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MAINTENANCE ANALYSIS PROCESS FOR SERVICE PLAN OPTIMIZATION

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FOREWORD

This study was carried out for and in close co-operation with Wärtsilä Marine Business Asset Management Services, Contract Management, and Reliability Specialist from Ramentor Oy. I would like to express my gratitude to the companies and all the colleagues and friends who enabled the study and assisted thorough. Special thanks to my thesis supervisor Tuomas Kangas for the effective co-operation.

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Joonas Sihto

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SYMBOLS AND ABBREVIATIONS

Symbols

C	Cost
N_{RxMax}	N=number of, R=receivers, x=variable, Max=maximum
S_{Tx}	S=set, T=transmitters, x=variable

Abbreviations

1oo2	One Out Of Two (works with any numbers, #oo#)
AD	Accidental Damage
BDA	Big Data analytics
CBM	Condition-Based Maintenance
CD	Condition Dependent
DNV GL	Det Norske Veritas & Germanischer Lloyd
DS	Design Science
ED	Environmental Deterioration
FBD	Functional Block Diagram
FD	Fatigue Damage
FF	Failure-Finding
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects, and Criticality Analysis
FTA	Fault Tree Analysis
GBS	Gravity Base Structure
IoT	Internet of Things
KISS	Keep it simple, stupid
LCC	Life Cycle Cost
LTA	Logic Tree Analysis
Ltd.	Limited Company
MMIS	Maintenance Management Information System
MTBF	Mean Time between Failures
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
NDI	Non-Destructive Inspection
OLAP	Online Analytic Processing
PT&I	Predictive Testing and Inspection
RAMS	Reliability, Availability, Maintainability and Safety
RBD	Reliability Block Diagram
RCM	Reliability-Centered Maintenance
RTF	Run-To-Failure
SQL	Structured Query Language
SSI	Structurally Significant Item
TBM	Time-Based Maintenance
TD	Time Dependent

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ABSTRACT:

Customers in different industries, such as marine, oil & gas, and energy sectors, are demanding more advanced and tailored services to match maintenance activities with their business needs and to optimize operating expenditures and inventory of the facilities without compromising reliability. Reliability-centered maintenance (RCM) is a well-known method in the industry for systematically analyzing and modifying standard maintenance plans to optimize asset availability and minimize total cost of ownership.

Research question: How to develop a systematic method to analyze customers' asset and business to optimize maintenance plan for long term service agreement? For answering the question, research is performed with a qualitative method (interviews) and design science (DS) method. Interviewed persons are: A specialist from Wärtsilä Marine Business Asset Management Services and Reliability Specialist from Ramentor Oy. Design science is information technology-based outcome of research.

The purpose of this study is to execute a servitization model for the services agreements business. The focus is to develop a maintenance analysis process for life cycle solutions for preventing the unexpected failures and their consequences as a part of the RCM process. Monitoring, collecting and processing data is a key factor to success. The best equipment for real-time monitoring and collecting data is performed by using IoT (internet of things) solutions.

Key findings of the study revealed that case company should develop and document a streamlined RCM process to create tailored maintenance plans of customers' assets, considering installation configuration and customer's business needs. In addition, the documented process enables case company to engage in discussions with classification societies regarding approval of Service Supplier notation for the streamlined RCM concept.

KEYWORDS: Maintenance management, RCM, Optimization, Servitization

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TIIVISTELMÄ:

Asiakkaat eri teollisuudenaloilla, kuten merenkulku-, öljy & kaasu-, ja energiasektoreilla, vaativat kehittyneempiä ja räätälöityjä palveluita saadakseen kunnossapitotoimet vastaamaan yrityksen tarpeisiin, sekä optimoidakseen operointikulunsa ja inventaarion, luotettavuutta heikentämättä. Toimintavarmuuskeskeinen kunnossapito (RCM) on teollisuudessa tunnettu menetelmä järjestelmälliseen analysointiin ja standardin huoltosuunnitelman muokkaamiseen, optimoidakseen resurssien saatavuuden ja minimoidakseen omistajuuden kokonaiskustannukset.

Tutkimuskysymys: Miten kehitetään järjestelmällinen menetelmä asiakkaiden resurssien ja liiketoiminnan analysointiin, jolla optimoidaan huoltosuunnitelma pitkäaikaisia huoltosopimuksia varten? Tutkimuskysymyksen vastaus saavutetaan kvalitatiivisella (haastattelut) sekä tietojärjestelmätutkimuksen (design science) menetelmillä. Haastatellut henkilöt ovat: Spesialisti Wärtsilän merenkulkuliiketoiminnan huoltosopimusyksiköstä, sekä luotettavuuteen erikoistunut spesialisti Ramentor Oy:stä. Tietojärjestelmätutkimus on informaatioteknologiakeskeinen tutkimusmenetelmä.

Tutkimuksen tarkoitus on toteuttaa palvelullistaminen ratkaisujen (solutions) liiketoimintamallina. Työn keskipisteessä on elinkaariratkaisujen huoltoanalyysiprosessin kehittäminen odottamattomien vikojen ehkäisemiseksi, joka on osana RCM -prosessia. Monitorointi sekä data kerääminen ja prosessointi, ovat onnistumisen avaintekijöitä. Paras tapa reaaliaikaiseen monitorointiin sekä datan keräämiseen onnistuu IoT:n (esineiden internet) avulla.

Tutkimuksen keskeiset löydökset osoittavat, että case -yrityksen kannattaa kehittää ja dokumentoida virtaviivainen RCM-prosessi luodakseen räätälöityjä huoltosuunnitelmia vastaamaan asiakkaiden resurssien ja liiketoiminnan tarpeisiin, ottaen huomioon eri installaatioiden rakenne. Lisäksi dokumentoitu prosessi edesauttaa case-yrityksen ryhtymistä neuvotteluihin luokituslaitosten kanssa, saadakseen hyväksyntä luotettavana palveluntarjoajana virtaviivaistetulle RCM -konseptille.

AVAINSANAT: Huollonhallintajärjestelmä, RCM, Optimointi, Palvelullistaminen

1. INTRODUCTION

Service as business logic is a globally growing trend (Vandermerwe & Rada, 1988:314). Customer demand-driven service, in several different industries, is adding value to corporations' core businesses (Vandermerwe & Rada, 1988:314). Creating customer value is a multilane process that consists of two distinct sub-processes: supplier's process of providing resources for customers use; and customers' process to turn service into value (Grönroos & Ravald, 2011:5).

> *"Smart organizations know they can no longer afford to see maintenance as just an expense" (Knutsen, Manno & Vartdal, 2014:2)*

Inside the big industrial companies integrating the maintenance is important within the business cycle for guarantying predictability, growth, and improve the overall quality of operations. The organization needs to get rid of an old-school regime, time schedule-based maintenance with on-condition maintenance. A new-school version of maintenance regime is data-driven and risk-based, which leads to more accurate and better on-time maintenance tasks, as well as avoiding downtime caused by a failure. Practical advantages gained by smarter maintenance are lower costs, increased safety, and availability of ship systems. (Knutsen, et al., 2014:2)

1.1. Background

Customers of Wärtsilä includes marine, oil & gas, and energy sectors. The customers are demanding more advanced and tailored services to match maintenance activities with their business needs and to optimize operating expenditures and inventory of the facilities without compromising reliability. Reliability-centered maintenance (RCM) is a well-known method in different fields of industries. RCM is used to systematically analyze and modify standard maintenance plans to optimize asset availability and minimize total cost of ownership. The issue is, that Wärtsilä has not been using the RCM method effectively as a tool of service solutions.

Therefore, the research question is: How to develop a systematic method to analyze customers' asset and business to optimize maintenance plan for long term service agreement? RCM method will be forming the base of the theory and then be further examined in the research section, in co-operatio with Ramentor's reliability specialist. RCM procedures consist of 7 steps for the maintenance processes, among industrial management literature, as well as practically used in different industries. This thesis is a part of developing and improving a risk assessment by launching the RCM process for Wärtsilä Services. An objective for the maintenance analysis process is to optimize life cycle costs (LCC) and availability, focusing on whichever is the best serving the customers' requirements to reach their goals.

This thesis strives for resulting a service logic, which provides an understanding of the process of value creation and its implications. It offers a terminology that supports researchers and practitioners understanding different roles of suppliers and customers in value creation and analyzing opportunities for value co-creation.

The main aim for this thesis is to develop and document a streamlined RCM process for Wärtsilä to create tailored maintenance plans of customers' assets considering installation configuration and customer's business needs. The scope of the thesis is limited to streamlined RCM process development and documentation for engine systems. The study utilizes the RCM method approach but also applies an FTA method to simulate the best performance. The focus will be in maintenance management. Used methods aim to comprehensively answer to the research question. In addition, the documented process enables Wärtsilä to engage in discussions with classification societies regarding approval of Service Supplier notation for the streamlined RCM concept.

1.2. Structure of the thesis

The structure of the thesis follows problem arrangement and the chosen research methodology. The introduction is followed by a chapter that forms the theory of service as business logic. The third chapter discusses maintenance management in general, including the definition of standards and guidelines that are relevant for the case study.

