have to be done for those analyses that are not performed, which is a risk in itself.
2. Additional elaborated steps to are incorporated to evaluate the associated risk to each failure mode, which takes longer and costs more than it would to conduct true RCM.

Z-008 suggests generic concepts or transforming of a RCM analysis to a GMC for later use on similar equipment (Z-008:20). Generic analyses should be treated with great caution (Moubray 2000). This is based on the argument that the operating context is a function of the process or system of which the asset forms part, so any asset should only be analyzed in the context of a specific process or system (Moubray 1997:279). Therefore, a generic list would be inconsistent with the context of a specific process or system, such as redundancy. Another argument is that some of the people working on an asset may prefer to use one type of proactive technology, while others working on an identical asset may be more comfortable using another (Moubray, 2000).

Speaking of Z-008, which is a risk-based approach, Selvik and Aven (2010) suggested an extension of RCM to RRCM which include risk as the reference for the analysis in addition to reliability. This framework was built on the ideas of Eisinger and Rakowsky (2001) which highlighted the fact that RCM ignores uncertainties in its decision process which may lead to suboptimal maintenance strategies. Especially the decision logic is criticized for not reflecting the uncertainties that exist when one only can choose between “YES” or “NO”. This problem is also addressed by Bloom (2006) who says that about 60% of all RCM programmes fail to be successfully implemented due to failure in the assessment of uncertainties.

When preparing to introduce RCM within an organization, a long-term approach is preferable, so as to increase management and employee commitment (F. Backlund and P.A. Akersten, 2003). Top management commitment to RCM can fade out due to unforeseen increased consumption of resources (Moubray 1997, Jones 1995) or insufficient knowledge of how and in what way RCM will be beneficial to the organization (Hipkin and DeCock,2000; Bowler et al., 1995). According to Harris and Moss (1994) RCM is often introduced in times of restraint and rationalization. In some cases, the challenge with RCM can be the alignment of the organization in accordance with the method (Smith, 1993). This is confirmed by Mokashi et al. (2002) who says that problems that are likely to be encountered in endeavor of implementing RCM on ships stem out of the cultural differences between the aviation and maritime industries. Nevertheless, RCM can also affect culture in other ways, according to (Bryant et al., 2009) who reports that RCM has been successfully used as a model for change to improve maintenance processes by engaging workforces and promoting the benefits of proactive maintenance.

Moubray (1997:286 – 290) sums up the main reasons for why some RCM analyses achieve little or nothing, based on experience:

1. The analysis is performed at too low a level
    a. Massive documentation, tedious, losing interest
2. To hurried or too superficial an application
    a. Typical in case of insufficient training, or too heavy an emotional investment in the status quo on the part of key participants. Often results in a set of tasks which are almost the same as they were to begin with.
3. Too much emphasis on failure data
    a. MTBF's and MTTR's are over-emphasized at the expense of properly defined and quantified performance standards, the thorough evaluation of failure consequences and the correct use of data such as P-F intervals.
4. Asking a single individual to apply the process may have two outcomes
    a. Inadequate technical validity, because no one understand the functions, failure modes, effects and failure consequences of the asset sufficiently alone. This leads to programs which are usually generic in nature, so people who are supposed to do them often see them as being incorrect of not totally irrelevant.
    b. Loss of ownership when operators view the schedules as unwelcome paperwork and do not feel committed to do them.
5. Using the maintenance department on its own to apply RCM may lead to
    a. Large numbers of inaccurate function statements and performance standards, and consequently to distorted or inappropriate programs designed to preserve those functions.
    b. Others understand less clearly why maintenance is essential and why operators need to be asked to carry out certain maintenance tasks.
6. Asking manufacturers or equipment vendors to apply RCM on their own
    a. Equipment manufacturers usually possess surprisingly little of the information needed to draw up truly context-specific maintenance programs. They also have other agendas when specifying such programs

7. Using outsiders to apply RCM
    a. Most outsiders know little about the dynamics of the organization for which the schedules are being written, such as the operating context of each asset, the risk which the organization is prepared to tolerate and the skills of the operators and maintainers of the asset. This often results in generic analyses which contain many more assumptions than if the analysis is facilitated by informed insiders. Also, an outsiders moves on to a new organization and there is no-one left with a sufficiently strong sense of ownership of the analyses and their outcomes to ensure that they stay alive. Also, third parties are usually working under contract with a need to finish on time and on budget, which created time pressure that can cause too many decisions to be taken too quickly.
8. Using computers to drive the process
    a. Too much emphasis on a computer means that RCM starts being seen as a mechanistic exercise in populating a database, rather than exploring the real needs of the asset under review.

No matter how one try to tweak or adjust RCM, the analysis will not be perfect anyway for the following reasons (Moubray 2000):

1. The evolution of a maintenance policy is inherently imprecise. Numerous decisions have to be made on the basis of incomplete or non-existent hard data, especially about the relationship between age and failure. Other decisions have to be made about the likelihood and the consequences of failure modes which haven't happened yet, and which may never happen. In an environment like this, it is inevitable that some failure modes and effects will be overlooked completely, while some failure consequences and task frequencies will be assessed incorrectly.
2. The assets and the processes of which they form part will be changing continuously. This means that even parts of the analysis which are completely valid today may become invalid tomorrow.

Abdul-Nour et al (1998) supports this by stating that the available information for analysis is not adequate in order to decide a suitable maintenance strategy when maintenance and operations are isolated from the design and engineering systems.

RCM and humans

Of all the factors which affect the ultimate quality of the RCM analysis, the skill of the facilitator is the most important (Moubray 1997:269). This applies to the technical quality of the analysis, the pace at which the analysis is completed, and the attitude of the participants towards the RCM process. Moubray (1997:270 – 277) have identified 45 key areas, grouped in 5 main skillsets, which an RCM facilitator has to be competent in to achieve a reasonable standard:

1. Applying the RCM logic
    a. All questions are asked in the correct sequence, understood and reached consensus
2. Managing the analysis
    a. Prepare for meetings
    b. Select levels of analysis/define boundaries
    c. Handle complex failure modes appropriately
    d. Know when to stop listing failure modes
    e. Interpret and record decisions with a minimum of jargon
    f. Recognize when the group doesn't know
    g. Curtail attempts to redesign the asset in RCM meetings
    h. Complete the RCM worksheet
    i. Prepare an audit file
    j. Enter RCM data into computerized database
3. Conducting the meetings
    a. Set the scene
    b. The conduct of the facilitator
    c. Ask the RCM questions in order
    d. Ensure that each question has been correctly understood
    e. Encourage everyone to participate
    f. Answering the questions
    g. Secure consensus
    h. Motivate the group
    i. Manage disruptions appropriately
    j. Coach the group or individual members
4. Time management

    a. Pace of working
    b. Total number of meetings held
    c. Actual completion date versus target completion date
    d. Time spent preparing for audit
    e. Time outside meetings
5. Administration, logistics and managing upwards
    a. Set up the RCM project as a whole
    b. Plan the project
    c. Communicate the plans
    d. The meeting venue
    e. Communicate urgent findings
    f. Communicate progress
    g. Ensure that RCM worksheets are audited
    h. Top management presentation
    i. Implementation
    j. A living program

The people involved in the process will change, or even leave so that their places are taken by others who need to learn why things are as they are (Moubray 1997:284). This means that the validity of the RCM also depends on the human attitude and competency to the process.

In most industries, historical records are seldom comprehensive enough to be used for answering the seven questions on their own (Moubray 1997:261). The diversity of the information which is needed and the diversity of the people from whom it must be sought mean that it can only be done on the basis of extensive consultation and cooperation, especially between production/operations and maintenance people (Moubray 1997:265). This involves the dimension of group dynamic to the RCM process, which is a study in itself. According to research, groups are in most cases better at choosing, judging, estimating, and problem solving than individuals are (Stasser & Dietz-Uhler, 2001), and the quality of the group's decision increases with the time spent in active discussion (Katz & Tushman, 1979). Five basic types of decision-making processes in groups are identified by Victor Vroom (2003) and his normative model of decision making in groups:

1. Leader making decisions alone, based on information from group members.
2. Leader consulting group members one-on one individually before making a decision.

3. Leader discussing problems with the group as a whole before a decision is made.
4. Leader coordinating collaborative analyses of problems and facilitates the group to reach consensus, and does not try to influence the group to adopt a particular solution.
5. The group functions independently of a leader and makes decisions autonomously.

An aspect of decision making in group is individuals' aptitude of spontaneously comparing themselves to others, and if a difference is found between their view and the group's, they may move toward the group's view (Sanders & Baron, 1977). This might be a challenge for decision making because it is strongly associated to groupthink; a mode of thinking that people engage in when they are deeply involved in a cohesive ingroup, when the members' strivings for unanimity override their motivation to realistically appraise alternative courses of action (Janis, 1982).

RCM and software

CMMS helps maintenance in automating and facilitating existing processes to improve efficiency, and add value to produce benefits otherwise not practically achievable (Palmer 2006:292). When large numbers of assets are to be analyzed, it is almost essential to use a computer for this purpose (Moubray 1997:211). This describes fairly well why computers have become a natural integrated part in RCM and maintenance management.

Many attempts have also been made to automate RCM with CMMS to optimize maintenance strategies further. Some claim that RCM-based CMMS can be adaptable to maintenance strategies and used to optimize maintenance for critical plants (H. A. Gabbar et al., 2003). (Cheng et al. 2007) suggests a framework for intelligent RCM analysis by introducing artificial intelligence technology. This approach is supposed to improve the efficiency of the analysis by using historical records from identical items to minimize the amount of repetitions within the analysis. This approach can be categorized as templating; using the analysis of one asset as a "template" for another. Templating has been both supported and criticized. It could save considerable amounts of time and effort if the items were virtually identical and the operating context was very similar, since in most cases, a substantial proportion of the analysis would remain unchanged for the subsequent items (Moubray 1997:281). However, templating could also have serious motivational drawbacks when the operators and maintainers of the subsequent assets were asked to accept decisions made by others, which naturally reduced their sense of ownership (Moubray 1997:281).

RCOM is another tactic presented as a state of the art service concept which links several systems into an interactive network, utilizing multimedia, expert systems and high-speed data communications, to form a complete digitized operating environment (Leppänen:1998). In this way, failure modes can continuously be identified, aiding the continuous improvement process in selecting optimum maintenance tasks. The power manufacturer Wärtsilä® has followed up this idea and applied it in some of their products since 2011 to monitor fuel consumption and make adjustments to engine health, propeller efficiency and hull efficiency (Wiesmann and Klockars: 2013). This approach may be a way to adapt a living program. A similar example is FRRM which uses an integrated system to include the management aspects of RCM to perform statistical analysis to indicate the actual and critical failure modes for critical events reassessment (K.W. Su et al., 2000).

Software can be helpful in optimizing maintenance where mathematical and statistical formulae can be implemented and used for this purpose. According to Rommert Dekker (1995) maintenance optimization models yield various results:

1. Policies can be evaluated and compared with respect to cost-effectiveness and reliability characteristics.
2. Results can be obtained on the structure of optimal policies.
3. Models can assist in the timing aspect on how often to inspect or maintain.

A vast number of models can be used. For maximizing availability of a system, Markov processes can be used to optimize the value of mean time to preventive maintenance (G. Petrovic et al., 2011). An age replacement policy is a well-known model which calculates the optimum interval for replacement of an item when failure replacement costs more than planned replacement and the failure rate is increasing with time (Barlow & Proschan, 1965). It is mathematically expressed in the equation below:

$$c(t_p) = \frac{c_p \cdot R(t_p) + c_c \cdot F(t_p)}{\int_0^{t_p} R(t)dt}$$

On the left hand side of the equation, $c(t_p)$ indicates the expected cost per unit time, which is desired to be minimized. On the right hand side of the equation, the cost of preventive maintenance, c_p, and the cost of corrective maintenance, c_c, are included in the numerator along with the reliability function, R(t), and the unreliability function F(t). Here, R(t) = 1 – F(t). On the denominator, the reliability function is integrated on an interval from zero to a given time. The interval, t_p, which gives the lowest value of expected cost per unit time, $c(t_p)$, is the suggested interval. An example on how this model would look like is given:

The optimum intervall for replacement of an asset is desired. The cost of preventive maintenance is 1,000 NOK and the cost of corrective maintenance is 50,000 NOK. Weibull distribution is assumed with scale paramtere of 200 and a shape parameter of 5, and the integral is running from 0 to 300 hours. MATLAB® is used in the following computation, and the programmed codes for the calculation can be found in appendix B.

First the reliability function is defined:

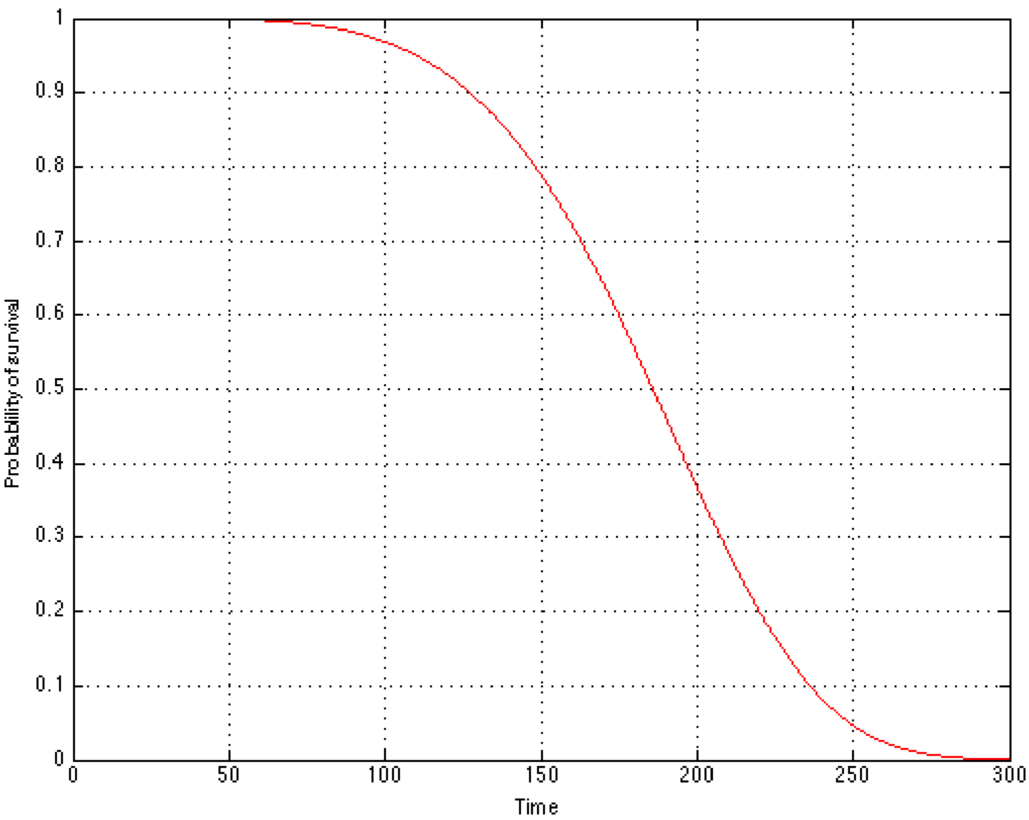

Figure 12: The reliability function with Weibull distribution.