The fourth chapter defines a theory of traditional RCM and FTA methods comprehensively. These background and theory chapters are then followed by the entire research case: Wärtsilä Services –chapter, which consists of explaining research methods and data collecting, background information of Wärtsilä Services, and then modified and streamlined RCM process thoroughly. Last chapters are conclusions and references.

1.3. Research approach

Research approach of this case study includes a plan and procedure that consist of the steps: data collection, analysis, and interpretation. Data collection was carried out during a couple of interactive discussions with the Specialist from Wärtsilä Marine Business Asset Management Services, and Reliability Specialist from Ramentor Oy. Therefore, the data collection follows partly qualitative approach, claiming transformative knowledge of developing the RCM method for the case study, and partly design science (DS) method. Asking some open-ended questions, but mainly the research data is collected and further analyzed from the interactive discussion. (Denzin & Lincoln, 1994)

Design science (DS) research methodology is an information technology-based outcome of research. DS offers guidelines for evaluation and iteration within research projects and focuses on designed items development and performance, with the intention of improving its functional performance. DS creates and evaluates information systems as an intention to solve identified organizational problems. Defining DS as any designed object with a fixed solution to an understood research problem. (Peffers, Tuunanen, Rothenberger & Chatterjee, 2007)

2. LITERATURE & THEORY

Adding value to corporations' core business offerings through the service is a growing trend in business. Through the world, through the industries, the trend is a customer demand-driven, and perceive corporations to sharpen their competitive boundaries (Vandermerwe & Rada, 1988:314-315). According to Grönroos & Ravald (2011) could be problematic to determine if a product provides value for an individual or organization, without understanding multiple different ways that product is used. It is the final customer that defines whether a product or service offers help to accomplish their desired purpose or goal. (Grönroos & Ravald, 2011:7)

Consumers have requirements for services in the market, with the different relevant value expectations. Cultural and personal values, consumption values, as well as product benefits, are the factors that define the service values in the market. Cultural environments (incl. social and familial) impacts in formation and development of individual views, which are representing widely shared beliefs about desired outcome. Personal values are individuals' beliefs of outcome desired for themselves, which are closely linked to needs. Consumption values refer to subjective beliefs about desired ways to achieve personal values or goals, through actions or activities, such as social interaction, economic exchange, and possession or consumption. In product benefits point of view, services are viewed as a bunch of benefits, not as attributes, which means that customers are less interested in the service's technical features than in what benefits they get from buying, using or consuming the service. (Lai, 1995:381-388)

2.1. Literature review

The author and founder of RCM, John Moubray (1997), as well as Smith and Hinchcliffe (2004), discusses traditional RCM method and its benefits. Project report from Hoseinie and Kumar (2016) composed different point of view: the RCM method used in practice. Modified RCM can be used to minimize LCC or maximize availability by optimizing operating expenditures, discussed by Rausand & Vatn (2008). FTA is explained briefly by Penttinen & Lehtinen (2016).

Standards and guidelines that needs to be considered for enabling case company to get Approval of Service Supplier notation for RCM concept are: SAE International (2009) for standard SAE JA1011; Finnish Electrotechnical Standards Association (SFS) (2001) for standard IEC 60300-3-11; and DNV GL (2018) rules for classification in Maritime Services. Classification society ABS, included for having a comparison for DNV GL classification society, from Maritime reporter (2005) and Conachey & Montgomery (2003).

A service business is concerned in the literature by Ylimäki & Vesalainen (2015) and Vargo & Lusch (2004), both papers discussing solution business. Servitization is a term for service-dominant and customer-focused type of business, which is explained by Rymaszewska, Helo & Gunasekaran (2017) and Vandermerwe & Rada (1988). As one can take a note, Vandermerwe and Rada have discussed servitization, how to add value by adding services, already in 1988. Analyzing maintenance needs and business to optimize operating expenditures is easier when assisted by big data knowledge of Russom (2011), and IoT literature of Yu, Liang, He, Hatcher, Lu, Lin & Yang (2018) and Wortmann & Flücher (2015).

2.2. Solution business

An interaction between the solution provider and a customer is vital (Ylimäki & Vesalainen, 2015:939). According to Ylimäki & Vesalainen (2015), continuous and seamless collaboration and knowledge-based communication are both in big roles when the customer co-produces value in the solution business. Approaches driven by service-dominant (S-D) logic is facing some practical challenges, even its theoretical idea is promising (Vargo and Lusch, 2004:2). The idea of S-D logic is basically to focus in the service business, for example, specialized skills and knowledge, instead of traditional goods-dominant (G-D) logic of business (Vargo and Lusch, 2004:2).

In the research of Ylimäki & Vesalainen (2015:939) some concerns about S-D logic is pondered if the service provider really understands their customers’ problems, and if the customers are capable of sufficiently expressing their needs. These concerns may be solved in the co-creation of value propositions in the pre-activity phase (Ballantyne, Frow, Varey, & Payne, 2011:204), which consist of negotiation and development of a full-service maintenance concept (Ylimäki & Vesalainen, 2015:939-940).

A value proposition is traditionally defined as a marketing offer or value promise that is formulated and communicated by a seller, with the intention of acceptation by a buyer (Ballantyne et al., 2011:203). This definition fits in G-D logic context, but the marketing and purchasing parts change when it comes to S-D logic where one-way communication gives way to mutual (reciprocal) or conversational (dialogical) communication in the cases where the parties are engaged by working and learning together purposefully (Ballantyne et al., 2011:203). Advisor and counselor McKinsey & Company explains the course of value propositions as following the segmented process (Figure 1.) (Lanning & Michaels, 1988):

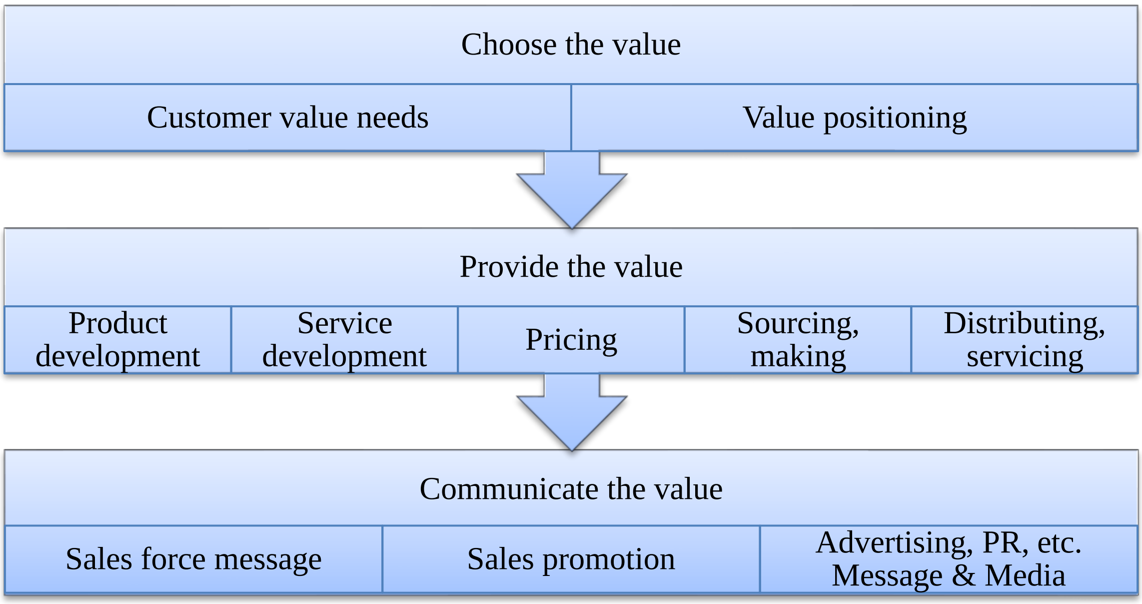


Figure 1. McKinsey & Co's value delivery system (Lanning & Michaels, 1988; Ballantyne et al., 2011:203)

2.3. Servitization

Service-dominant and customer-focused movement is called a *servitization* of business (Vandermerwe & Rada, 1988). The servitization is a powerful feature of a total market strategy and it is leading to new relationships between solution provider and customer. Necessary enabler for servitization is digitalization, therefore during a transition from manufacturing to services, the organization need to develop and upgrade their digital tools simultaneously (Rymaszewska, Helo & Gunasekaran, 2017:93). Managers of the company must operate with the cumulative effects of servitization, which are caused by the combined results of past, current and future activities of human (Therivel & Ross, 2007:366). These cumulative effects are changing the competitive dynamics. The key challenge is beneficially blend services into the overall strategies of the industrial companies (Vandermerwe & Rada, 1988).

Servitization brings lots of benefits to the company's business activities. For example, in providers point of view the involvement in services provision, in addition to production, lock in the customer relationship with the provider. Alternatively, in customer's point of view, servitization enhances the customer convenience of resolving issues and problems associated with products, when earlier the customer needed to solve the problems by themselves. The service establishment may also lead to an increase in the products life cycle. (Vandermerwe & Rada, 1988:92)

Even though the servitization of industry is a powerful feature, according to Hojnik (2016) there are challenges that are crucial to the success of servitization projects. Some of the challenges are caused by EU law implications from the competition and consumer law perspective, but also servitization in cross-border trade (Hojnik, 2016:1575; European Commission, 2014:5). Following list (Figure 2.) clarifies benefits versus challenges arrangement, which are set by the EU law and policy:

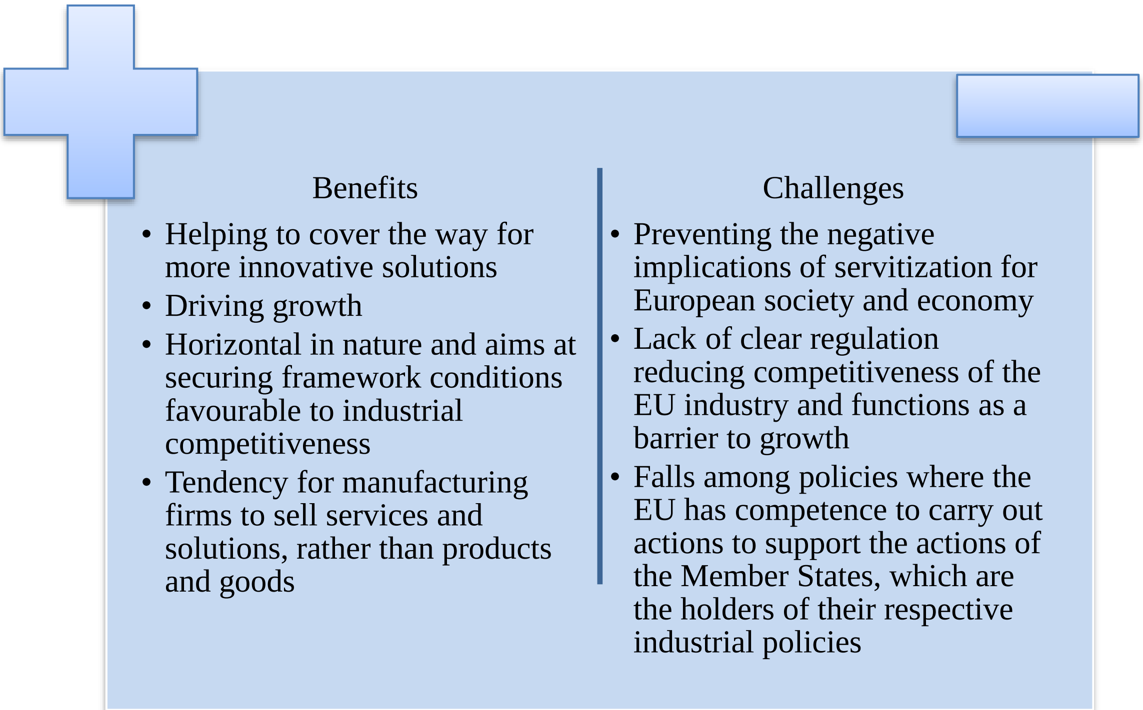


Figure 2. Servitization benefits versus challenges set by EU law (Hojnik, 2016:1575; European Commission, 2014:5)

2.4. Internet of Things (IoT)

Maintenance process is much easier to plan and execute with adequate equipment, internet of things (IoT) assisted equipment is one of the possibilities to utilize. IoT is defined by McClelland (2019) as “a system of interrelated computing devices, mechanical and digital machines, objects, animals or people that are provided with unique identifiers and the ability to transfer data over a network without requiring human-to-human or human-to-computer interaction” (McClelland, 2019). Therefore, the internet of things (IoT) can enable possibilities of servitization for manufacturing companies (Rymaszewska et al., 2017:92).

IoT provides an opportunity to access end-user operations and therefore building service-products on data analytics (Rymaszewska et al., 2017:94). Following pyramid diagram (Figure 3.) illustrates the architecture of edge computing-based IoT in three layers: IoT devices, Edge Computing, and Cloud Computing. The base of the figure is IoT devices, which are all end-users for edge computing. In this type of architecture IoT can benefit from both edge computing and cloud computing, allowed by two characteristics of the structures (i.e. high computational capacity and large storage). (Yu, Liang, He, Hatcher, Lu, Lin & Yang, 2018)

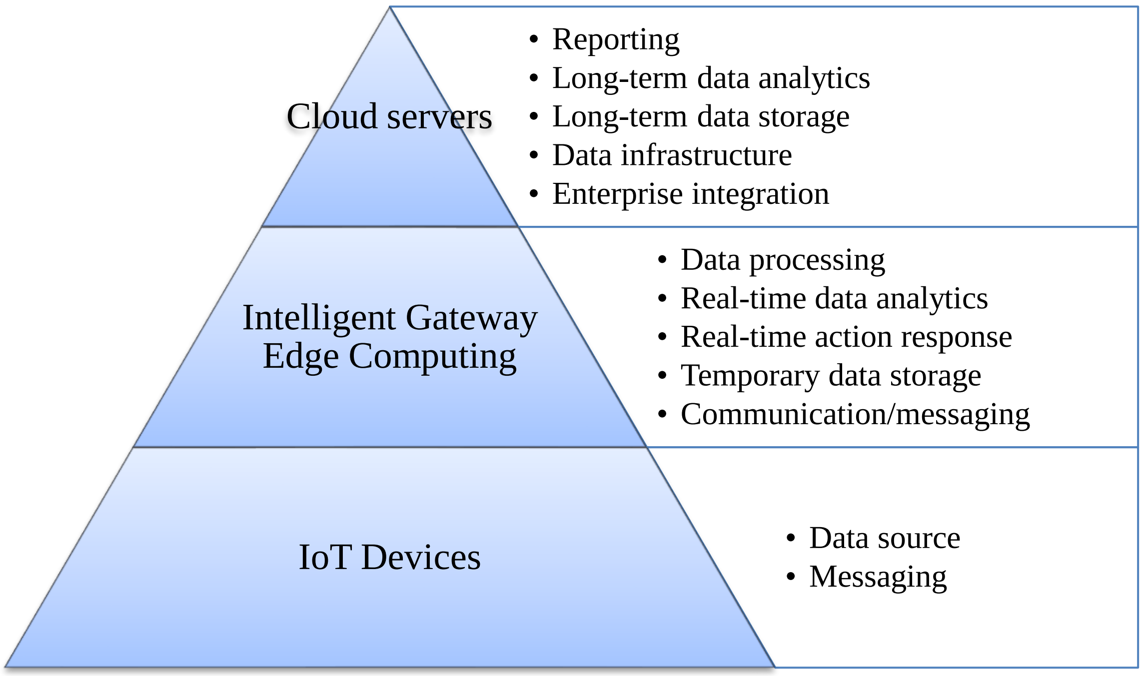


Figure 3. The three-layer architecture of edge computing-based IoT (Yu et al., 2018).

The IoT is playing an important role in our daily lives, during the progressing development of information technology (Wortmann & Flücher, 2015:221). Interconnected sensors and devices can collect and exchange different data back and forth through modern communication network infrastructure, which is connected by millions of IoT nodes (Yu et al., 2018:6900). These sensors and devices cause massive amount of data, which, after being processed, provides intelligence to service providers, as well as for users. Using mainstream cloud computing requires that all data is uploaded to centralized servers, where after computation the results are sent back to the sensors and devices (Yu et al., 2018:6900; Wortmann & Flücher, 2015:222). This cycle-process creates pressure on the network, especially in the data transmission costs of bandwidth and resources (Yu et al., 2018:6900). Besides that, increased pressure is also making the performance of the network worse, since the size of data has grown as well (Yu et al., 2018:6900).

The main three components that enable the IoT are: (1) hardware, which is a group of sensors, actuators, and fixed communication hardware; (2) middleware, which includes on-demand storing and computing tools for data analysis; (3) communication stack (i.e. presentation), which includes visualization and interpretation tools, is innovative and easy to use, and it can be extensively accessed; and (4) the secure data aggregation. (Gubbi, Buyya, Marusic & Palaniswami, 2013:1648)

IoT can be divided into two main categories of identification: radio frequency identification (RFID), and wireless sensor networks (WSNs) (Gubbi et al., 2013:1648). IoT tools that enable the IoT process are typically categorized as (1) sensing; (2) communication (e.g. RFID systems, tags, and sensor networks); and (3) middleware, which is basically a software layer located between technological and application levels (Rymaszewska et al., 2017:94). Following hierarchy chart (Figure 4.) demonstrates the relations under IoT:

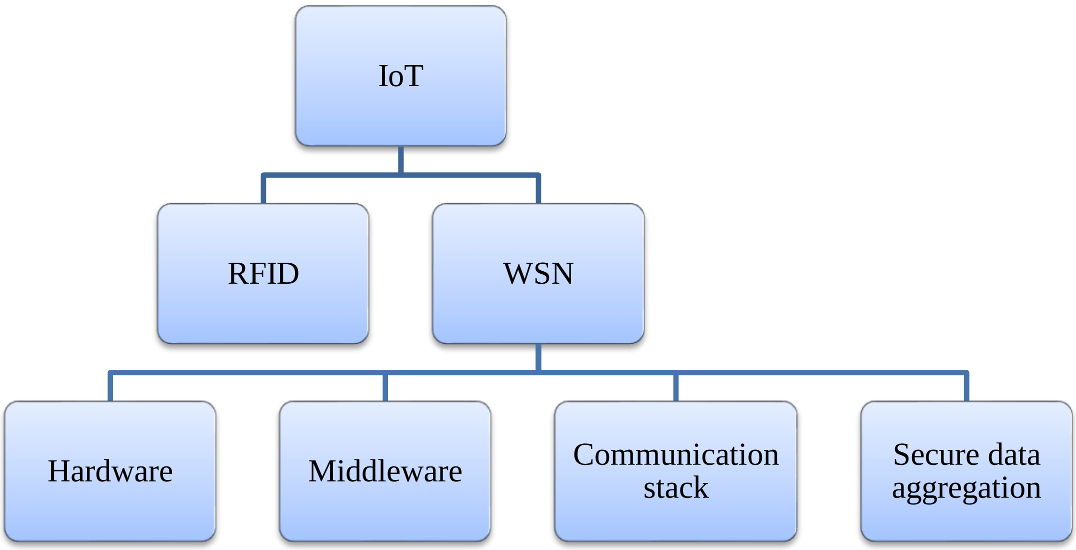


Figure 4. Main components of the IoT (Rymaszewska et al., 2017:94; Gubbi et al., 2013)

2.5. Big Data

IoT is one adequate equipment to collect information for planning and executing the maintenance process, and the big data deals with the huge amount of collected transaction data (Gandomi & Haider, 2015:138). The data coming from IoT devices is handled with the Big Data Analytics (BDA). Big data allows isolating and tracking pertinent metrics to ensure that IoT devices are used in their full capability (Gandomi & Haider, 2015:138). Therefore, big data is also a part of effective maintenance planning and executing process.

During recent years, big data has been defined in multiple various terms. An online survey collected the most relevant definitions of big data from 154 global executives in April 2015. The results are presented in the International Journal of Information Management as follows (Gandomi & Haider, 2015:139):

1. 28%: Massive growth of transaction data, including data from customers and the supply chain
2. 24%: New technologies designed to address the 3 Vs (volume, variety, and velocity) challenges of big data
3. 19%: Requirements to store and archive data for regulatory and compliance
4. 18%: Explosion of new data sources such as social media, mobile device, or machine-generated devices
5. 11%: Other definitions

The significance of Big Data Analytics (BDA) by Philip Russom (2011:5):

> *"Where advanced analytic techniques operate on big data sets. Big data is about two things – big data and analytics – plus how the two have teamed up to create one of the most profound trends in business intelligence (BI) today" (Russom, 2011:5)*

In recent years, advanced analytics has created a huge change in different industrial businesses. Analytics helps to discover what has changed and how to react. A scale of different business opportunities that should be seized is enormous. Advanced analytics helps provider for discovering new customer segments, identifying new suppliers, associating products of affinity, understanding sales seasonality, etc. (Russom, 2011:5).

Even the service provider should already have related experience in data warehousing, reporting, and online analytic processing (OLAP), since technical requirements are different for advanced forms of analytics. By choosing the correct form of advanced analytics and preparing big data for advanced analysis, users can make more intelligent decisions as they embrace analytics. Rephrasing the term *advanced analytics* as Russom (2011:5): it is a collection of related techniques and tool types. Typically, it includes predictive analytics such as data mining, statistical analysis, and complex SQL (Structured Query Language) (Harkins & Reid, 2002). It is possible to extend the list covering the data visualization, artificial intelligence, natural language processing, and database capabilities to support analytics. (Russom, 2011:4)

A better term for advanced analytics would be “discovery analytics”. According to Russom (2011:5), BDA user is typically a business analyst who is trying to discover new business facts and information that no other analyst in the enterprise knew before. This is only possible with a large volume of data and a big amount of details. This data is often the one that the enterprise has not yet tapped for analytics. (Russom, 2011:5)

The big data is not just about data volume. Certainly, the amount of data matters, but there are other important attributes of big data as well, such as data variety and data velocity. These three Vs (volume, variety, and velocity) establishes a comprehensive definition of the big data. For analytics, each of three Vs has its own ramifications as following Radial Venn (Figure 5.) visualizes (Russom, 2011:6):

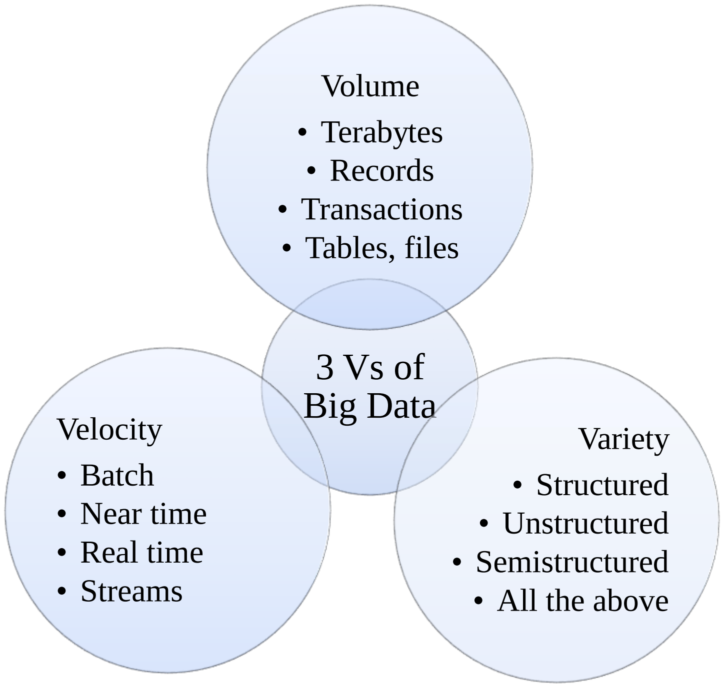


Figure 5. The three Vs of big data (Russom, 2011)

Even the data volume is the primary attribute of big data, it can also be analyzed by counting records, transactions, tables, or files. In addition, the scope of big data affects its quantification as well (Russom 2011:6; Michael & Miller, 2013:22). According to TDWI research by Russom (2011), collected data for general data warehousing differs from collected data specifically for analytics. Therefore, different analytic forms may have different datasets.

The best outcome of using IoT is reached when big data is synchronized with analytics. Analytic tool results are enhanced with gigantic statistical samples provided by big data. Most of the tools are designed for data mining or statistical analysis, optimized for large datasets. The general rule by Russom (2011:9):

The larger the data sample, the more accurate the statistics and other products of the analysis (Russom, 2011:9).

Cost of data storage and processing bandwidth are relatively affordable, even for the smaller companies (Russom, 2011:9). Therefore, tools and platforms for BDA are not anymore just for the biggest businesses. Small-to-midsize businesses that like to dig deeper into digital processes for sales, customer interactions, or supply chain, can also manage and control big data (Feijóo, Gómez-Barroso & Aggarwal, 2016).

3. MAINTENANCE MANAGEMENT

Maintenance is considered as a blend of all technical, administrative and managerial actions during the life cycle of an item. Intention is to retain or restore the item to a state that it can perform the required function (BSI Standards Publication, 2010:5). Maintenance is defined in the Cambridge dictionary (cited 24.1.2019) as a work needed to keep a road, building, machine, etc. in good condition.

Maintenance plays an important role in an effective engine. Small problems could be detected and corrected before they become a major problem, by carrying out short weekly inspections, lubricating, cleaning and performing some minor adjustments. Carelesness could lead to major problem, which can cause an engine failure. To achieve the company’s goals, maintenance should keep the systems functioning properly. This includes meeting the requirements of CRAMP parameters (Cost, Reliability, Availability, Maintainability, and Productivity) for any automated systems. Not only systems themselves need to be able to integrate the evaluations, but also their interactions with each other and their environment (Gustafson, Schunnesson, Galar & Kumar, 2013).

For example, engines have a lot of moving components inside, and moving components cause erosion on its surface. By collecting data and analyzing further how and when the components of the engine need maintenance or to be changed, a risk for the complete failure decreases (Peshkin & Hoerner, 2004:4). Maintaining the engine also avoids costs of engines in poor condition that are low in efficiency or may face the quenching completely after an unexpected failure. In addition, timing and planned procedures take big roles in the process planning, therefore, maintenance process should be available when calculated (Peshkin & Hoerner, 2004:4).

3.1. Preventive Maintenance

Maintenance is divided into three main categories: corrective, predictive and preventive (Moubray, 1997:171). Corrective maintenance means overhauling items when they are found to be failing or after the item already failed, which is a reactive type of maintenance.

Corrective maintenance could be planned or unplanned (Moubray, 1997:171). Predictive tasks require checking if something is failing (Moubray, 1997:171). Preventive Maintenance (PM) is the target and core part of the RCM process, therefore PM will be explained comprehensively in this chapter. The traditional RCM process and its development are in the focus of this thesis.