Next, the calculation is performed and plotted in a graph which shows the expected cost per unit time. The optimum interval for replacement was calculated to be 70 hours, which is the lowest point on the graph in the following figure:

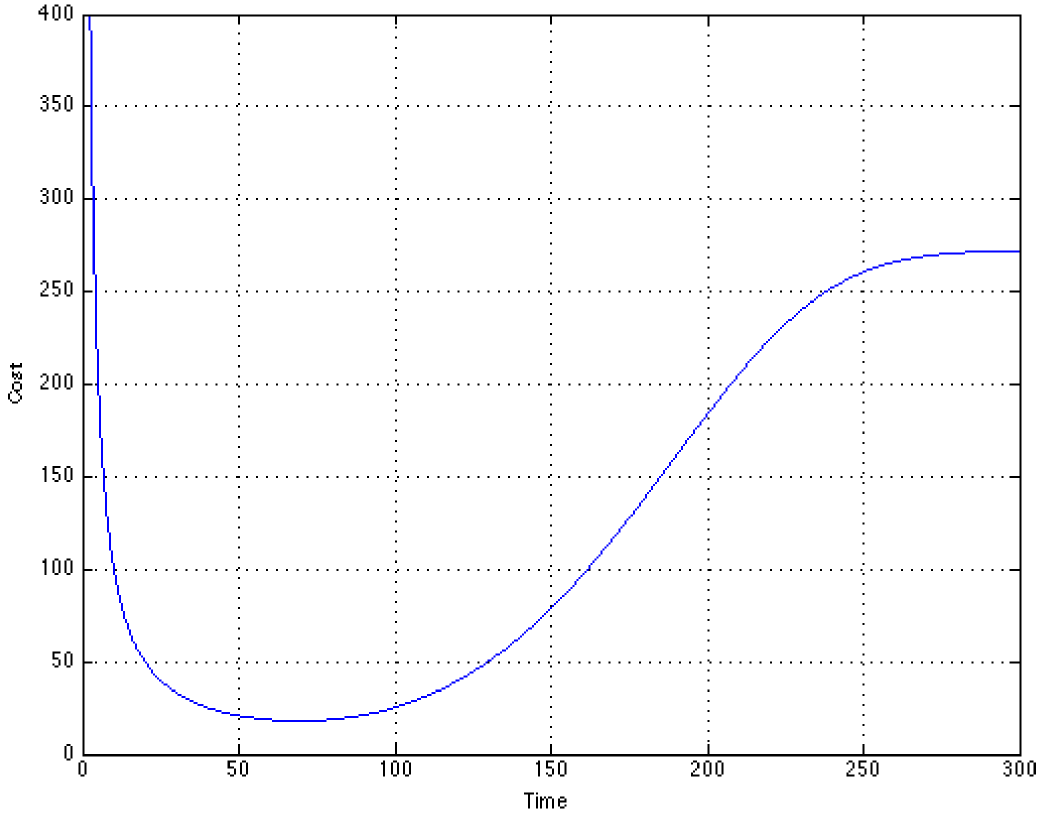

Figure 13: Expected cost per unit time by using the age replacement policy with the given input.

Choosing the right software for RCM analyses may not be an easy choice. A product can be evaluated according to attributes such as quality and price (A. C. Marques & C. Blanchar: 2004). For RCM software, the quality attributes are composed of two sets of criteria: methodological criteria and functional criteria, while price attributes consist of all aspects related to the total cost of the product (Barbera et al.:2011). Software criteria may be defined from ISO/IEC CD 25010 (2008).

Method

The research problem addressed in this thesis aims to unveil the challenges of RCM as an analysis method for large tag structures on the Norwegian shelf.

To answer the problem, it was unavoidable to get in contact with those who work as RCM facilitators and have experience with analyses on large tag structures. The objective was to gain insight in a structured manner, and at the same let the respondents elaborate freely around the topic. Quantitative data was desired in order to differentiate the various aspects of RCM from one another, but at the same one could not evade qualitative information to truly get an in-depth knowledge to the problem addressed.

The thesis follows a mixed research method, also known as a semi-quantitative method. This approach involves a mix of less quantitative precision and more qualitative description, compared to an ordinary quantitative research method. The reason for this selection of method was its appropriateness to ensure both quantitative and qualitative data, which was considered important for the problem addressed. It was also an adequate approach in gathering quantitative data when the number of available RCM facilitators with relevant experience was hard to obtain for a fully qualified quantitative approach.

A fully quantitative or qualitative approach would probably provide better results for the one of those methods chosen, but it would at the same time lose insight in the other method not chosen. For the specific problem addressed in this thesis, it was considered valuable to gain insight in both. The goal is have the respondents to put their own words to what they see as challenging with RCM for large tag structures on the qualitative part, and uncover tendencies in the quantitative part that none were aware of or explicitly would or could confirm in the qualitative approach. An open process of data gathering is desired, but a structured survey is provided deliberately to ensure validity to the thesis.

Seven RCM facilitators have filled out a quantitative survey and been interviewed to explain the numbers behind their answers. The survey consisted of 64 criterions divided into three attributes, in accordance with A. C. Marques & C. Blanchar (2004) and Barbera et al. (2011). The methodological criterions have been derived from SAE JA1011, the "Evaluation Criteria for Reliability-Centered Maintenance (RCM) Processes". The functional criterions are derived from ISO/IEC CD 25010, named "Software engineering – Software product Quality Requirements and Evaluation (SQuaRE) – Software and quality in use models". Five economic criterions have been defined, based on the economic events that are reasonable to believe will occur throughout the life cycle of a software.

The quantitative data have been sorted in a QFD diagram. QFD is a common methodology for business purposes to ensure that customers' requirements are met throughout a process (Evans 2011:104). In this thesis, QFD is being used for RCM processes on large tag structures to investigate how these processes comply with the criterions. With this approach, one will get a clear insight in how the different aspects of a RCM analysis are considered important and ensured. By adding up these numbers one will also get an overview of the different criterions and the facilitators with their software in use. Qualitative data are integrated among the quantitative data to explain the essence of what lies behind the numbers.

Besides being a method to investigate RCM processes for large tag structures on the Norwegian continental shelf, the survey is also meant to be a general tool for systematic self-evaluation for those who participate in RCM processes. Since the criterions in the survey are based on applicable standards, the survey will hopefully raise awareness and knowledge to the process itself and to RCM software as a tool in the process.

The background and experiences of the facilitators were versatile, but it would have been desirable to have more than seven respondents. Therefore, the reliability of the results may vary if this study is being re-examined later. Nevertheless, a re-examination should be easy to conduct with the standardized survey established.

Among the seven different respondents who participated, there were three different RCM software under evaluation. They can be differed from one another as A, B and C. Respondents A1, B1 and C1 is the same person, who evaluates on basis of all three software. All the other respondents are unique and are only assessing one software. Table 1 gives an overview of the respondents.

Table 1: Data on respondents who contributed in the survey.

Respondent	Software	Years of experience with the software	Years of experience as a RCM facilitator
A1	A	10	10
A2	A	7	7
A3	A	2	2
B1	B	7	10
B2	B	5	8
B3	B	4	4
B4	B	1,5	1,5
B5	B	3	7
C1	C	0	10

The information provided to the respondents before answering the survey can be found in appendix C. The survey, as presented to the respondents, is presented on the next pages.

Table 2: Survey "Formalities".

	INPUT
What RCM software are you assessing in this survey?	
How many years of experience do you have with this RCM software?	
In general, how many years of experience do you have with RCM?	
Rate the following criterions for conducting RCM analysis on large tag structures, with respect to:	
1. The importance of each criterion in order to achieve a successfull analysis:	**IMPORTANCE** 1 = Insignificant 2 = Partly 3 = Important
2. The relation between each criterion and the software in use:	**RELATION** 1 = None 3 = Partly 9 = Highly

Quality attribute 1: Assessment of methodological criterions

Table 3: Survey "Functions".

#	FUNCTIONS Criterion	Importance 1 = Insignificant 2 = Partly 3 = Important	Relation 1 = None 3 = Partly 9 = Highly	Score
1	The ability to define the operating context of the asset.			
2	The ability to identify all functions of the asset/system.			
3	The ability to describe functions by the use of a verb, an object, and a performance standard.			
4	The ability to adjust the performance standards incorporated in function statements to the level of performance as desired by the owner or user of the asset/system in its operating context.			
	Score "Functions"			

Table 4: Survey "Functional failures".

#	FUNCTIONAL FAILURES Criterion	Importance 1 = Insignificant 2 = Partly 3 = Important	Relation 1 = None 3 = Partly 9 = Highly	Score
5	The ability to identify and associate all the failed states to a function.			
	Score "Functional failures"			

Table 5: Survey "Failure modes".

#	FAILURE MODES Criterion	Importance 1 = Insignificant 2 = Partly 3 = Important	Relation 1 = None 3 = Partly 9 = Highly	Score
6	The ability to identify all failure modes reasonably likely to cause each functional failure.			
7	The ability to establish what is meant by "reasonably likely" that the owner or user of the asset finds acceptable.			
8	The ability to identify failure modes at a level of causation that makes it possible to identify an appropriate failure management policy.			
9	The ability to include lists with failure modes that have happened before, are currently being prevented by existing maintenance programs, and failure modes that have not yet happened but that are thought to be reasonably likely in the operating context.			
10	To ability to include any event or process that is likely to cause a functional failure, including deterioration, design defects, and human error whether caused by operators or maintainers, in the lists of failure modes.			
	Score "Failure modes"			

Table 6: Survey "Failure effects".

#	FAILURE EFFECTS Criterion	Importance 1 = Insignificant 2 = Partly 3 = Important	Relation 1 = None 3 = Partly 9 = Highly	Score
11	The ability to describe failure effects as what would happen if no specific task is done to anticipate, prevent, or detect the failure.			
12	The ability to include all the information needed to support the evaluation of the consequences of a failure, with regard to failure effects.			
	Score "Failure effects"			

Table 7: Survey "Failure consequence categories".

#	FAILURE CONSEQUENCE CATEGORIES Criterion	Importance 1 = Insignificant 2 = Partly 3 = Important	Relation 1 = None 3 = Partly 9 = Highly	Score
13	The ability to separate hidden failure modes from evident failure modes.			
14	The ability to clearly distinguishing safety and/or environmental consequences (operational) from economic consequences (non-operational).			
15	The ability to carry out the assessment of failure consequences as if no specific task is currently being done to anticipate, prevent, or detect the failure.			
	Score "Failure consequence categories"			

Table 8: Survey "Failure management policy selection".

#	FAILURE MANAGEMENT POLICY SELECTION Criterion	Importance 1 = Insignificant 2 = Partly 3 = Important	Relation 1 = None 3 = Partly 9 = Highly	Score
16	To what degree it is emphasized in the failure management selection process that the conditional probability of some failure modes might increase with age, others not change with age, and yet others will decrease with age.			
17	To what degree it is emphasized that all scheduled tasks shall be technically feasible and worth doing.			
18	To what degree it is emphasized, if two or more proposed failure management policies are technically feasible and worth doing, that the policy which is most cost-effective shall be selected.			
19	To what degree it is emphasized that selection of failure management policies shall be carried out as if no specific task is currently being done to anticipate, prevent or detect the failure.			
	Score "Failure management policy selection"			

Table 9: Survey "Failure management policies - scheduled tasks".

#	FAILURE MANAGEMENT POLICIES - SCHEDULED TASKS			
#	**Criterion**	**Importance** 1 = Insignificant 2 = Partly 3 = Important	**Relation** 1 = None 3 = Partly 9 = Highly	**Score**
20	In the case of an evident failure mode that has safety or environmental consequences, it is conjured for a task that reduces the probability of the failure mode to a level that is tolerable to the owner or user of the asset.			
21	In the case of a hidden failure mode where the associated multiple failure has safety or environmental consequences, it is conjured for a task that reduces the probability of the hidden failure mode to an extent which reduces the probability of the associated multiple failure to a level that is tolerable to the owner or user of the asset.			
22	In the case of an evident failure mode that does not have safety or environmental consequences, it is conjured for a task with less direct and indirect costs than the direct and indirect costs of the failure mode when measured over comparable periods of time.			
23	In the case of a hidden failure mode where the associated multiple failure does not have safety or environmental consequences, it is conjured for a task with less direct and indirect costs than the direct and indirect costs of the multiple failure plus the cost of repairing the hidden failure mode when measured over comparable periods of time.			
	Score "Failure management policies - Scheduled tasks"			

Table 10: Survey "On-condition tasks".