Preventive maintenance aims to prevent the failure, which means it is a proactive type of maintenance. Basically, PM means overhauling items or replacing components at fixed intervals (Moubray, 1997:171). There are three different preventive maintenance types performed: condition-based, scheduled failure-finding, and periodic overhauls. Condition-based is executed by making continuous measurements and periodic inspections. Periodic overhauls are managed by calendar time or operating time (Rausand & Vatn, 2008). Hierarchy chart (Figure 6.) clarifies these relations:

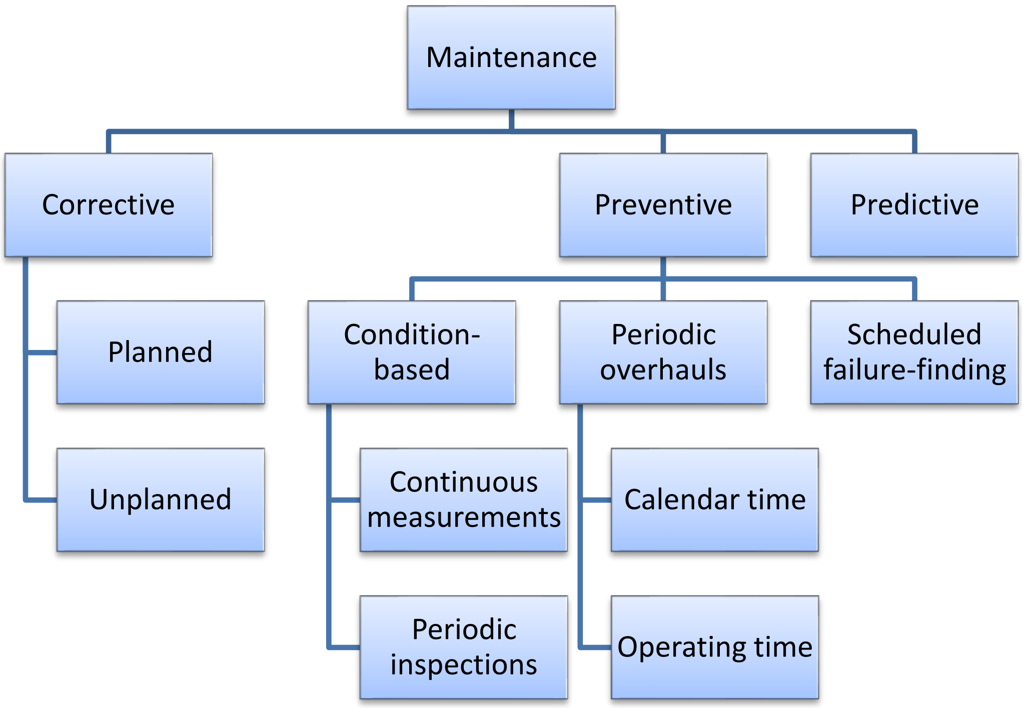


Figure 6. Different types of maintenance (Davies, 1998:509-510; Rausand & Vatn, 2008:79)

Preventive maintenance itself is overall target and core part of RCM process (Moubray, 1997:171). A key factor in the definition of PM is preplanning. In developing a proactive maintenance model and culture, preplanning (i.e. scheduling) has an important role. PM is an equipment maintenance strategy that is based on replacing, overhauling or remanufacturing an item (Wang, 2002). The strategy is performed either by fixed or adaptive intervals, despite of its condition at the time. PM actions can be divided into categories: prevent (or mitigate) failure, detect an onset of failure, discover hidden failure, and do nothing – valid limitations. Identifying these four factors leads to the stage for defining the four task categories from which a PM action may be specified (Smith & Hinchliffe, 2004):

1. Time-based maintenance (TBM) aims to prevention or retardation of failure. Preventive policy, in which precautionary maintenance actions are carried out at pre-specified time intervals, is the traditional time-based maintenance (TBM) or use based maintenance (UBM). Important things about time-directed task categorizing are: (1) preset periodicity of the task action, occurs without further input; (2) the action is recognized to directly provide failure prevention or retardation benefits; and (3) the task generally requires some form of intrusion into the equipment. For example, TBM/UBM may be used at once in a month – type of maintenance, or after every 1000 running hours. (Pintelon & Van Puyvelde, 2006:97)
2. Condition-based maintenance (CBM) aims to detect the failing component and its failure modes, in other words, detecting failures or failure symptoms (Veldman, Klingenberg, & Wortmann, 2011). PM is carried out whenever a given system parameter (i.e. system condition) reaches or approaches a predetermined value or situation. Important factors when classifying a CBM task is that the measurable parameter which correlates with failure onset is defined, as well as the value of a measurable parameter itself. CBM was initially limited to high-risk environments, such as aviation and nuclear power generation, now it is widely practiced. (Pintelon & Van Puyvelde, 2006:97)
3. Failure-finding (FF) aims to discover a hidden failure before an operational request (Pintelon & Van Puyvelde, 2006:97). When the systems and facilities are large and complex, several equipment items or a whole system or subsystem might face some failure. In the normal course of operation, nobody would get to identify that such a failure occurred – this is called “hidden failure” (Narayan, 2004:59). For example, a pump seal leaks in a normally unattended unit. Usually

there would be some evidence of the leak (pool of process liquid on the pump-bed), but only because the operator was not present, and nobody saw it happening, the event from an evident to a hidden failure occurs. The leak would have been obvious if the operator was present, and any further actions would not be necessary.

4. Run-to-failure (RTF) is a measured decision to run some component until the failure when the other options are not possible, failure event has no or only little consequence (Narayan, 2004:196), or the economics are less profitable (Nowlan & Heap, 1978; Smith & Hinchcliffe, 2004). The item needs to fail before any maintenance work. By using the knowledge (e.g. big data) of RTF, it is possible to reduce the workload of preventive maintenance significantly. Narayan (2004:94) states that such unnecessary maintenance results in additional failure are often caused by poor materials or lack of employees' skill level. Eliminating the unnecessary maintenance has an impact on decreasing early failures and eliminating some breakdown work as well. The equipment uptime or availability also rises consistently (Narayan, 2004:94).

Even the PM is the core of the RCM process, sometimes it is impossible to apply PM in engineering assets in a few different reasons. For example, in the case such as: (1) if there is not any PM task found that would bring any value regardless of how much money the user might be able to spend; or (2) if the available and potential PM task is too expensive. This concern arises, when the item is less costly to fix when it fails, with no safety impact at issue in RTF decision. In addition, (3) the equipment failure should not occur since it is one the lowest on the priority list to warrant attention within the allocated PM budget. (Hoseinie & Kumar, 2016:39-40)

What if is necessary to create a new PM program or update an existing PM program? Essentially, the process would be the same. First, determining what the PM program would include and what to do with it (Kobbacy & Murthy, 2008). Using necessary steps to build an ideal program into infrastructure and set it to action. Following horizontal hierarchy chart (Figure 7.) illustrates the development of a preventive program (Smith & Hinchcliffe, 2004):

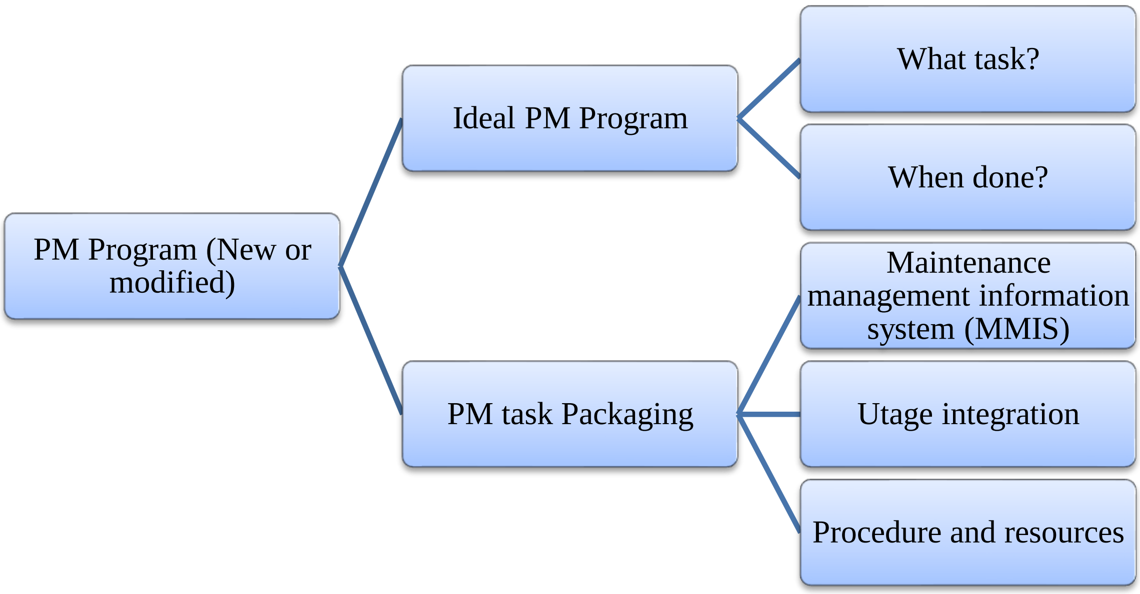


Figure 7. Preventive program development (Smith & Hinchcliffe, 2004).

3.1.1. Condition Monitoring

Maintenance related expectations have grown significantly over the past 70 years. Evolving from the reactive process to the preventive activity has an outstanding impact on savings of temporal and economical point of view. Maintenance framework RCM is a solution for preventive maintenance process, which includes the adoption of Condition Monitoring (CM) as one of the main segments. CM increases safety and availability in a cost-effective manner. (Knutsen, et al., 2014:4)

There are different condition monitoring techniques. CM increases the safety level by reducing the risk of loss of life and property, as well as minimizes the costs of the component or system when being maintained timely (Knutsen, et al., 2014:4). In other words, reliability rate increases. These enchantments achieved by monitoring possible failure mechanisms, taking actions through operational measures in the short-term and through maintenance in the long-term, both supporting to avoid the development of a failure (Knutsen, et al., 2014:4). Therefore, CM leads to avoidance of a potential breakdown of the component or the system (Knutsen, et al., 2014:4). Following Radial Venn (Figure 8.) shows common condition monitoring techniques (Davies, 1998:304):

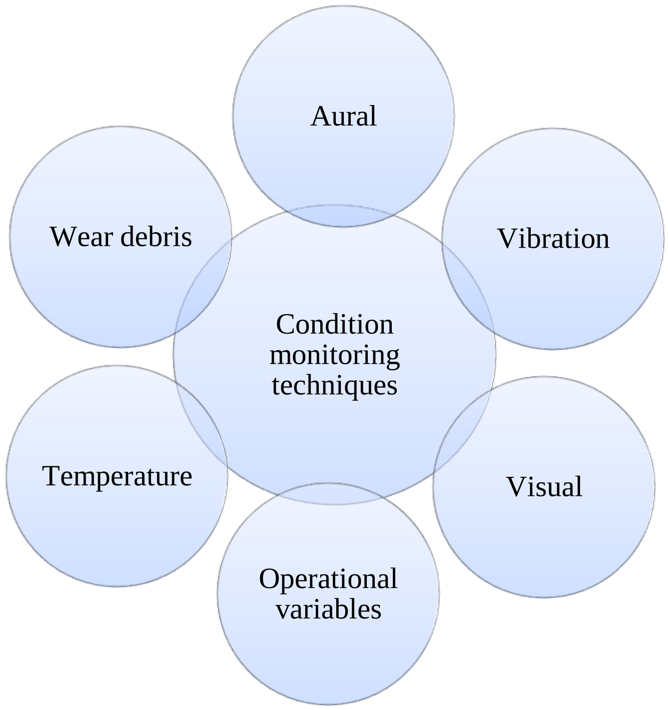


Figure 8. Condition monitoring techniques (Davies, 1998:304)

Monitoring techniques explained (Davies, 1998:304-305)

- Aural and visual: basic and the most common forms of surveying machine condition. It is commonly accepted that skilled personnel, with comprehend knowledge of machines, can identify a potential failure by simply listening to the sounds of distress emitted of a machine nearby. The aural technique can be assisted by stethoscope, or by placing a spanner or rod against the machine and using ear or earmuffs for listening. The visual inspection can be assisted by borescope or stroboscope, which are light assisted devices.
- Operational variables: also considered as performance or duty-cycle monitoring. Focus is to assess each machine’s performance regarding its intended duty. Any major warnings from expected problem, or design values indicating signs of a problem existing, often relates to malfunction of the machine.
- Temperature: measuring the operational and the component surface temperatures. Monitoring component temperatures is related to wear occurring in machine elements where lubrication is either inadequate or absent, particularly in journal

bearings. The technique can be assisted by optical pyrometers, thermocouples, thermography, and resistance thermometers.

- Wear debris: generated of load-bearing machine elements moving surfaces. Possibility to assess the condition of these surfaces if the wear debris is collected and analyzed. Debris defined as a broken or torn piece of something larger (Cambridge Dictionary, cited 1.12.2018)
- Vibration: the basic measurement of CM. The technique works by a wide selection of transducers, such as a piezoelectric accelerometer, which is a popular measurement transducer in use. Obtaining acceleration signals from transducers can be integrated to produce velocity or even displacement values for different applications. After processing these signals in alternative ways to highlight different aspects of the data, they can be used to detecting and diagnosing the machine condition. The various techniques can be divided under the categories as shown in following Diverging Radial chart (Figure 9.):

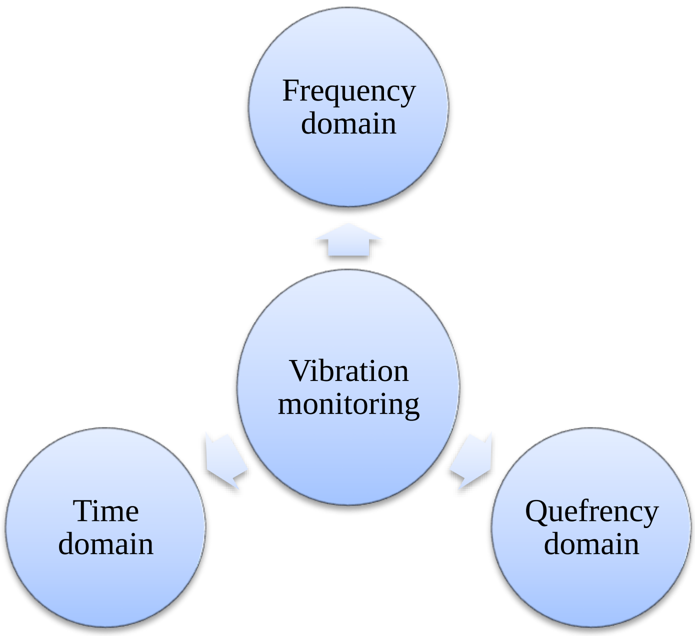


Figure 9. Vibration monitoring techniques (Davies, 1998:306)

Optimal sensor placement needs to be considered in condition monitoring. In condition monitoring process the sensors need to be placed optimally for efficient failure diagnosis. Vital metrics of sensor network optimization are the selection of the location, type, and number of sensors (Oskouei & Pourgol-Mohammad, 2016).

The sensor placement is not an easy task and it might face some challenges on the process. Representing a maritime region, the challenge is determining the least expensive configuration required to reach a given level of coverage in a fixed volume. The mentioned challenge is a planning problem where the aim is to develop a tool that can provide the decision maker, which includes every possible cost-coverage trade-off. (Ngatchou, Fox & El-Sharkawi, 2006:2714)

Given a set of transmitters (S_{Tx}) and a set of receivers (S_{Rx}), the cost objective is a weighted sum of the number of sensors. The weights are basically the respective costs of the sensors. In this case, all given type sensors have the same cost for transmitters (C_{Tx}) and for receivers (C_{Rx}). This cost objective element can be formulated as (Ngatchou, et al., 2006:2714):

$$Cost = C_{Tx}N_{Tx} + C_{Rx}N_{Rx}$$

In this formula, $N_{Tx}$and N_{Rx} are the number of transmitters and the number of receivers respectively. Generally, the receivers are cheaper than the transmitters (C_{Tx}>C_{Rx}). Limitations on the cost objective are only the maximum number of transmitters and receivers (Ngatchou, et al., 2006:2714):

$$1 \le N_{Tx} \le N_{TxMax} \text{ and } 1 \le N_{Rx} \le N_{RxMax}$$

In the sensor networks optimization process, determining logical relationships between components and sub-systems is performed through altered methods, such as FMEA, FTA, and RBD (Reliability Block Diagram). Potential sensor locations are first determined through Sensor Placement Index (SPI), which depends on the importance of the failure modes, as well as the cost monitoring processes of failure modes. Potential places of sensors result different scenarios for sensor placement. (Oskouei & Pourgol-Mohammad, 2016)

Following process flow chart (Figure 10.) describes further how the sensor placement structure is managed step by step (Oskouei & Pourgol-Mohammad, 2016:85):