#	ON-CONDITION TASKS			
#	**Criterion**	**Importance** 1 = Insignificant 2 = Partly 3 = Important	**Relation** 1 = None 3 = Partly 9 = Highly	**Score**
24	The ability to ensure a clearly defined potential failure when selecting on-condition tasks.			
25	The ability to ensure an identifiable P-F interval when selecting on-condition tasks.			
26	The ability to ensure a task interval less than the shortest likely P-F interval when selecting on-condition tasks.			
27	The ability to ensure that it is physically possible to do the task at intervals less than the P-F interval when selecting on-condition tasks.			
28	The ability to ensure that the shortest time between the discovery of a potential failure and the occurrence of the functional failure is long enough for predetermined action to be taken to avoid, eliminate, or minimize the consequences of the failure mode.			
	Score "On-condition tasks"			

Table 11: Survey "Scheduled discard tasks".

	SCHEDULED DISCARD TASKS			
#	Criterion	Importance 1 = Insignificant 2 = Partly 3 = Important	Relation 1 = None 3 = Partly 9 = Highly	Score
29	The ability to ensure a clearly defined age at which there is an increase in the conditional probability of the failure mode under consideration, when selecting scheduled discard tasks.			
30	The ability to ensure that a sufficiently large proportion of the occurrences of failure modes that require scheduled discard tasks occur after the clearly defined age, to reduce the probability of premature failure to a level that is tolerable to the owner or user of the asset.			
	Score "Scheduled discard tasks"			

Table 12: Survey "Scheduled restoration tasks".

	SCHEDULED RESTORATION TASKS			
#	Criterion	Importance 1 = Insignificant 2 = Partly 3 = Important	Relation 1 = None 3 = Partly 9 = Highly	Score
31	The ability to ensure a clearly defined age at which there is an increase in the conditional probability of the failure mode under consideration when selecting a scheduled restoration task.			
32	The ability to ensure that a sufficiently large proportion of the occurrences of failure modes that require scheduled restoration tasks occur after the clearly defined age, to reduce the probability of premature failure to a level that is tolerable to the owner or user of the asset.			
33	To what degree it is emphasized that a scheduled restoration task shall restore the resistance to failure of the component to a level that is tolerable to the owner or user of the asset.			
	Score "Scheduled restoration tasks"			

Table 13: Survey "Failure finding tasks".

	FAILURE FINDING TASKS			
#	Criterion	Importance 1 = Insignificant 2 = Partly 3 = Important	Relation 1 = None 3 = Partly 9 = Highly	Score
34	To what degree it is emphasized that the selection of a failure-finding task interval shall take into account the need to reduce the probability of the multiple failure of the associated protected system to a level that is tolerable to the owner or user of the asset.			
35	To what degree it is emphasized that the task shall confirm that all components covered by the failure mode description are functional.			
36	To what degree it is emphasized that the failure-finding task and associated interval selection process should take into account any probability that the task itself might leave the hidden function in a failed state.			
37	To what degree it is emphasized that it shall be physically possible to do the task at the specified intervals.			
	Score "Failure finding tasks"			

Table 14: Survey "One-time changes".

#	ONE-TIME CHANGES			
#	**Criterion**	**Importance** 1 = Insignificant 2 = Partly 3 = Important	**Relation** 1 = None 3 = Partly 9 = Highly	**Score**
38	To what degree it is emphasized that the RCM process shall endeavor to extract the desired performance of the system as it is currently configured and operated by applying appropriate scheduled tasks.			
39	The ability to ensure a one-time change that reduces the probability of the multiple failure to a level tolerable to the owner or user of the asset, when the failure is hidden and the associated multiple failure has safety or environmental consequences.			
40	The ability to ensure a one-time change that reduces the probability of the failure mode to a level tolerable to the owner or user of the asset, when the failure mode is evident and has safety or environmental consequences.			
41	The ability to ensure that a one-time change must be cost-effective in the opinion of the owner or user of the asset, when the failure mode is hidden and the associated multiple failure does not have safety or environmental consequences.			
42	The ability to ensure that a one-time change must be cost-effective in the opinion of the owner or user of the asset, when the failure mode is evident and does not have safety or environmental consequences.			
	Score "One-time changes"			

Table 15: Survey "Run to failure".

#	RUN-TO-FAILURE			
#	**Criterion**	**Importance** 1 = Insignificant 2 = Partly 3 = Important	**Relation** 1 = None 3 = Partly 9 = Highly	**Score**
43	To what degree it is emphasized that any run-to-failure policy shall not have any multiple failure or failure mode with safety or environmental consequences.			
	Score "Run-to-failure"			

Table 16: Survey "A living program".

#	A LIVING PROGRAM			
#	**Criterion**	**Importance** 1 = Insignificant 2 = Partly 3 = Important	**Relation** 1 = None 3 = Partly 9 = Highly	**Score**
44	To what degree it is provided for a periodic review of both the information used to support the decisions and the decisions themselves.			
	Score "A living program"			

Table 17: Survey "Mathematical and statistical formulae".

#	MATHEMATICAL AND STATISTICAL FORMULAE			
#	**Criterion**	**Importance** 1 = Insignificant 2 = Partly 3 = Important	**Relation** 1 = None 3 = Partly 9 = Highly	**Score**
45	To what degree any mathematical and statistical formula used in the application of the process is logically robust, and be available to and approved by the owner or user of the asset.			
	Score "Mathematical and statistical formulae"			

Quality attribute 2: Assessment of software criterions

Table 18: Survey "Suitability" of software.

#	SUITABILITY			
#	**Criterion**	**Importance** 1 = Insignificant 2 = Partly 3 = Important	**Relation** 1 = None 3 = Partly 9 = Highly	**Score**
46	To what degree the software provides functions that meet stated and implied needs of the user.			
47	To what degree the software provides precise and accurate results.			
	Score "Suitability"			

Table 19: Survey "Reliability" of software.

#	RELIABILITY			
#	**Criterion**	**Importance** 1 = Insignificant 2 = Partly 3 = Important	**Relation** 1 = None 3 = Partly 9 = Highly	**Score**
48	To what degree the software is operational and available when required for use.			
49	To what degree the software product can maintain a specified level of performance in case of software faults.			
50	To what degree the software can re-establish a specified level of performance and recover the data directly affected in the case of failure.			
	Score "Reliability"			

Table 20: Survey "Performance efficiency" of software.

#	PERFORMANCE EFFICIENCY			
#	**Criterion**	**Importance** 1 = Insignificant 2 = Partly 3 = Important	**Relation** 1 = None 3 = Partly 9 = Highly	**Score**
51	To what degree the software provides appropriate response and processing times when performing its function.			
	Score "Performance efficiency"			

Table 21: Survey "Operability" of software.

	OPERABILITY			
#	Criterion	Importance 1 = Insignificant 2 = Partly 3 = Important	Relation 1 = None 3 = Partly 9 = Highly	Score
52	To what degree the software enables user to learn its application.			
53	To what degree the software is easy for the user to operate and control.			
54	To what degree the software provides help when user needs assistance.			
55	To what degree the software is attractive to the user.			
	Score "Operability"			

Table 22: Survey "Security" of software.

	SECURITY			
#	Criterion	Importance 1 = Insignificant 2 = Partly 3 = Important	Relation 1 = None 3 = Partly 9 = Highly	Score
56	To what degree system items are protected from accidental or malicious access, use, modification, destruction, or disclosure.			
	Score "Security"			

Table 23: Survey "Compatability" of software.

	COMPATABILITY			
#	Criterion	Importance 1 = Insignificant 2 = Partly 3 = Important	Relation 1 = None 3 = Partly 9 = Highly	Score
57	To what degree the software can exchange information with other systems and databases.			
	Score "Compatability"			

Table 24: Survey "Maintainability" of software.

	MAINTAINABILITY			
#	Criterion	Importance 1 = Insignificant 2 = Partly 3 = Important	Relation 1 = None 3 = Partly 9 = Highly	Score
58	To what degree the software can be modified to corrections, improvements or adaption to changes in environment, requirements and functional specifications.			
	Score "Maintainability"			

Table 25: Survey "Transferability" of software.

	TRANSFERABILITY			
#	Criterion	Importance 1 = Insignificant 2 = Partly 3 = Important	Relation 1 = None 3 = Partly 9 = Highly	Score
59	To what degree the software can be transferred from one environment to another.			
	Score "Transferability"			

Quality attribute 3: Assessment of economic criterions

Table 26: Survey "Economic criterions".

	PRICE			
#	Criterion	Importance 1 = Insignificant 2 = Partly 3 = Important	Relation 1 = None 3 = Partly 9 = Highly	Score
60	To what degree the cost of purchase is acceptable.			
61	To what degree the cost of installation is acceptable.			
62	To what degree the cost of training is acceptable.			
63	To what degree the cost of annual maintenance is acceptable.			
64	To what degree the cost of updates is acceptable.			
	Score "Price"			

Results

The results from the quantitative and the qualitative data gathering are presented together. The quantitative results have also been colored with green, yellow or red which groups the different criterions based on their score. A green color indicates a score on the upper part of the scale; yellow color indicated middle part of the scale, and red lower part of the scale.

Assessment of methodological criterions

Step 1

What are the functions and associated desired standards of performance of the asset in its present operating context (functions)?

Table 27: The importance of step 1.

		IMPORTANCE											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
1	The ability to define the operating context of the asset.	2	2	3	2	3	3	2	2	2	21	2,33	0,47
2	The ability to identify all functions of the asset/system.	2	3	2	2	3	3	2	3	2	22	2,44	0,50
3	The ability to describe functions by the use of a verb, an object, and a performance standard.	2	2	3	2	3	3	2	3	2	22	2,44	0,50
4	The ability to adjust the performance standards incorporated in function statements to the level of performance as desired by the owner or user of the asset/system in its operating context.	1	2	2	1	2	2	1	3	1	15	1,67	0,67

Table 28: The relation between RCM software and step 1.

		RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
1	The ability to define the operating context of the asset.	9	3	9	3	9	9	9	9	9	69	7,67	2,49
2	The ability to identify all functions of the asset/system.	9	3	9	9	3	3	9	9	9	63	7,00	2,83
3	The ability to describe functions by the use of a verb, an object, and a performance standard.	9	9	3	3	9	3	3	9	9	57	6,33	2,98
4	The ability to adjust the performance standards incorporated in function statements to the level of performance as desired by the owner or user of the asset/system in its operating context.	6	9	9	3	3	3	3	9	3	48	5,33	2,75

Table 29: "Importance" multiplied with "Relation" for step 1.

		IMPORTANCE x RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
1	The ability to define the operating context of the asset.	18	6	27	6	27	27	18	18	18	165	18,33	7,67
2	The ability to identify all functions of the asset/system.	18	9	18	18	9	9	18	27	18	144	16,00	5,66
3	The ability to describe functions by the use of a verb, an object, and a performance standard.	18	18	9	6	27	9	6	27	18	138	15,33	7,80
4	The ability to adjust the performance standards incorporated in function statements to the level of performance as desired by the owner or user of the asset/system in its operating context.	6	18	18	3	6	6	3	27	3	90	10,00	8,25

Qualitative data – step 1

Defining the operating context was considered important in cases were the context was considered HSE critical. In general, the RCM software in consideration could easily allow for a detailed description of the context of any asset, as desired.

The ability to identify and describe all functions of the asset/system was considered above average important, but this proved to be a truth with modifications for some of the respondents. The recurring issue was that all assets were identified, but not necessarily all associated functions. This was primarily due to three reasons:

1. It was easier to define assets only rather than all associated functions, because assets could be downloaded electronically from a database into the RCM software.
2. It required a lot of effort to define a set of functions for each asset when the tag structures consisted of about 70,000 tags.
3. A concrete performance standard was unknown or difficult to define in many cases.
4. In accordance with the activity regulation set out by PSA for maintenance on the Norwegian shelf, there were no requirements to classification of functions, but classification of tags.

Nevertheless, the respondents admitted that the criterion itself was important and that it would be the best maintenance practice to define all functions. However, the amount of resources it required pushes on for more time saving approaches. Even generic lists of functions in the RCM software was not reason enough for defining all functions to an asset. In should be said that these generic lists did not include performance standards, but were more general like "pump pumps".

Adjustment of performance standards was a rare thing and therefore rated low in importance. For most RCM software the performance standard could be changed if desired.

Step 2

In what ways can it fail to fulfill its functions (functional failures)?

Table 30: The importance of step 2.

		IMPORTANCE											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
5	The ability to identify and associate all the failed states to a function.	3	3	3	3	3	3	3	3	3	27	3,00	0,00

Table 31: The relation between RCM software and step 2.

		RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
5	The ability to identify and associate all the failed states to a function.	9	3	3	9	3	3	9	9	9	57	6,33	2,98

Table 32: "Importance" multiplied with "Relation" for step 2.

		IMPORTANCE x RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
5	The ability to identify and associate all the failed states to a function.	27	9	9	27	9	9	27	27	27	171	19,00	8,94

Qualitative data – step 2

Step 2 got a high score because it was considered very important by all respondents, and most of them thought their RCM software were appropriate to this criterion. Most of the respondents said they used a generic list of functional failures that they could add to each tag. Some also said that they were more interested in spending time defining how an asset could fail, rather defining its functions.

A full score was not given from everyone in their evaluation of RCM software on step 2 for the following reasons:

1. A function was not always established in the first place so it would be wrong to say that the failed state chosen from the generic list was associated to a function, but rather a tag.
2. The functional failure provided by the generic list was not always the best. One could define a new and custom functional failure as desired, or comment the selection of functional failure from the generic list, but this was considered an additional effort.

Step 3

What causes each functional failure (failure modes)?

Table 33: The importance of step 3.

		IMPORTANCE											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
6	The ability to identify all failure modes reasonably likely to cause each functional failure.	3	3	3	3	3	3	3	3	3	27	3,00	0,00
7	The ability to establish what is meant by "reasonably likely" that the owner or user of the asset finds acceptable.	3	2	3	3	3	3	3	1	3	24	2,67	0,67
8	The ability to identify failure modes at a level of causation that makes it possible to identify an appropriate failure management policy.	2	3	3	2	3	3	3	2	2	23	2,56	0,50
9	The ability to include lists with failure modes that have happened before, are currently being prevented by existing maintenance programs, and failure modes that have not yet happened but that are thought to be reasonably likely in the operating context.	2	3	3	2	3	3	3	2	2	23	2,56	0,50
10	To ability to include any event or process that is likely to cause a functional failure, including deterioration, design defects, and human error whether caused by operators or maintainers, in the lists of failure modes.	3	3	2	3	3	3	3	2	3	25	2,78	0,42

Table 34: The relation between RCM software and step 3.

		RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
6	The ability to identify all failure modes reasonably likely to cause each functional failure.	9	3	3	9	9	9	9	9	9	69	7,67	2,49
7	The ability to establish what is meant by "reasonably likely" that the owner or user of the asset finds acceptable.	9	3	9	9	3	3	9	9	1	55	6,11	3,28
8	The ability to identify failure modes at a level of causation that makes it possible to identify an appropriate failure management policy.	3	3	1	9	9	9	9	9	1	53	5,89	3,54
9	The ability to include lists with failure modes that have happened before, are currently being prevented by existing maintenance programs, and failure modes that have not yet happened but that are thought to be reasonably likely in the operating context.	3	3	9	9	3	3	9	9	1	49	5,44	3,24
10	To ability to include any event or process that is likely to cause a functional failure, including deterioration, design defects, and human error whether caused by operators or maintainers, in the lists of failure modes.	9	3	9	3	3	1	9	9	9	55	6,11	3,28

Table 35: "Importance" multiplied with "Relation" for step 3.

		IMPORTANCE x RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
6	The ability to identify all failure modes reasonably likely to cause each functional failure.	27	9	9	27	27	27	27	27	27	207	23,00	7,48
7	The ability to establish what is meant by "reasonably likely" that the owner or user of the asset finds acceptable.	27	6	27	27	9	9	27	9	3	144	16,00	10,00
8	The ability to identify failure modes at a level of causation that makes it possible to identify an appropriate failure management policy.	6	9	3	18	27	27	27	18	2	137	15,22	9,89
9	The ability to include lists with failure modes that have happened before, are currently being prevented by existing maintenance programs, and failure modes that have not yet happened but that are thought to be reasonably likely in the operating context.	6	9	27	18	9	9	27	18	2	125	13,89	8,52
10	To ability to include any event or process that is likely to cause a functional failure, including deterioration, design defects, and human error whether caused by operators or maintainers, in the lists of failure modes.	27	9	18	9	9	3	27	18	27	147	16,33	8,73

Qualitative data – step 3

All criterions in step 3 were, in general, defined as important by the RCM facilitators. However, only the ability to identify all failure modes reasonably likely to cause each functional failure was said to be highly ensured by the RCM tools.

The reason for why only the first criterion was taken maximum advantage of was because the rest of the RCM was primarily based on the identified failure modes, to define proper maintenance tasks for the established failure modes in the RCM process.

The remaining criterions related to the RCM tools had varying scores from the respondents. The entire range from 1 to 9 was used for every criterion, and from different users. This could be explained by differences in the software and different perspectives with regards to experience and familiarity between the facilitator and their software.

The establishment of what was meant as reasonably likely was usually done in advance by the owner of the equipment in a local risk analysis within their company. It could be implemented into the process, but there were various experiences on how this was implemented into the software when it was already established and often printed out to those executing the analysis.

Tool B has undoubtedly the best relation of the tools in identifying failure modes at a level of causation that makes it possible to identify an appropriate failure management policy. This was because tool B in general was more flexible and able to make custom adjustments to its users, than tool A and C.

Most of the respondents had experience with inclusion of generic lists of failure modes, but not for tool C which got a low score. There were also some personal divergences between the respondents on how well they thought their tool actually was on this criterion.

For the last criterion, only respondent B3 gave the lowest score; 1. Beyond that RCM tools got at least one top score of 9 and a middle score of 3. Respondent B3 is also the one among the respondents who has given the lowest total in the evaluation of the methodological criterions. This matter is most likely related to personal use of the software, rather than the software design.

Step 4

What happens when each failure occurs (failure effects)?

Table 36: The importance of step 4.

		IMPORTANCE											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
11	The ability to describe failure effects as what would happen if no specific task is done to anticipate, prevent, or detect the failure.	3	3	3	3	3	3	3	3	3	27	3,00	0,00
12	The ability to include all the information needed to support the evaluation of the consequences of a failure, with regard to failure effects.	3	3	2	3	3	3	3	2	3	25	2,78	0,42

Table 37: The relation between RCM software and step 4.

		RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
11	The ability to describe failure effects as what would happen if no specific task is done to anticipate, prevent, or detect the failure.	9	9	9	9	9	9	9	9	9	81	9,00	0,00
12	The ability to include all the information needed to support the evaluation of the consequences of a failure, with regard to failure effects.	9	9	9	9	9	9	9	9	9	81	9,00	0,00

Table 38: "Importance" multiplied with "Relation" for step 4.

		IMPORTANCE x RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
11	The ability to describe failure effects as what would happen if no specific task is done to anticipate, prevent, or detect the failure.	27	27	27	27	27	27	27	27	27	243	27,00	0,00
12	The ability to include all the information needed to support the evaluation of the consequences of a failure, with regard to failure effects.	27	27	18	27	27	27	27	18	27	225	25,00	3,74

Qualitative data – step 4

The ability to describe failure effects as what would happen if no specific task is done to anticipate, prevent or detect the failure was unquestionably considered very important and deeply rooted in the RCM software. All respondents expressed this matter as crucial in order to move on in the process and usually relied on experts in the analysis group to describe these failure effects. What was interesting was that some also said that “effects” and “consequences” could easily be interpreted as the same part of the process. This could lead to that the effects were not described properly, or even forgotten.

The ability to include all information needed to support the evaluation of the consequences of a failure, with regard to failure effects, was well preserved in the RCM tools. Most of the respondents found this an important criterion. Nevertheless, two of the respondents defined this criterion as medium important after having experience with system experts who already possessed needed information. Their knowledge was not considered important to write down into the analysis as long as the experts shared this information so that the right decisions could be made.

Step 5

In what way does each failure matter (failure consequences)?

Table 39: The importance of step 5.

		IMPORTANCE											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
13	The ability to separate hidden failure modes from evident failure modes.	3	3	3	3	3	3	3	3	3	27	3,00	0,00
14	The ability to clearly distinguishing safety and/or environmental consequences (operational) from economic consequences (non-operational).	2	3	3	2	2	3	2	3	2	22	2,44	0,50
15	The ability to carry out the assessment of failure consequences as if no specific task is currently being done to anticipate, prevent, or detect the failure.	1	3	2	1	1	1	1	1	1	12	1,33	0,67

Table 40: The relation between RCM software and step 5.

		RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
13	The ability to separate hidden failure modes from evident failure modes.	3	3	9	3	9	1	3	9	3	43	4,78	3,05
14	The ability to clearly distinguishing safety and/or environmental consequences (operational) from economic consequences (non-operational).	9	9	9	9	9	9	9	9	3	75	8,33	1,89
15	The ability to carry out the assessment of failure consequences as if no specific task is currently being done to anticipate, prevent, or detect the failure.	3	9	9	3	2	1	3	1	3	34	3,78	2,90

Table 41: "Importance" multiplied with "Relation" for step 5.

		IMPORTANCE x RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
13	The ability to separate hidden failure modes from evident failure modes.	9	9	27	9	27	3	9	27	9	129	14,33	9,14
14	The ability to clearly distinguishing safety and/or environmental consequences (operational) from economic consequences (non-operational).	18	27	27	18	18	27	18	27	6	186	20,67	6,70
15	The ability to carry out the assessment of failure consequences as if no specific task is currently being done to anticipate, prevent, or detect the failure.	3	27	18	3	2	1	3	1	3	61	6,78	8,70

Qualitative data – step 5

The ability to separate hidden failure modes from evident failure modes was considered highly important by all facilitators in the survey. At the same time, few of them practiced this at all times as the RCM decision diagram was described in theory. Instead of starting with asking whether a failure would become hidden or evident in the decision logic, many of the facilitators started by asking whether or not the asset is critical or not. If not, then it has been allowed to run to failure regardless if the failure is hidden or evident. This approach has also saved the facilitators for a lot of time when conducting an analysis with many tags, because they don't have to answer so many questions in the decision diagram with this logic.

The ability to clearly distinguish safety and environmental consequences from economic consequences was for most of the respondents considered very important. Those who did not give a full score for this criterion replied that this was not very important if the consequence was very low. It still did matter, but was not considered very important and therefore balanced their rating. Some also supplied that their software was capable of distinguishing between more specific consequences, such as reputation, internal or external, welfare, third person.

Criterion 15; carrying out the assessment of failure consequences as if no specific task currently was being done to anticipate, prevent or detect the failure, was not considered important by most of the respondents. They expressed this as not an important criterion because it was understood as a natural and underlying factor within the RCM process. The exception was one who felt that it was a good an important point, even though it was automatically taken care of. The relation of this criterion to the RCM software had varying results when some felt that there were no function within the software that supported this criterion, while others thought that their software was built in way that prepared for this to be taken care of as the criterion asked for.

Step 6

What should be done to predict or prevent each failure (proactive tasks and task intervals)?

Table 42: The importance of step 6.

		IMPORTANCE											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
16	To what degree it is emphasized in the failure management selection process that the conditional probability of some failure modes might increase with age, others not change with age, and yet others will decrease with age.	3	2	2	3	3	2	2	3	3	23	2,56	0,50
17	To what degree it is emphasized that all scheduled tasks shall be technically feasible and worth doing.	2	2	2	2	2	1	2	3	2	18	2,00	0,47
18	To what degree it is emphasized, if two or more proposed failure management policies are technically feasible and worth doing, that the policy which is most cost-effective shall be selected.	2	2	3	2	3	1	2	2	2	19	2,11	0,57
19	To what degree it is emphasized that selection of failure management policies shall be carried out as if no specific task is currently being done to anticipate, prevent or detect the failure.	2	2	2	2	3	1	2	1	2	17	1,89	0,57
20	In the case of an evident failure mode that has safety or environmental consequences, it is conjured for a task that reduces the probability of the failure mode to a level that is tolerable to the owner or user of the asset.	3	3	3	3	3	3	3	3	3	27	3,00	0,00
21	In the case of a hidden failure mode where the associated multiple failure has safety or environmental consequences, it is conjured for a task that reduces the probability of the hidden failure mode to an extent which reduces the probability of the associated multiple failure to a level that is tolerable to the owner or user of the asset.	3	3	3	3	3	3	3	3	3	27	3,00	0,00
22	In the case of an evident failure mode that does not have safety or environmental consequences, it is conjured for a task with less direct and indirect costs than the direct and indirect costs of the failure mode when measured over comparable periods of time.	3	3	3	3	3	3	3	3	3	27	3,00	0,00
23	In the case of a hidden failure mode where the associated multiple failure does not have safety or environmental consequences, it is conjured for a task with less direct and indirect costs than the direct and indirect costs of the multiple failure plus the cost of repairing the hidden failure mode when measured over comparable periods of time.	3	3	3	3	3	3	3	3	3	27	3,00	0,00
24	The ability to ensure a clearly defined potential failure when selecting on-condition tasks.	2	3	3	2	3	3	2	1	2	21	2,33	0,67
25	The ability to ensure an identifiable P-F interval when selecting on-condition tasks.	2	3	2	2	3	2	2	3	2	21	2,33	0,47
26	The ability to ensure a task interval less than the shortest likely P-F interval when selecting on-condition tasks.	2	3	2	2	2	2	2	3	2	20	2,22	0,42
27	The ability to ensure that it is physically possible to do the task at intervals less than the P-F interval when selecting on-condition tasks.	2	3	2	2	2	1	2	3	2	19	2,11	0,57
28	The ability to ensure that the shortest time between the discovery of a potential failure and the occurrence of the functional failure is long enough for predetermined action to be taken to avoid, eliminate, or minimize the consequences of the failure mode.	2	3	3	2	2	1	2	3	2	20	2,22	0,63
29	The ability to ensure a clearly defined age at which there is an increase in the conditional probability of the failure mode under consideration, when selecting scheduled discard tasks.	2	2	3	2	3	3	3	3	2	23	2,56	0,50
30	The ability to ensure that a sufficiently large proportion of the occurrences of failure modes that require scheduled discard tasks occur after the clearly defined age, to reduce the probability of premature failure to a level that is tolerable to the owner or user of the asset.	1	2	2	1	3	2	2	1	1	15	1,67	0,67
31	The ability to ensure a clearly defined age at which there is an increase in the conditional probability of the failure mode under consideration when selecting a scheduled restoration task.	2	2	3	2	3	3	3	3	2	23	2,56	0,50
32	The ability to ensure that a sufficiently large proportion of the occurrences of failure modes that require scheduled restoration tasks occur after the clearly defined age, to reduce the probability of premature failure to a level that is tolerable to the owner or user of the asset.	1	2	2	1	3	2	2	1	1	15	1,67	0,67
33	To what degree it is emphasized that a scheduled restoration task shall restore the resistance to failure of the component to a level that is tolerable to the owner or user of the asset.	1	3	3	1	3	1	2	1	1	16	1,78	0,92

Table 43: The relation between RCM software and step 6.

		RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
16	To what degree it is emphasized in the failure management selection process that the conditional probability of some failure modes might increase with age, others not change with age, and yet others will decrease with age.	9	1	9	9	3	9	3	9	3	55	6,11	3,28
17	To what degree it is emphasized that all scheduled tasks shall be technically feasible and worth doing.	3	3	1	3	3	1	3	1	3	21	2,33	0,94
18	To what degree it is emphasized, if two or more proposed failure management policies are technically feasible and worth doing, that the policy which is most cost-effective shall be selected.	3	3	3	3	3	3	3	9	3	33	3,67	1,89
19	To what degree it is emphasized that selection of failure management policies shall be carried out as if no specific task is currently being done to anticipate, prevent or detect the failure.	3	9	9	3	3	1	3	1	3	35	3,89	2,85
20	In the case of an evident failure mode that has safety or environmental consequences, it is conjured for a task that reduces the probability of the failure mode to a level that is tolerable to the owner or user of the asset.	9	9	9	9	9	9	9	9	9	81	9,00	0,00
21	In the case of a hidden failure mode where the associated multiple failure has safety or environmental consequences, it is conjured for a task that reduces the probability of the hidden failure mode to an extent which reduces the probability of the associated multiple failure to a level that is tolerable to the owner or user of the asset.	9	9	9	9	9	3	9	9	9	75	8,33	1,89
22	In the case of an evident failure mode that does not have safety or environmental consequences, it is conjured for a task with less direct and indirect costs than the direct and indirect costs of the failure mode when measured over comparable periods of time.	9	9	9	9	9	3	9	9	9	75	8,33	1,89
23	In the case of a hidden failure mode where the associated multiple failure does not have safety or environmental consequences, it is conjured for a task with less direct and indirect costs than the direct and indirect costs of the multiple failure plus the cost of repairing the hidden failure mode when measured over comparable periods of time.	9	9	9	9	9	3	9	9	9	75	8,33	1,89
24	The ability to ensure a clearly defined potential failure when selecting on-condition tasks.	1	9	3	1	1	1	1	3	1	21	2,33	2,49
25	The ability to ensure an identifiable P-F interval when selecting on-condition tasks.	9	3	3	9	9	9	9	1	3	55	6,11	3,28
26	The ability to ensure a task interval less than the shortest likely P-F interval when selecting on-condition tasks.	3	3	9	1	1	3	3	9	1	33	3,67	2,98
27	The ability to ensure that it is physically possible to do the task at intervals less than the P-F interval when selecting on-condition tasks.	3	3	9	1	1	1	3	9	1	31	3,44	3,10
28	The ability to ensure that the shortest time between the discovery of a potential failure and the occurrence of the functional failure is long enough for predetermined action to be taken to avoid, eliminate, or minimize the consequences of the failure mode.	3	3	3	1	1	1	3	1	1	17	1,89	0,99
29	The ability to ensure a clearly defined age at which there is an increase in the conditional probability of the failure mode under consideration, when selecting scheduled discard tasks.	9	9	9	9	9	9	9	9	9	81	9,00	0,00
30	The ability to ensure that a sufficiently large proportion of the occurrences of failure modes that require scheduled discard tasks occur after the clearly defined age, to reduce the probability of premature failure to a level that is tolerable to the owner or user of the asset.	3	3	9	3	3	3	3	1	3	31	3,44	2,06
31	The ability to ensure a clearly defined age at which there is an increase in the conditional probability of the failure mode under consideration when selecting a scheduled restoration task.	9	3	9	9	9	9	9	9	9	75	8,33	1,89
32	The ability to ensure that a sufficiently large proportion of the occurrences of failure modes that require scheduled restoration tasks occur after the clearly defined age, to reduce the probability of premature failure to a level that is tolerable to the owner or user of the asset.	3	3	9	3	3	3	3	1	3	31	3,44	2,06
33	To what degree it is emphasized that a scheduled restoration task shall restore the resistance to failure of the component to a level that is tolerable to the owner or user of the asset.	3	9	9	3	3	1	3	1	3	35	3,89	2,85

Table 44: "Importance" multiplied with "Relation" for step 6.

		IMPORTANCE x RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
16	To what degree it is emphasized in the failure management selection process that the conditional probability of some failure modes might increase with age, others not change with age, and yet others will decrease with age.	27	2	18	27	9	18	6	27	9	143	15,89	9,22
17	To what degree it is emphasized that all scheduled tasks shall be technically feasible and worth doing.	6	6	2	6	6	1	6	3	6	42	4,67	1,94
18	To what degree it is emphasized, if two or more proposed failure management policies are technically feasible and worth doing, that the policy which is most cost-effective shall be selected.	6	6	9	6	9	3	6	18	6	69	7,67	4,03
19	To what degree it is emphasized that selection of failure management policies shall be carried out as if no specific task is currently being done to anticipate, prevent or detect the failure.	6	18	18	6	9	1	6	1	6	71	7,89	5,92
20	In the case of an evident failure mode that has safety or environmental consequences, it is conjured for a task that reduces the probability of the failure mode to a level that is tolerable to the owner or user of the asset.	27	27	27	27	27	27	27	27	27	243	27,00	0,00
21	In the case of a hidden failure mode where the associated multiple failure has safety or environmental consequences, it is conjured for a task that reduces the probability of the hidden failure mode to an extent which reduces the probability of the associated multiple failure to a level that is tolerable to the owner or user of the asset.	27	27	27	27	27	9	27	27	27	225	25,00	5,66
22	In the case of an evident failure mode that does not have safety or environmental consequences, it is conjured for a task with less direct and indirect costs than the direct and indirect costs of the failure mode when measured over comparable periods of time.	27	27	27	27	27	9	27	27	27	225	25,00	5,66
23	In the case of a hidden failure mode where the associated multiple failure does not have safety or environmental consequences, it is conjured for a task with less direct and indirect costs than the direct and indirect costs of the multiple failure plus the cost of repairing the hidden failure mode when measured over comparable periods of time.	27	27	27	27	27	9	27	27	27	225	25,00	5,66
24	The ability to ensure a clearly defined potential failure when selecting on-condition tasks.	2	27	9	2	3	3	2	3	2	53	5,89	7,75
25	The ability to ensure an identifiable P-F interval when selecting on-condition tasks.	18	9	6	18	27	18	18	3	6	123	13,67	7,50
26	The ability to ensure a task interval less than the shortest likely P-F interval when selecting on-condition tasks.	6	9	18	2	2	6	6	27	2	78	8,67	8,01
27	The ability to ensure that it is physically possible to do the task at intervals less than the P-F interval when selecting on-condition tasks.	6	9	18	2	2	1	6	27	2	73	8,11	8,35
28	The ability to ensure that the shortest time between the discovery of a potential failure and the occurrence of the functional failure is long enough for predetermined action to be taken to avoid, eliminate, or minimize the consequences of the failure mode.	6	9	9	2	2	1	6	3	2	40	4,44	2,95
29	The ability to ensure a clearly defined age at which there is an increase in the conditional probability of the failure mode under consideration, when selecting scheduled discard tasks.	18	18	27	18	27	27	27	27	18	207	23,00	4,47
30	The ability to ensure that a sufficiently large proportion of the occurrences of failure modes that require scheduled discard tasks occur after the clearly defined age, to reduce the probability of premature failure to a level that is tolerable to the owner or user of the asset.	3	6	18	3	9	6	6	1	3	55	6,11	4,77
31	The ability to ensure a clearly defined age at which there is an increase in the conditional probability of the failure mode under consideration when selecting a scheduled restoration task.	18	6	27	18	27	27	27	27	18	195	21,67	6,90
32	The ability to ensure that a sufficiently large proportion of the occurrences of failure modes that require scheduled restoration tasks occur after the clearly defined age, to reduce the probability of premature failure to a level that is tolerable to the owner or user of the asset.	3	6	18	3	9	6	6	1	3	55	6,11	4,77
33	To what degree it is emphasized that a scheduled restoration task shall restore the resistance to failure of the component to a level that is tolerable to the owner or user of the asset.	3	27	27	3	9	1	6	1	3	80	8,89	9,96

Qualitative data – step 6

Step 6 consists of 18 criterions, which can be organized in five subgroups:

1. Criterion 16 – 19: Failure management policy selection
2. Criterion 20 – 23: Failure management policies scheduled tasks:
3. Criterion 24 – 28: On-condition tasks
4. Criterion 29 – 30: Scheduled discard tasks
5. Criterion 31 – 33: Scheduled restoration tasks

For the failure management policy selection, only criterion 16 was in general considered above average important by the respondents. From those who gave this criterion a top score, the impact that the conditional probability of a failure could have on the selection of a failure management policy was considered. From the rest of the respondents, who rated a medium score on this criterion, it was said that this was more of a theoretical matter which sometimes was based on assumptions and not always of importance to the equipment. It seemed to be a matter of individual software skills to judge whether or not their RCM tool ensured this criterion, since different user of the same software gave different answers.

Criterion 17, 18 and 19 were in general found less important than average. This had to do with the common sense of not initiating a scheduled task which was not technically feasible or worth doing, choosing the most cost-effective one if two or more were applicable, and also the common sense of carrying out the analysis as if no specific task was currently chosen. There were no specific functions in the RCM tools that actively ensure these criterions. Therefore these score low. Nevertheless, some of the respondents did not rate the lowest score on the relations between the software and the criterion, since they found the software to be of a characteristic state that would not block or confuse the user in ensuring these criterions. Meaning, that if the facilitator were aware of the criterion, the software was working just fine in ensuring these.

Criterion 20, 21, 22 and 23 were all considered very important, with no deviation among the respondents. Also the relation between the RCM software and these criterions got top score from all respondents, except from B3 who gave a medium score on the last three criterions. The reason for this was because of the demand for classifying safety related consequences, which gave criterion 20 top score from B3. Criterion 21 did not get a top score, even though it also was safety related, because hidden failures were not always taken into account. Respondent B3 was also the only one rating lower than the others on the relation between software and criterion 13, the ability to separate hidden failure modes from evident failure modes.

All criterions concerning on-condition tasks were overall rated medium important, and the relation between their software and these criterion were in general found to be weak. It was said that the criterion were important for defining a good maintenance programme, but it was something which was hard to define accurately early in an analysis and that it needed continuous follow-up. Defining P-F interval was said to be very theoretical without experience and that one rarely used this for all failure modes. Therefore it was not considered very important, and also the fact that their RCM software didn’t aid much in this process may also have affected the RCM facilitators not to view this as an important part of RCM.

Criterion 29 and 30 both applies to scheduled discard tasks, but only criterion 29 got a high score in importance and relation while criterion 30 were both unimportant and with hardly any relation to the software. It was repeated by the facilitators that a clear and defined age was important to determine and this was easy to do in their software. However, ensuring that a sufficiently large proportion of the occurrences of failure modes that require scheduled restoration tasks occur after this age was not something that the facilitators cared much about. It was considered fiddling work and something one rather would consider doing in the continuous improvement process, as described in ISE 60300-3-11.

Criterion 31, 32 and 33 applies to scheduled restoration tasks and were evaluated pretty much in the same style as for the scheduled discard tasks. The ability to define a clear and defined age was important and easy to achieve with their software. However, ensuring that a sufficiently large proportion of the occurrences of failure modes that require scheduled restoration tasks occur after this age was not something that the facilitators cared much about. As with the scheduled discard tasks, it was considered fiddling work.

Step 7

What should be done if a suitable proactive task cannot be found (default actions)?

Table 45: The importance of step 7.

		IMPORTANCE											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
34	To what degree it is emphasized that the selection of a failure-finding task interval shall take into account the need to reduce the probability of the multiple failure of the associated protected system to a level that is tolerable to the owner or user of the asset.	3	3	3	3	3	3	3	1	3	25	2,78	0,63
35	To what degree it is emphasized that the task shall confirm that all components covered by the failure mode description are functional.	3	2	3	3	3	3	3	1	3	24	2,67	0,67
36	To what degree it is emphasized that the failure-finding task and associated interval selection process should take into account any probability that the task itself might leave the hidden function in a failed state.	1	2	2	1	2	2	1	1	1	13	1,44	0,50
37	To what degree it is emphasized that it shall be physically possible to do the task at the specified intervals.	2	3	2	2	1	1	2	1	2	16	1,78	0,63
38	To what degree it is emphasized that the RCM process shall endeavor to extract the desired performance of the system as it is currently configured and operated by applying appropriate scheduled tasks.	2	2	2	2	2	2	2	3	2	19	2,11	0,31
39	The ability to ensure a one-time change that reduces the probability of the multiple failure to a level tolerable to the owner or user of the asset, when the failure is hidden and the associated multiple failure has safety or environmental consequences.	2	3	3	2	2	2	3	1	2	20	2,22	0,63
40	The ability to ensure a one-time change that reduces the probability of the failure mode to a level tolerable to the owner or user of the asset, when the failure mode is evident and has safety or environmental consequences.	3	3	3	3	2	2	2	1	3	22	2,44	0,68
41	The ability to ensure that a one-time change must be cost-effective in the opinion of the owner or user of the asset, when the failure mode is hidden and the associated multiple failure does not have safety or environmental consequences.	2	3	2	2	2	2	2	1	2	18	2,00	0,47
42	The ability to ensure that a one-time change must be cost-effective in the opinion of the owner or user of the asset, when the failure mode is evident and does not have safety or environmental consequences.	2	3	2	2	2	2	2	1	2	18	2,00	0,47
43	To what degree it is emphasized that any run-to-failure policy shall not have any multiple failure or failure mode with safety or environmental consequences.	3	3	3	3	3	3	3	3	3	27	3,00	0,00

Table 46: The relation between RCM software and step 7.

		RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
34	To what degree it is emphasized that the selection of a failure-finding task interval shall take into account the need to reduce the probability of the multiple failure of the associated protected system to a level that is tolerable to the owner or user of the asset.	9	9	9	9	9	9	9	1	9	73	8,11	2,51
35	To what degree it is emphasized that the task shall confirm that all components covered by the failure mode description are functional.	3	3	3	9	3	9	9	1	9	49	5,44	3,24
36	To what degree it is emphasized that the failure-finding task and associated interval selection process should take into account any probability that the task itself might leave the hidden function in a failed state.	1	3	3	1	1	3	1	1	1	15	1,67	0,94
37	To what degree it is emphasized that it shall be physically possible to do the task at the specified intervals.	3	3	3	3	1	1	3	1	3	21	2,33	0,94
38	To what degree it is emphasized that the RCM process shall endeavor to extract the desired performance of the system as it is currently configured and operated by applying appropriate scheduled tasks.	9	9	9	3	3	3	3	9	9	57	6,33	2,98
39	The ability to ensure a one-time change that reduces the probability of the multiple failure to a level tolerable to the owner or user of the asset, when the failure is hidden and the associated multiple failure has safety or environmental consequences.	3	9	9	3	3	3	3	1	3	37	4,11	2,69
40	The ability to ensure a one-time change that reduces the probability of the failure mode to a level tolerable to the owner or user of the asset, when the failure mode is evident and has safety or environmental consequences.	3	9	9	3	3	3	3	1	3	37	4,11	2,69
41	The ability to ensure that a one-time change must be cost-effective in the opinion of the owner or user of the asset, when the failure mode is hidden and the associated multiple failure does not have safety or environmental consequences.	3	3	3	3	3	3	3	1	3	25	2,78	0,63
42	The ability to ensure that a one-time change must be cost-effective in the opinion of the owner or user of the asset, when the failure mode is evident and does not have safety or environmental consequences.	3	3	3	3	3	3	3	1	3	25	2,78	0,63
43	To what degree it is emphasized that any run-to-failure policy shall not have any multiple failure or failure mode with safety or environmental consequences.	9	9	9	9	9	9	9	9	9	81	9,00	0,00

Table 47: "Importance" multiplied with "Relation" for step 7.