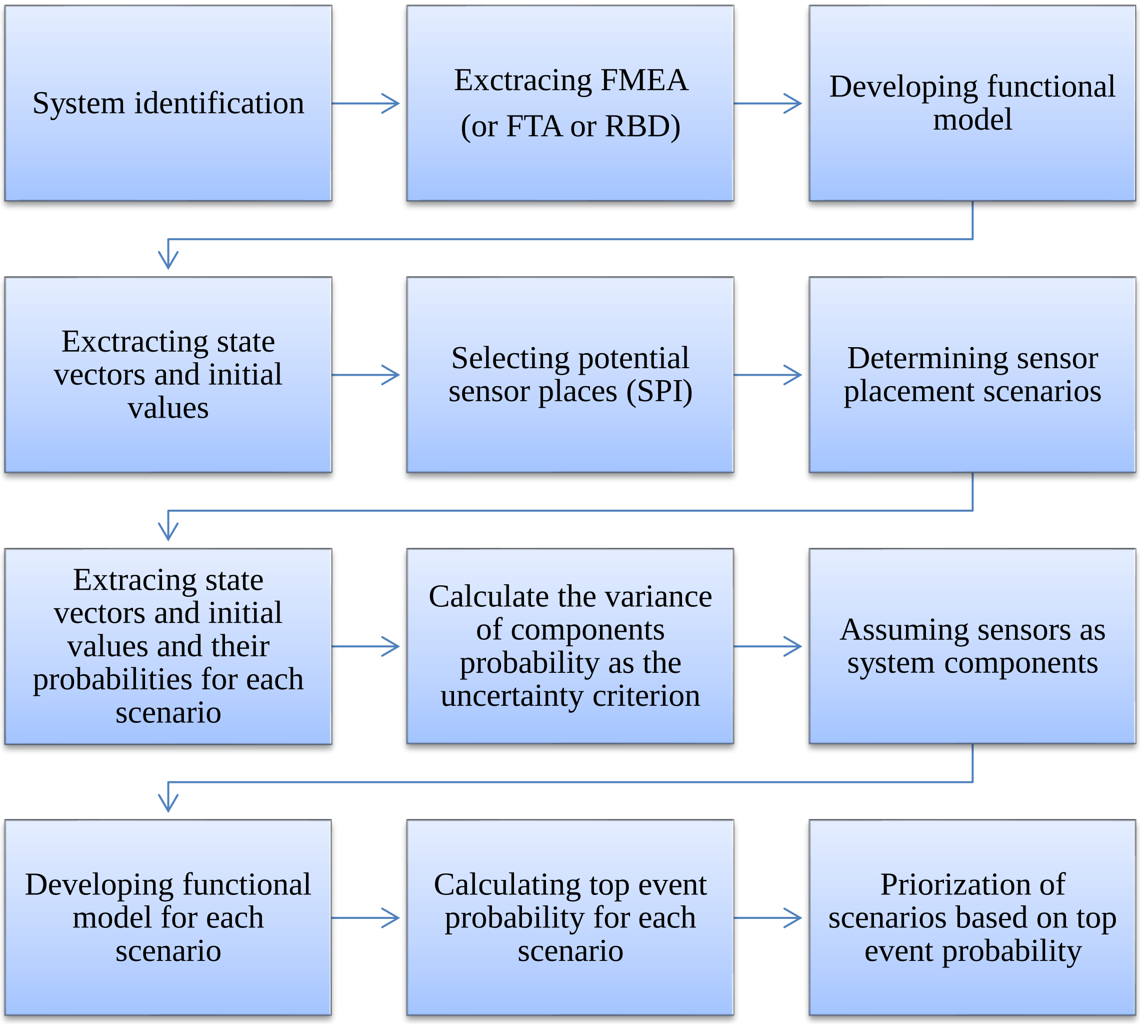


Figure 10. Sensor placement methodology structure (Oskouei & Pourgol-Mohammad, 2016:85)

3.2. RAMS

Reliability, availability, maintainability, and safety (RAMS) are generic essential risk related system quality attributes (Stapelberg, 2009:3; Penttinen & Lehtinen, 2016:473). Generic attributes that can be used for all types of risk management irrespective of the item type considered. Defining an item as part, component, device, subsystem, functional unit, equipment, or individually described and considered item for the system. The term RAMS consists of dependability (RAM) and safety (S). (Penttinen & Lehtinen, 2016:473)

The system risk can be divided into availability and safety risks. Availability risks of the system are formed by the combination of probabilities and consequences of dependability related risk sources. Likewise, safety risks are formed by the combination of probabilities and consequences of hazards. The following block chart (Figure 11.) illustrates the terms of risk and RAMS (Penttinen & Lehtinen, 2016:474):

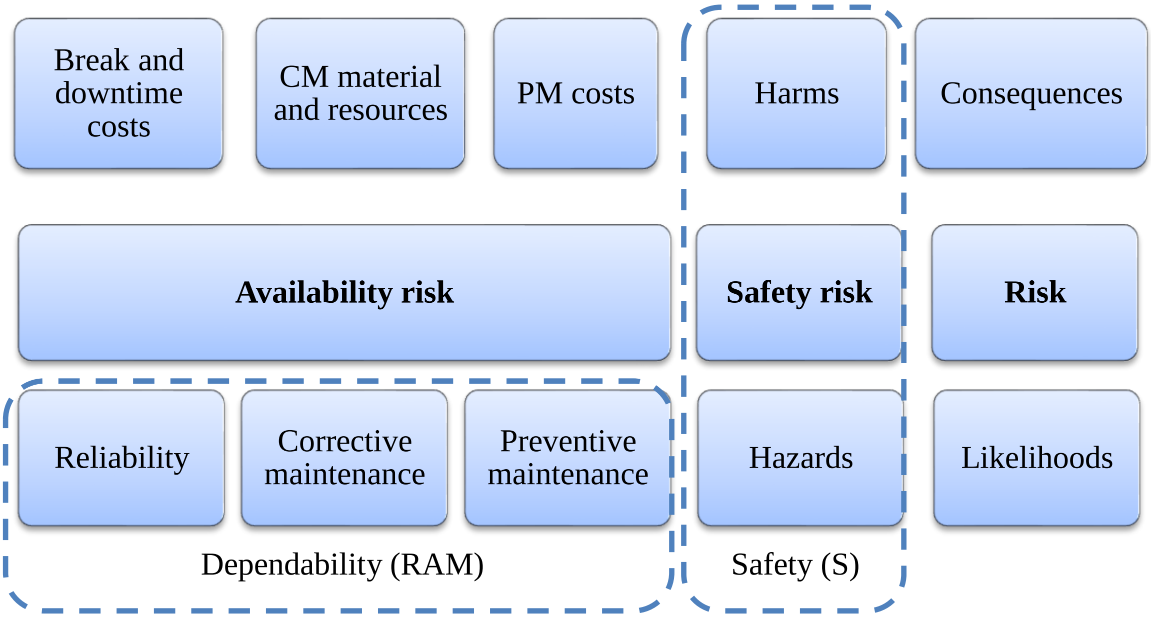


Figure 11. The terms of risk and RAMS (Penttinen & Lehtinen, 2016:474).

3.3. DNV GL – Rules for classification

Roots stretch all the way back to 1864 when Norway’s mutual marine insurance clubs together established a set of rules and procedures, which were used in assessing the risk of underwriting individual vessels. Norwegian group Det Norske Veritas (DNV), founded as a membership organization, aimed to provide reliable classification and taxation of Norwegian ships. DNV became operational company after merging with Germanischer Lloyd (GL) in September 2013.

DNV GL Group is today a globally leading quality assurance and risk management company. Operating in over 100 countries with more than 100,000 customers across the maritime, oil and gas, energy, food, and healthcare industries, and a variety of other sectors. DNV GL states to help companies to become safer, smarter and greener.

(dnvgl.com – about DNV GL, 2018). It is an organization with the objective of safeguarding life, property, and the environment. Operating through a limited company (Ltd.) DNV GL AS, which is registered in Norway, and through a worldwide network of affiliates and offices. (DNVGL-RU-SHIP, 2018)

DNV GL carries out classification, certification and other verification services related to ships, systems, facilities, materials and components, and performs research in connection with these functions. DNV GL might perform assignments that utilize its knowledge or contribute to developing knowledge that is required for the performance of these tasks. In addition, providing its integrity is not impaired. (DNVGL-RU-SHIP, 2018:7)

With DNV GL approval of services supplier, the supplier can build trust and confidence with its customer. Service companies benefit from smart approval processes by following proven programs: DNV GL proof of quality leading to new market opportunities; boosted trust between shipping companies, operators and the supplier due to DNV GL certification; expert guidance on requirements and how to achieve compliance; as well as listing of approved service suppliers in DNV GL database, so that potential customers can easily find the supplier. (DNV GL, 2018)

Nevertheless, suppliers delivering services relevant to ship operators or the classification of ships need to fulfill specific requirements. When serving DNV GL ships, these requirements are subject to approval. Experts of DNV GL approve the service supply business according to DNV GL rules, which guarantees that the supplier company meets common qualification, capability, and delivery requirements. The following list of services (Figure 12.) include all that DNV GL offers as approval for suppliers (DNV GL, 2018):

DNV GL services: Approval for suppliers

- Ultrasonic thickness measurements of ship structures
- Non-destructive testing for offshore projects/units
- Ultrasonic tightness testing of hatches
- In-water survey of ships
- Survey and maintenance of fire extinguishing equipment and breathing apparatus
- Service of radio communication equipment
- Service of inflatable life rafts, inflatable life jackets, evacuation systems and more
- Service of gas welding and cutting equipment on board
- Examination of Ro-Ro ship bow, stern, side and inner doors
- Survey of low location-lighting systems using photo-luminescent materials
- Sound-pressure level measurements of alarm systems
- Service and testing of voyage data recorder
- Resign casting of chock foundations, stern tubes, etc.
- Vibration monitoring and diagnostics of machinery on board ships
- Inspection and testing of navigational equipment and systems on board ships
- Inspection and testing of Inventory list of Hazardous Materials (IHM)
- Renewal survey examination of mooring chain intended for mobile offshore units
- Testing of coating systems (IMO PSPC)
- Servicing of lifeboats, launching appliances and on-load release gear
- Condition monitoring of machinery onboard ships and mobile offshore units
- Testing of ballast water management systems - environmental testing
- Testing of ballast water management systems - land-based and shipboard testing
- Services in terms of guidelines for compliance with MLC 2006 noise and vibration requirements

Figure 12. List of DNV GL approval for supplier services (DNV GL, 2018)

Certification by an authoritative third party, such as classification society DNV GL, is a value-adding validation. Following chart of relations (Figure 13.) explains how the DNV Certification represents a value-adding validation in the CMC process. CMC signifies Certification of Materials and Components and it is third-party certification.