		IMPORTANCE x RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
34	To what degree it is emphasized that the selection of a failure-finding task interval shall take into account the need to reduce the probability of the multiple failure of the associated protected system to a level that is tolerable to the owner or user of the asset.	27	27	27	27	27	27	27	1	27	217	24,11	8,17
35	To what degree it is emphasized that the task shall confirm that all components covered by the failure mode description are functional.	9	6	9	27	9	27	27	1	27	142	15,78	10,30
36	To what degree it is emphasized that the failure-finding task and associated interval selection process should take into account any probability that the task itself might leave the hidden function in a failed state.	1	6	6	1	2	6	1	1	1	25	2,78	2,30
37	To what degree it is emphasized that it shall be physically possible to do the task at the specified intervals.	6	9	6	6	1	1	6	1	6	42	4,67	2,75
38	To what degree it is emphasized that the RCM process shall endeavor to extract the desired performance of the system as it is currently configured and operated by applying appropriate scheduled tasks.	18	18	18	6	6	6	6	27	18	123	13,67	7,36
39	The ability to ensure a one-time change that reduces the probability of the multiple failure to a level tolerable to the owner or user of the asset, when the failure is hidden and the associated multiple failure has safety or environmental consequences.	6	27	27	6	6	6	9	1	6	94	10,44	9,06
40	The ability to ensure a one-time change that reduces the probability of the failure mode to a level tolerable to the owner or user of the asset, when the failure mode is evident and has safety or environmental consequences.	9	27	27	9	6	6	6	1	9	100	11,11	8,81
41	The ability to ensure that a one-time change must be cost-effective in the opinion of the owner or user of the asset, when the failure mode is hidden and the associated multiple failure does not have safety or environmental consequences.	6	9	6	6	6	6	6	1	6	52	5,78	1,93
42	The ability to ensure that a one-time change must be cost-effective in the opinion of the owner or user of the asset, when the failure mode is evident and does not have safety or environmental consequences.	6	9	6	6	6	6	6	1	6	52	5,78	1,93
43	To what degree it is emphasized that any run-to-failure policy shall not have any multiple failure or failure mode with safety or environmental consequences.	27	27	27	27	27	27	27	27	27	243	27,00	0,00

Comments

Criterion 34 was unambiguously important and well taken care of with the software in use, except from respondent B5 who simply disagreed on this being an important criterion or something that the software aided much in. The argument was that it was almost practically impossible to select an interval that would reduce a probability of multiple failure when the probability was not known. It was further replied that his was very often the case in RCM processes, that there were lack of theoretical approaches and probabilities to the equipment under assessment.

Criterion 35 was also found important by most respondents, but it was nothing that the software would provide much help with.

Criterion 36 was found to be too something that rarely was discussed during RCM processes. The criterion was simply stated as too rare to be considered important, and that most tasks chosen usually did the job adequately enough. Some also confessed that they were not aware of this criterion in their processes and therefore didn’t find it very important either since most

RCM analyses went well without awareness on this one. There were not much help from the RCM software on this criterion.

The possibility to physically do a default task at specified intervals got low scores for its importance on criterion 37. This was because many of the respondents associated this with a run to failure, which was not found to be important with a defined interval. Again, their software did not aid much in this criterion.

Criterion 38 was perceived to be more of an aspect of RCM relevant for all the stages of the process; not only default tasks. Therefore is was not found to be a very important criterion, but more of a natural self-explanatory aspect of the process. This also applied for the rating of the software in use, which automatically ensured this.

Criterion 39 and 40 were almost similarly rated, which dealt with one-time changes to reduce the probability of multiple-failures when the failure was hidden (criterion 39) or evident (criterion 40) and the associated multiple failure had safety or environmental consequences. What kept it back from top importance rating was due to the formulation "that reduces the probability of the multiple failure to a level tolerable to the owner or user of the asset". This was hard to know exactly when was achieved, and the formulation of the criterion therefore made it rated less important. Beyond that it was found to be of importance because it had to do with safety and environmental consequences.

Criterion 41 and 42, however, who are similar to criterion 39 and 40 except they are not involved with safety or environmental consequences, were not found important due the fact that their consequences were not found harmful. These failure modes were often put to run to failure.

Criterion 43 got a maximum score with regard to both importance and software relation. This had to do with safety when letting an item run-to-failure. The decision logic in the software aided in ensuring that no multiple failures with safety or environmental consequences would be put to run-to-failure.

A living program

Table 48: The importance of a living program.

		IMPORTANCE											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
44	To what degree it is provided for a periodic review of both the information used to support the decisions and the decisions themselves.	3	3	2	3	3	3	2	2	3	24	2,67	0,47
45	To what degree any mathematical and statistical formula used in the application of the process is logically robust, and be available to and approved by the owner or user of the asset.	2	2	2	2	1	1	2	1	2	15	1,67	0,47

Table 49: The relation between RCM software and a living program.

		RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
44	To what degree it is provided for a periodic review of both the information used to support the decisions and the decisions themselves.	9	9	9	1	3	3	1	9	9	53	5,89	3,54
45	To what degree any mathematical and statistical formula used in the application of the process is logically robust, and be available to and approved by the owner or user of the asset.	3	3	1	1	1	1	1	1	1	13	1,44	0,83

Table 50: Importance multiplied with "Relation" for a living program.

		IMPORTANCE x RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
44	To what degree it is provided for a periodic review of both the information used to support the decisions and the decisions themselves.	27	27	18	3	9	9	2	18	27	140	15,56	9,62
45	To what degree any mathematical and statistical formula used in the application of the process is logically robust, and be available to and approved by the owner or user of the asset.	6	6	2	2	1	1	2	1	2	23	2,56	1,89

Comments

Criterion 44, providing for periodic reviews, was in general defined important by the respondents and something they wish was done more often. However, this was rarely the case, and RCM was rather something which was only done in the beginning of a lifetime or during modifications on the equipment. The software in use did not either push for performing a review either, but at the same time it could easily be done.

Criterion 45, use of mathematical and statistical formulae, was generally not found important because it required data that was not available. Also, only tool A was known for decent tools to perform mathematical analysis. It was simply stated that there wasn't a culture for gathering data for analysis among equipment owners or manufacturers, and therefore lack of data for mathematical approaches in the analysis. One rather leaned on subjective and qualitative experiences.

Assessment of software criterions

Table 51: The importance of software criterions.

		IMPORTANCE											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
46	To what degree the software provides functions that meet stated and implied needs of the user.	3	3	3	3	3	3	3	3	3	27	3,00	0,00
47	To what degree the software provides precise and accurate results.	3	3	3	3	3	3	3	3	3	27	3,00	0,00
48	To what degree the software is operational and available when required for use.	3	3	3	3	3	3	3	3	3	27	3,00	0,00
49	To what degree the software product can maintain a specified level of performance in case of software faults.	3	3	3	3	3	3	3	2	3	26	2,89	0,31
50	To what degree the software can re-establish a specified level of performance and recover the data directly affected in the case of failure.	3	3	3	3	3	3	3	3	3	27	3,00	0,00
51	To what degree the software provides appropriate response and processing times when performing its function.	3	3	3	3	3	3	3	3	3	27	3,00	0,00
52	To what degree the software enables user to learn its application.	3	3	3	3	3	3	3	3	3	27	3,00	0,00
53	To what degree the software is easy for the user to operate and control.	3	3	3	3	3	3	3	2	3	26	2,89	0,31
54	To what degree the software provides help when user needs assistance.	3	3	3	3	3	3	3	3	3	27	3,00	0,00
55	To what degree the software is attractive to the user.	2	3	2	2	2	3	2	3	2	21	2,33	0,47
56	To what degree system items are protected from accidental or malicious access, use, modification, destruction, or disclosure.	3	3	3	3	3	3	3	2	3	26	2,89	0,31
57	To what degree the software can exchange information with other systems and databases.	2	3	2	2	3	3	3	3	2	23	2,56	0,50
58	To what degree the software can be modified to corrections, improvements or adaption to changes in environment, requirements and functional specifications.	3	3	3	3	3	3	3	3	3	27	3,00	0,00
59	To what degree the software can be transferred from one environment to another.	3	3	3	3	3	3	3	3	3	27	3,00	0,00

Table 52: The relation between RCM software and the software criterions.

		RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
46	To what degree the software provides functions that meet stated and implied needs of the user.	3	3	9	9	3	3	9	9	1	49	5,44	3,24
47	To what degree the software provides precise and accurate results.	9	3	9	3	3	3	3	9	9	51	5,67	2,98
48	To what degree the software is operational and available when required for use.	9	9	9	9	3	3	9	3	9	63	7,00	2,83
49	To what degree the software product can maintain a specified level of performance in case of software faults.	9	3	9	1	1	1	1	3	9	37	4,11	3,54
50	To what degree the software can re-establish a specified level of performance and recover the data directly affected in the case of failure.	9	3	3	9	9	3	9	9	9	63	7,00	2,83
51	To what degree the software provides appropriate response and processing times when performing its function.	9	9	9	9	9	3	9	9	9	75	8,33	1,89
52	To what degree the software enables user to learn its application.	9	9	9	3	9	9	9	9	9	75	8,33	1,89
53	To what degree the software is easy for the user to operate and control.	9	9	9	3	9	9	9	9	3	69	7,67	2,49
54	To what degree the software provides help when user needs assistance.	9	9	9	1	1	1	1	3	3	37	4,11	3,54
55	To what degree the software is attractive to the user.	9	9	9	3	3	3	3	9	3	51	5,67	2,98
56	To what degree system items are protected from accidental or malicious access, use, modification, destruction, or disclosure.	9	9	9	9	9	9	9	3	9	75	8,33	1,89
57	To what degree the software can exchange information with other systems and databases.	3	9	9	9	9	3	9	9	3	63	7,00	2,83
58	To what degree the software can be modified to corrections, improvements or adaption to changes in environment, requirements and functional specifications.	9	9	9	3	3	3	3	1	9	49	5,44	3,24
59	To what degree the software can be transferred from one environment to another.	9	9	9	9	9	9	9	9	9	81	9,00	0,00

Table 53: "Importance" multiplied with "Relation" for software criterions.

		IMPORTANCE x RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
46	To what degree the software provides functions that meet stated and implied needs of the user.	9	6	27	27	9	9	27	27	3	144	16,00	10,00
47	To what degree the software provides precise and accurate results.	27	9	27	9	9	9	9	27	27	153	17,00	8,94
48	To what degree the software is operational and available when required for use.	27	27	27	27	9	9	27	9	27	189	21,00	8,49
49	To what degree the software product can maintain a specified level of performance in case of software faults.	27	9	27	3	3	3	3	6	27	108	12,00	10,77
50	To what degree the software can re-establish a specified level of performance and recover the data directly affected in the case of failure.	27	9	9	27	27	9	27	27	27	189	21,00	8,49
51	To what degree the software provides appropriate response and processing times when performing its function.	27	27	27	27	27	9	27	27	27	225	25,00	5,66
52	To what degree the software enables user to learn its application.	27	27	27	9	27	27	27	27	27	225	25,00	5,66
53	To what degree the software is easy for the user to operate and control.	27	27	27	9	27	27	27	18	9	198	22,00	7,48
54	To what degree the software provides help when user needs assistance.	27	27	27	3	3	3	3	9	9	111	12,33	10,62
55	To what degree the software is attractive to the user.	18	27	18	6	6	9	6	27	6	123	13,67	8,50
56	To what degree system items are protected from accidental or malicious access, use, modification, destruction, or disclosure.	27	27	27	27	27	27	27	6	27	222	24,67	6,60
57	To what degree the software can exchange information with other systems and databases.	6	27	18	18	27	9	27	27	6	165	18,33	8,77
58	To what degree the software can be modified to corrections, improvements or adaption to changes in environment, requirements and functional specifications.	27	27	27	9	9	9	9	3	27	147	16,33	9,71
59	To what degree the software can be transferred from one environment to another.	27	27	27	27	27	27	27	27	27	243	27,00	0,00

Comments

All software criterions were considered important, with exception of the software being attractive. It was considered convenient, but not necessary as long as it was understandable and easy to use.

What shines through here is tool B that scores lower than the other tools criterions 47, 48, 49, 54 and 58. This had to do with reasons that cannot be explained without revealing the identity of the manufacturer, which has no purpose for the goal of this thesis. These criterions had more to do with customer service rather than the software itself, the respondents explained.

An interesting thing with the qualitative research part of the survey was how the respondents elaborated a lot more when it came to software criterions and RCM, compared to the methodological criterions. What was said of interest for RCM on large tag structures was the direct challenges that they personally experienced, and what they wished could have been done in order to makes these processes run more smoothly.

Experienced challenges as defined by RCM facilitators when performing RCM on large tag structures:

1. It's hard to get a full overview on where one is in the process. Especially when one is jumping from one place to another in the process, which often happens when the structure is large.
2. It is difficult to predict the amount of time that will be spent on the process.
3. If an asset changes its identification number in the tag hierarchy it is hard to catch this in an RCM analysis. That is because the asset is saved in a CMMS, where the RCM software downloads components for analysis. Changes in the CMMS do not necessarily update the RCM automatically.
4. The complex nature of large tag structures often leads to sources of error that slows down the process.

Wishes for RCM analysis of large tag structures in the future, based on experiences by RCM facilitators:

1. A tab indicating an overview on the entire process, so one would always know where one is in the process.
2. The ability to comment on all functions in the process.

3. The ability to copy an object where thousands of identical objects exist. In this way, one only had to do an analysis of one asset and then copy it to thousands of other identical tags which operate in identical contexts.

Assessment of economic criterions

Table 54: The importance of economic criterions.

		IMPORTANCE											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
60	To what degree the cost of purchase is acceptable.	0	2	0	0	0	0	0	0	0	2	0,22	0,63
61	To what degree the cost of installation is acceptable.	0	2	0	0	0	0	0	0	0	2	0,22	0,63
62	To what degree the cost of training is acceptable.	0	3	3	0	0	0	0	0	0	6	0,67	1,25
63	To what degree the cost of annual maintenance is acceptable.	0	2	0	0	0	0	0	0	0	2	0,22	0,63
64	To what degree the cost of updates is acceptable.	0	2	0	0	0	0	0	0	0	2	0,22	0,63

Table 55: The relation between RCM software and the economic criterions.

		RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
60	To what degree the cost of purchase is acceptable.	0	9	0	0	0	0	0	0	0	9	1,00	2,83
61	To what degree the cost of installation is acceptable.	0	9	0	0	0	0	0	0	0	9	1,00	2,83
62	To what degree the cost of training is acceptable.	0	9	9	0	0	0	0	0	0	18	2,00	3,74
63	To what degree the cost of annual maintenance is acceptable.	0	9	0	0	0	0	0	0	0	9	1,00	2,83
64	To what degree the cost of updates is acceptable.	0	9	0	0	0	0	0	0	0	9	1,00	2,83

Table 56: "Importance" multiplied with "Relation" for economic criterions.

		IMPORTANCE x RELATION											
		A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
60	To what degree the cost of purchase is acceptable.	0	18	0	0	0	0	0	0	0	18	2,00	5,66
61	To what degree the cost of installation is acceptable.	0	18	0	0	0	0	0	0	0	18	2,00	5,66
62	To what degree the cost of training is acceptable.	0	27	27	0	0	0	0	0	0	54	6,00	11,22
63	To what degree the cost of annual maintenance is acceptable.	0	18	0	0	0	0	0	0	0	18	2,00	5,66
64	To what degree the cost of updates is acceptable.	0	18	0	0	0	0	0	0	0	18	2,00	5,66

Comments

Only one of the respondents had insight into the economic criterions of the software in use. For the problem addressed in this thesis, unveiling the challenges of RCM as an analysis method for assets on the Norwegian continental shelf, it was not necessary for the respondents to answer these either in order to answer problem addressed.

The criterion is still included to reach the secondary goal with this thesis, which was to provide for a systematic approach to those who participate in RCM processes, so that they can evaluate their own processes and RCM tools towards applicable standards and costs.

Total score

Table 57: Total score "Importance".

	IMPORTANCE											
	A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
SCORE "METHODOLOGY"	101	119	115	101	117	105	106	96	101	961	106,78	7,76
SCORE "SOFTWARE"	40	42	40	40	41	42	41	39	40	365	40,56	0,96
SCORE "ECONOMIC"	0	11	3	0	0	0	0	0	0	14	1,56	3,47
TOTAL SCORE	**141**	**172**	**158**	**141**	**158**	**147**	**147**	**135**	**141**	1340	148,89	10,99

Table 58: Total score "Relation".

	RELATION											
	A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
SCORE "METHODOLOGY"	266	253	309	241	222	197	253	263	231	2235	248,33	29,69
SCORE "SOFTWARE"	114	102	120	80	80	62	92	94	94	838	93,11	16,84
SCORE "ECONOMIC"	0	45	9	0	0	0	0	0	0	54	6,00	14,07
TOTAL SCORE	**380**	**400**	**438**	**321**	**302**	**259**	**345**	**357**	**325**	3127	347,44	50,78

Table 59: "Total score Importance" multiplied with "Total score Relation".

	IMPORTANCE x RELATION											
	A1	A2	A3	B1	B2	B3	B4	B5	C1	SUM	AVG	DEV
SCORE "METHODOLOGY"	648	683	793	593	624	521	658	674	573	5767	640,78	72,96
SCORE "SOFTWARE"	330	303	342	228	237	186	273	267	276	2442	271,33	46,93
SCORE "ECONOMIC"	0	99	27	0	0	0	0	0	0	126	14,00	31,21
TOTAL SCORE	**978**	**1085**	**1162**	**821**	**861**	**707**	**931**	**941**	**849**	8335	926,11	130,41

Comments

The results show that the respondents are more or less unanimous in the rating of importance to the criterion, with small deviations for both the methodological and software criterions. There are, however, differences among the respondents when it comes to evaluation of their software in use during RCM processes. Especially software B scores lower than the others both in methodological criterions and software criterions. All in all, the quantitative results show that tool A is in general better rated for RCM analysis of large tag structures than the others. Even though there are individual differences, respondent A1, B1 and C1, who is the same person, scores higher on tool A than the others which confirms the norm.

Discussion

Risk as the guiding principle for maintenance decisions

The need for maintenance on the Norwegian continental shelf has with time resulted in the maintenance baseline study with its maintenance management model. This model has been referred to in the establishment of PSA and Z-008. The Activity Regulation, put out by the PSA, states that all equipment on the Norwegian continental shelf shall be classified as regards the health, safety and environment consequences of potential functional failures (Activity Regulation 2014). This has led to Z-008, which defines risk assessment as the guiding principle for maintenance decisions (Z-008:11). This implies that the primary motivation for maintenance on the Norwegian continental shelf is risk centered, rather than reliability centered. That is a fundamental challenge for RCM, with its reliability focus, when merging in with the main objective of risk assessment as the guiding principle for maintenance decisions.

In this process, equipment is first risk assessed and associated with those functional failures that can lead to serious consequences. The Activity Regulation states that all various fault modes', failure causes, failure mechanisms and probability of failure that can lead to serious consequences shall be identified. For this purpose, RCM is very suitable and has become a frequent and important contributor for maintenance on the Norwegian continental shelf. RCM is then recommended as an option along with FMECA, RBI and SIL for more in-depth evaluations.

In this way, risk assessment is considered in advance of RCM and placing RCM side by side with FMECA, RBI and SIL. Since the Activity Regulation puts emphasis on "consequences shall be identified" were all analysis methods can be used, it signals that the method or process chosen is not as important as long as the consequence is identified. A possible consequence could be that RCM may not be considered very important to learn or perform as laid down by standards, since it can be chosen away for the advantage of other methods. Apparently, there are various views among the RCM facilitators of what is important or not when performing RCM analysis for large tag structures, which has been proved in the analysis of this thesis.

A future solution to this problem could be implementation of RRCM, as suggested by Selvik and Aven (2010), which includes risk as the reference for the analysis in addition to reliability.

Two standards

Two standards for the application of RCM has been presented; IEC 60300-3-11 and SAE JA1011. IEC 60300-3-11 provides guidelines for RCM process, while SAE JA1011 describes the minimum criteria that any process must comply with in order to be called RCM.

A repeated pattern in the IEC 60300-3-11 is the use of words like "could" and "should", and the absence of definite words like "shall" and "must" which are more present in SAE JA1011. IEC 60300-3-11 is more open and advisory, rather than categorical or legislative in its procedure. However, the goals for performing RCM are stated clearly. This results in an application guide to RCM that is free of absolute requirements and demands, and more of a proposal on how RCM "could" or "should" be performed in order to achieve the goals that are set. This in turn provides the analysis with freedom to make own judgment and trust one's own common sense. This allows for a variety of approaches and considerations of what is worth placing emphasis on, within the framing as described in the application guide. Such an open approach may not necessarily encourage in memorizing criterions and detailed requirements, but rather getting an overview of the process itself and to reach goals.

One may ask whether or not the SAE JA1011 should be emphasized for RCM analyses on the Norwegian continental shelf, since it is an American standard and not a part of the European standardization catalogue. However, it would be ignorant to neglect the work and effort put down in SAE JA1011, which is done on basis of an international demand for standardization of RCM criterions. SAE JA1011 was then developed on the basis of the most widely-accepted and widely-used RCM documents available. The fact that RCM actually originated, got its history, and was development in America along with the SAE JA1011, makes another reason for taking use of it in combination with the IEC 60300-3-11. It provides a clear and understandable description of what is required to be done in an RCM analysis, and it probably wouldn't hurt to use it actively.

However, the two standards operate with different definitions on central issues. The most significant is the definition of *failure mode*. IEC 60300-3-11 defines a failure mode as an effect by which a failure is observed on the failed item, while SAE JA1011 defines a failure mode as a single event, which causes a functional failure. A misalignment might arise if the IEC-definition of a failure mode is understood as manners in which a functional failure can be observed, while the SAE-definition is understood as the causes of functional failure.

Generally, the two standards correspond quite a lot on the main processes of RCM and the differences are not considered to be of great significance. For someone who has read both standards and understood their intention and structure, there should be no trouble in getting through an RCM process in accordance with both standards. However, they could have referred to each other and be supplementary to each other along with common standardization of central definitions.

GMC and streamlined concepts

Z-008 recommends GMC. For large tag structures GMC is found to make the maintenance management process more efficient, but may not necessarily be an effective method in all situations. GMC puts the quality of the analysis at risk if an analysis is copied on an item that operates in another context so that unexpected failures could occur, improbable failure modes could be implemented in the analysis, redundancy may not be treated correctly, and performance standards may change for items. When an analysis is performed on one asset and copied over to thousands of other similar items, there would be a need to ensure the integrity of the analysis by making sure that every single item has been treated properly.

IEC 60300-3-11 also states that actual or generic failure data used in isolation has limited value without understanding failure mechanisms and the operating context (2009:19). This is an important statement to see in relation to Z-008, which desires GMC to a large degree.

Nevertheless, GMC analyses GMC would help saving valuable time, but caution should be made to ensure that the process is not increasing risk, which is what the whole maintenance philosophy on is about to minimize. GMC is not viewed as a challenge to RCM in Z-008, but rather a relief for large tag structures. However, it may be argued that GMC are hidden challenges to RCM that does not come to sight at first glance, like a hidden failure.

In the survey, one can easily pick out what parts of the RCM methodology that are emphasized more than others. Those that are considered both important and well taken care of by the software in use are 13 out of 45 criterions; about 29%. Interestingly enough, they are stretched out quite evenly from the start to the end of the RCM process. It is likely to believe that a streamlined RCM would preferably be about these criterions as the core processes in such an analysis. The number to each of these criterions are put in parenthesis:

1. Functions
    a. (2) The ability to identify all functions of the asset/system.
2. Failure modes
    a. (6) The ability to identify all failure modes reasonably likely to cause each functional failure.
3. Failure effects
    a. (11) The ability to describe failure effects as what would happen if no specific task is done to anticipate, prevent or detect the failure.
    b. (12) The ability to include all the information needed to support the evaluation of the consequences of a failure, with regard to failure effects.
4. Failure consequence categories
    a. (14) The ability to clearly distinguish safety and/or environmental consequences (operational) from economic consequences (non-operational).
5. Failure management policies – scheduled tasks
    a. (20) In the case of an evident failure mode that has safety or environmental consequences, it is conjured for a task that reduces the probability of the failure mode to a level that is tolerable to the owner or user of the asset.
    b. (21) In the case of a hidden failure mode where the associated multiple failure has safety or environmental consequences, it is conjured for a task that reduces the probability of the hidden failure mode to an extent which reduces the probability of the associated multiple failure to a level that is tolerable to the owner or user of the asset.
    c. (22) In the case of an evident failure mode that does not have safety or environmental consequences, it is conjured for a task with less direct and indirect costs than the direct and indirect costs of the failure mode when measured over comparable periods of time.
    d. (23) In the case of a hidden failure mode where the associated multiple failure does not have safety or environmental consequences, it is conjured for a task with less direct and indirect costs than the direct and indirect costs of the multiple failure plus the cost of repairing the hidden failure mode when measured over comparable periods of time.
6. Scheduled discard tasks

   a. (29) The ability to ensure a clearly defined age at which there is an increase in the conditional probability of the failure mode under consideration, when selecting scheduled discard tasks.

7. Scheduled restoration tasks
   a. (31) The ability to ensure a clearly defined age at which there is an increase in the conditional probability of the failure mode under consideration when selecting a scheduled restoration task.
8. Failure finding tasks
   a. (34) To what degree it is emphasized that the selection of a failure-finding task interval shall take into account the need to reduce the probability of the multiple failure of the associated protected system to a level that is tolerable to the owner or user of the asset.
9. Run-to-failure
   a. (43) To what degree it is emphasized that any run-to-failure policy shall not have any multiple failure or failure mode with safety or environmental consequences.

What recognizes these criterions is that they are primarily the main drivers from the different segments of the RCM process. A process (though fragmented) could be driven from start to end with only these criterions to redeem the requirements of the Activities Regulation for classification and establishment of a maintenance programme. Those criterions from the survey that are not included here could be read as superfluous in achieving the requirements of the Activity Regulation in section 46 and section 47 (see appendix A).

On this basis, some questions arises:

1. Is RCM then too circumstantial?
2. Is the maintenance philosophy on the Norwegian continental shelf promoting superfluous analyses?
3. Are RCM facilitators making crosscuts in the analysis?
4. Is there a combination of all of these?

It is nearly impossible to give a general and unmistakable “yes” or “no” answer to any these questions without parameters to measure against. Nevertheless, many sources claim that RCM actually is too circumstantial, but those who do not think so would probably not make as much out of it if they were happy with the method. RCM has been a success in the commercial aviation industry where there are high requirements to ensure safety and reliability. Answering the question if RCM is too circumstantial could therefore depend on the objective of the analysis and the consequences of not following the process to the letter.

The maintenance philosophy on the Norwegian shelf is to a high degree leaning on the common sense of the operators and deliberately avoiding excessive amounts of rules. Instead, operators are encouraged to reflect and think for themselves on what would be the best solution in order to achieve safety and low risk within given requirements. It would be wrong to say that the maintenance philosophy encourages superfluous analyses, but more right to say that it encourages freedom to reflect and think freely of what is most practical in order to achieve the best solutions that ensures safety.

Such a philosophy would allow for crosscuts if appropriate, and according to the survey and the criterions listed there are crosscuts. However, if the maintenance philosophy is not occupied with the criterions listed in this survey, and allows for GMC, streamlined RCM, and refers to IEC 60300-3-11 which mainly state “should” or “could” in its guiding of RCM, one can argue that crosscuts are not made.

The best answer that could be given is perhaps a combination of all the questions risen above. Since none of these questions have an unequivocal basis for answering “yes” or “no”, this one won’t either. A challenge on this matter is that there is no definite measure to state whether or not a RCM analysis too circumstantial, superfluous, or if crosscuts are made. Until further notice, one would not know.

The discussion on streamlined RCM can be summed up as the desire for making RCM more lean, as in getting rid of those parts of the analysis that are superfluous. Rotton (1994) and Johnson (1995) have fronted such approaches, while Moubray (1997, 2000) is against such methods. The origin of such streamlined RCM concepts might have to do with culture.

Culture

A motivation for streamlined RCM processes is obviously that the method is found to be a very cumbersome and resource demanding process. Performing a true RCM in accordance with standards is supposed to be a process of both learning of the system under review, and defining the maintenance activities. It seems that the demand for streamlining of RCM is motivated of finding the answer as quickly as possible, with less interest in learning from the process. Bowler et. al (1995) and Hipkin and DeCock (2000) have already pointed out that insufficient knowledge of how and it what way RCM will be beneficial to an organization makes people lose interest in performing the analysis correctly. This might be an explanation to Harris and Moss' statement (1994), that RCM is often introduced at times of restraint and rationalization. However, this is also a paradox that someone chooses to perform the analysis at hard times if the argument for not doing it is because it is resource demanding. Perhaps the underlying reason is that RCM is after all acknowledged for its capacity, but one doesn't do the analysis until one have to. That would be like fastening the seatbelt after collision.

It can be derived that RCM suits those organizations who wants to learn their assets and at the same time define the optimal maintenance tasks. A long-term approach is required (F. Backlund and P.A. Akersten, 2003) and a committed top management (Moubray 1997, Jones 1995). In other words, it requires a culture within the organization to appreciate RCM. Smith (1993), Mokashi et al. (2002) and Bryant et al. (2009) validate this.

A living program

Both Abdul-Nour et al (1998) and Moubray (2000) says that there is not possible to perform a perfect analysis anyway due to improper data, evolution of maintenance and assets. This is an implicit recommendation for a living program. The respondents also replied in the survey that a living program was considered important. However, it was rarely performed because RCM was generally viewed as an analysis only performed in the beginning of a lifetime or during modifications on the equipment. This was also related to the reason for why mathematical and statistical formulae were not considered important or taken advantage of, because there were no good data to begin with and no second analysis were information was gathered. Hence, the maintenance management process as illustrated in Z-008 (figure 2), would stop somewhere between "analysis" and "maintenance execution". This is considered a major challenge for RCM because it affects more than just the analysis, but also the entire maintenance management process.

A solution for implementation of RCM in organizations could perhaps simply be to emphasize more on the living program than the initial analysis. Splitting the analysis in smaller sub-analyses allocated with one facilitator on those who have responsibility for the system under review, would involve no big analysis to be performed at once. Rather, many smaller analyses would be performed with the same facilitator with those who work on the equipment. This could also be supplied with RCOM (Leppänen:1998) which links several systems into an interactive network for automatic update with continuous input. Such an approach would not feel time consuming in the same way if the process was limited to demand less than one day per analysis. If the analysis would be several times with appropriate intervals, one would have gathered information from direct sources on how each system functions that would prepare for high quality in the analyses. This could increase the appreciation of RCM, accuracy of the assessment, and lower the impression of the analysis being resource demanding. At least it worked for Bryant et al. (2009) and it is in accordance with Moubray (1997:277).

The human factor

The skill of the RCM facilitator has been defined by Moubray (1997) as the most important factor which affect the quality of the RCM analysis. By looking at the survey, one can see how the facilitators view different parts of the analysis contrarily on evaluation of importance to the criterions. It does not mean that anyone is a better or worse facilitator than any other, but it shows how the human factor affects the process. It could be both a strength and a weakness, depending on the facilitator. With lack of criterions it would be completely up to the RCM group to decide what is most reasonable to decide for. Since RCM is performed in a group, the power of group dynamic would play an important role in the process since people are influenced by each other. Unconsciousness about one behavior and relationship to other people is therefore a reasonable challenge for a RCM analysis, especially with a lack of clear criterions as a basis for decisions in an analysis.

Software

It is undeniable that RCM software comes in handy when performing RCM for large tag structures, but the use of software also brings in some potential challenges. As stated by the respondents, the ability to jump from one place to another in the process also made it hard to get a full overview on where one is in the process. This is rather a problem that the facilitator causes to oneself when no barrier to do so is induced in the software. Another challenge stated by the respondents was if an assets would change its identification in the tag hierarchy, it would not be automatically updated in the RCM analysis. This is a purely computer technological challenge, which illustrates that a RCM software cannot be developed without a deep understanding of the methodology. This supports the need for a clear methodology so that appropriate software can be developed.

In the survey, it is clear that some software are more liked than others when it comes to RCM analyses. Human factors also plays a role here, but with one respondent evaluating all three software, who follows the trend of the others, one can state that software does affect the RCM process and cause some challenges to the process together with the user.

Software is also strongly linked to streamlining and GMC, which is already discussed. The challenge is not how to do streamlining or GMC with the software, but rather why to do it and what the risk and gains are. With such tools at hand, it can be tempting to make crosscuts instead of doing the entire analysis step by step.

Conclusion

This thesis has unveiled the challenges of RCM as an analysis method for assets on the Norwegian continental shelf. These challenges were revealed by viewing RCM as part of a whole on the Norwegian continental shelf, and also by investigating details in the RCM method thoroughly by gathering quantitative and qualitative data from RCM facilitators. Relevant literature have also been reviewed. From this research, five main challenges have been derived:

1. RCM is perceived as a rigid and cumbersome process which demands a lot of resources to be carried out. Several attempts have been made to solve this by streamlining the process, which involves a threat to the quality of the analysis in terms of crosscuts.

2. The lack of adequate data to perform mathematical calculations is a challenge caused by several reasons:
    a. Maintenance is a dynamic process that always changes policies, assets under review are changing and the processes that the assets take part in are also dynamic.
    b. A living program is rarely established and data is rarely gathered so that an analysis can be improved after the initial analysis was carried out in the first place.
    c. Many of the respondents in the survey revealed in the quantitative part of the survey that they were unfamiliar with mathematical and statistical formulae, which means that it wouldn't help if data was gathered when one cannot analyze them.

3. The primary motivation for maintenance on the Norwegian continental shelf is risk centered, instead of reliability centered. Still it is called for RCM, but not for all the capacities RCM holds in ensuring reliability. When it comes to risk, RCM ignores uncertainties in its decision process, which may lead to suboptimal maintenance strategies. Especially the decision logic has been criticized for not reflecting the uncertainties that exist when the only options to choose among are "YES" or "NO".

4. RCM depends to a large degree on the humans and their competencies in being familiar with the RCM methodology and applicable standards, understanding the equipment under assessment, and the ability to cooperate and handle the group dynamic while carrying out the analysis. The survey in this thesis has revealed variations among RCM facilitators.

5. Handling large tag structures in a RCM analysis is a challenge due to the complexity, and also to keep track of where one is in the analysis process. Besides, the vast number of tags also makes it difficult to estimate the time it required to do the analysis. Also, if an asset changes its identification number in the tag hierarchy, it is hard to catch this in an RCM analysis. That is because the asset is saved in a CMMS, where the RCM software downloads the components for analysis. Changes in the CMMS do not necessarily update the RCM automatically, which could potentially cause trouble.

A secondary goal with the thesis was to develop a systematic approach for assessment of future RCM processes. The intention of this was to provide RCM participants with a tool that would aid in gaining increased awareness on the process itself with relation to standardized criterions for methodology, software and the cost of purchasing and using RCM software. The results in this thesis has shown that this could be useful, and hopefully it will aid in ensuring safe analyses in the future by strengthening the human factor and decreasing the need for more regulations and frameworks. This is meant to be in line with how PSA operates on the Norwegian continental shelf.

Recommendation for further study

The author would like to recommend that the survey developed in this thesis to be used on more RCM facilitators to gain more data on the challenges to RCM on the Norwegian continental shelf. This is also recommended on a basis of getting feedback on how well it works as a tool in providing increased awareness on the RCM methodology and software in use.

Another suggestion is to develop standardized methods and some criteria for how RCM actually is supposed to be performed on the Norwegian continental shelf. The standards are available for reading, but how it is understood and done can still vary. Further research could of course be done to investigate this further, or courses could be arranged to train for a unisonant method. This recommendation is based on the various approaches to what is important or not in a RCM analysis, the different standards available, and level of competency people possesses with respect to the RCM methodology.

There should also be focused more on collecting maintenance data to ensure continuous improvement processes. It is of the author’s opinion that this could be a matter of culture as well as technological, and is a field of research for many different disciplines.

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Appendix

APPENDIX A - The Activities Regulations

CHAPTER IX - MAINTENANCE

Section 45

Maintenance

The responsible party shall ensure that facilities or parts thereof are maintained, so that they are capable of carrying out their intended functions in all phases of their lifetime.

Section 46

Classification

Facilities' systems and equipment shall be classified as regards the health, safety and environment consequences of potential functional failures.

For functional failures that can lead to serious consequences, the responsible party shall identify the various fault modes with associated failure causes and failure mechanisms, and predict the probability of failure for the individual fault mode.

The classification shall be used as a basis in choosing maintenance activities and maintenance frequencies, in prioritising between different maintenance activities and in evaluating the need for spare parts.

Section 47

Maintenance programme

Fault modes that may constitute a health, safety or environment risk, cf. Section 46, shall be systematically prevented through a maintenance programme.

This programme shall include activities for monitoring performance and technical condition, which ensure identification and correction of fault modes that are under development or have occurred.

The programme shall also contain activities for monitoring and control of failure mechanisms that can lead to such fault modes.

Section 48
Planning and prioritisation

An overall plan shall be prepared for conducting the maintenance programme and corrective maintenance activities, cf. Section 12 of the Management Regulations.

Criteria shall be available for setting priorities with associated deadlines for carrying out the individual maintenance activities. The criteria shall consider the classification as mentioned in Section 46.

Section 49
Maintenance effectiveness

The maintenance effectiveness shall be systematically evaluated based on registered performance and technical condition data for facilities or parts thereof.

The evaluation shall be used for continuous improvement of the maintenance programme, cf. Section 23 of the Management Regulations.

Section 50
Special requirements for technical condition monitoring of structures, maritime systems and pipeline systems

Technical monitoring of new structures and maritime systems shall be carried out during their first year of service.

For new types of load-bearing structures, data shall be collected during two winter seasons to compare them with the design calculations, see Section 17 of the Facilities Regulations.

When using facilities beyond their original design life, instrumentation of relevant structure sections shall be considered so as to measure any ageing effects.

When facilities are disposed of, the operator shall carry out studies of the structure's condition. The results shall be used to assess the safety of similar facilities.

On pipeline systems where fault modes may constitute an environmental or safety hazard, cf. Section 46, inspections shall be carried out to monitor potential fault modes that may affect the integrity of the pipeline system.

The first inspection shall be performed after the maintenance programme as mentioned in Section 47. The timing shall be based on the risk assessments performed.

Section 51
Specific requirements for testing of blowout preventer and other pressure control equipment

The blowout preventer with associated valves and other pressure control equipment on the facility shall be pressure tested and function tested, cf. Sections 45 and 47.

The blowout preventer with associated valves and other pressure control equipment on the facility shall undergo a complete overhaul and recertification every five years.

APPENDIX B – Calculation of Age Replacement Policy in MATLAB®

```
clear
close all

cp = 1000;
cc = 50000;

beta = 5;
eta = 200;

t = 0;
dt = 0.1;
t1 = 300;

time = zeros(t1/dt,1);
R_tp = zeros(t1/dt,1);
C_tp = R_tp;

for i=1:(t1/dt)
    R_tp(i) = exp(-(t/eta)^beta);
    time(i) = t;
    t = t + dt;
end

F_tp = 1 - R_tp;

R_tp_int = cumtrapz(time,R_tp); % Integration

C_tp = (cp.*R_tp + cc.*F_tp)./R_tp_int;

[r,c] = find(C_tp==min(min(C_tp)));     % Find the minimum point
time(r)

figure('Position', [700,50,600,450]);
plot(time,C_tp,'B');
grid on
xlabel('Time')
ylabel('Cost')
ylim([0 400]);
xlim([0 t1]);

figure('Position', [1,50,600,450]);
plot(time,R_tp,'R');
grid on
xlabel('Time')
ylabel('Probablility of breakdown')
ylim([0 1]);
xlim([0 t1]);
```

APPENDIX C – Information about the survey

Thank you for participating in this survey for my master's thesis where the problem to be addressed is "what are the challenges with RCM for large tag structures on the Norwegian shelf?".

The survey is made with the objective of gathering quantitative and qualitative data.

In the quantitative part you are asked to evaluate 64 criterions related to RCM when analyzing large tag structures. Based on your experience with RCM, you are asked to evaluate the importance of each criterion and its relation to your software, when conducting RCM analysis for large tag structures.

In the qualitative part you will be interviewed on basis of your evaluation in the quantitative part.

The quantitative and the qualitative analysis are estimated to take one hour each.

It is optional to participate and you can at any point withdraw from the survey without giving a reason for doing so. If you withdraw, all information you have given will be deleted. All information will be treated confidentially. In the final thesis, all data will be depersonalized and no will information will be traceable to any of the participants.