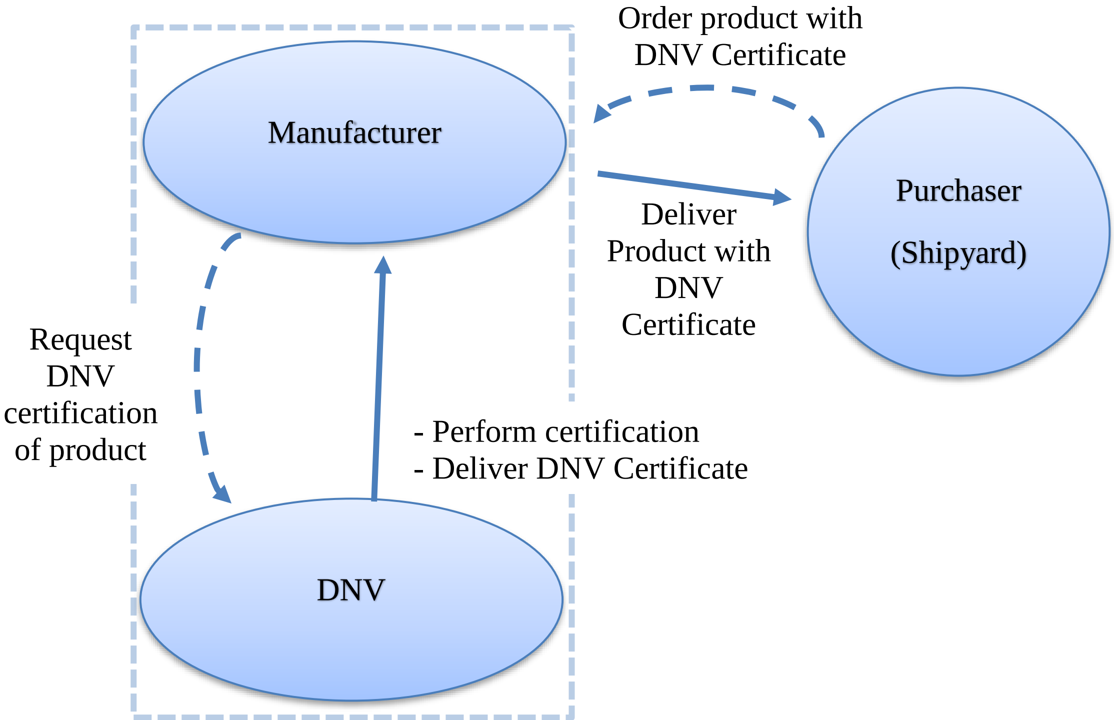


Figure 13. DNV Certification is a value-adding validation (Marsh, 2010)

Principles of marine operations consist of general information, verification services, approval services, and warranty surveys (Det Norske Veritas, 2010):

- General: During the phases of design, construction, and operations, the verification may cover the marine operations phase, which includes transit and installation, depending on an agreement with the customer.
- Verification services: Independent third-party verification services of marine operations or operation-parts. Depending on the agreed scope, it may involve elements such as independent reviews, analysis, inspection, and surveys.
- Approval services and warranty surveys: During the issuance of a Marine Operation Declaration, DNV may confirm acceptability of the object under consideration, equipment, planning, and preparation. Confirming the compliance is executed by reviewing of analysis, strength calculations, equipment certificates, verification statements, plans and procedures, test programs, and personnel qualifications.

All work performed by DNV is based on three DNV rules for planning and execution of marine operations: The first rule includes delivering needed information and instructions to users, as well as the systematic and alphabetic indexes; the second rule specifies the general knowledge of operational and technical basis that are common for all types of marine operations; and the third rule defines specific requirements and guidance for various types of operations, e.g. load-out, lifting, transportation, offshore installation, sub-sea installations, location approvals, etc.

The most relevant sections from “DNV Rules for Planning and Execution of Marine Operations” for an offshore gas terminal are planning of operations, design loads, structural design, towing, and special sea transports. Mentioned aspects assessed with respect to marine operations would typically include structural strength ballast systems and equipment, commissioning of ballast system, stability, minimum bollard pulling tug requirements, number and size of tugs required, towing arrangement and equipment, soil, grouting, operational procedures, and weather restrictions (Det Norske Veritas, 2010).

Used structural typologies in offshore power generation mostly depend on the bearing capacity of the foundation, depth of the sea and wave conditions, the impact of the landscape, and features of the offshore wind farm (Escobar, López-Gutiérrez, Esteban & Negro, 2018:931). Subject to these input data is Gravity Base Structures (GBS), or other types of structures, which are robust and constitute a solid substructure for the topsides (Tistel, Eiksund, NTNU, Kvaerner, Bye & Athanasiu, 2015). GBS design is used to ease decision-making processes (Escobar, et al., 2018:931). GBS works by applying different calculation schemes in the two different hydrodynamic domains: according to Morison’s fluid dynamics equation theory $D/L<0.20$; and to diffraction theory $D/L>0.20$ (Escobar, et al., 2018:931; Morison, O’Brian, Johnson & Schaaf, 1950), where the variable D stands for drag force, which is proportional to the square of the instantaneous flow velocity, and variable L stands for inertia force, which is in phase with the local flow acceleration (Samui, Chakraborty & Kim, 2017:130).

Typically the most critical aspects for a GBS gas terminal are (1) out of dock operation; (2) LNG storage tanks installation in the GBS base; (3) towing of GBS from construction site to deck mating site; (4) mooring of GBS during completing the work (needs to stand the loads of environment e.g. wind, waves and current); (5) mating of GBS and topside; (6) towing of the completed GBS platform to the installation site; and (7) installation of the platform on the seabed (positioning requirements and arrangements, soil behavior, etc.). (Det Norske Veritas, 2010)

Renewal of the certificate is good to perform in intervals, at least in every third year. Renewal is made by verification through audits that approved conditions are maintained or on expiry of the supplier's approval received from an equipment manufacturer, depending of which comes first. When the renewal is not made in time, the DNV GL Society will be informed by the service supplier. (DNV GL AS, 2018)

3.4. ABS SafeShip

American Bureau of Shipping (ABS) is comparable classification society for DNV GL. ABS SafeShip is a program designed to apply advanced technology to reduce risk in the design, construction, and maintenance of a new and safer generation of cost-efficient vessels. ABS SafeShip helps providing a method of collecting information, early in the initial design and drawings phase, and then applying the most advanced, dynamic based assessment of the hull structure at any time throughout the vessel's life (Maritime Reporter, 2003).

RCM is a process for systematically analyzing an engineered system to determine the following information (Conachey & Montgomery, 2003:39):

- System functions and impact of functional failures
- Equipment failure modes and causes that can result in functional failures
- An optimal strategy for managing potential failures, which includes the maintenance to prevent the failures from occurring or to detect potential failures before they occurred
- Spare parts holding requirements

ABS SafeShip RCM analysis process consists of five basic elements: (1) define systems; (2) identify functions and functional failures; (3) conduct a Failure Modes, Effects, and Criticality Analysis (FMECA); (4) select a failure management strategy; and (5) document the analysis (Conachey & Montgomery, 2003:41)

4. RELIABILITY-CENTERED MAINTENANCE (RCM)

Total Productive Maintenance (TPM) and Reliability-Centered Maintenance (RCM) are two methods for maintenance strategy planning. TPM is a strategy for improving productivity through improved maintenance practices, which include functions for maintaining plant and equipment. In comparison, RCM has a primary objective to preserve system function. Consequently, critical systems and equipment need to be inspected and tested regularly to confirm preservation. Reviewing and combining both methods in planning the maintenance program can potentially lead to better processes, improved teamwork and production output, as well as cut costs. (Ahuja & Khamba, 2008:724; PdMA, 2014)

TPM method, developed in Japan, is an approach to maintenance management that focuses on six major losses (Ahuja & Khamba, 2008:724):

1. Breakdown losses
2. Setup and adjustment losses
3. Idling and minor stoppages
4. Reduced speed losses
5. Defects in the process and reworking losses
6. Yield losses

These six losses determine the effectiveness of the overall equipment. This effectiveness is an indicator of how machines, production lines, and processes perform when it comes to availability, quality and performance (Rausand, 2004). This thesis will focus on RCM, therefore TPM is explained only shortly.

RCM is a systematic process integrating Preventive Maintenance (PM), Predictive Testing and Inspection (PT&I), reactive maintenance, and proactive maintenance to better probability that a machine or component will function in the required way over its planned life cycle with a minimum amount of maintenance and downtime. This approach aims to reduce the Life Cycle Cost (LCC) of an installation to a minimum while allowing the installation to function as intended, meeting the required levels of reliability and availability. The basic steps of the RCM process are defined in following continuous block process (Figure 14.) (Moubray, 1997):

Figure 14. The basic steps of the RCM process (Moubray, 1997)

4.1. Definition and history

Maintenance process has changed over the years in terms of increased complexity of systems and developed maintenance techniques. RCM is a result of the process evolving as a reliable method for maintenance planning. RCM method is in use to control planning and executing maintenance process (J. Moubray, 1997:1). The RCM method is defined by Rausand and Vatn (2008:79) as:

> *"A systematic approach for identifying effective and efficient preventive maintenance tasks for items in accordance with a specific set of procedures and for establishing intervals between maintenance tasks". (Rausand & Vatn, 2008:79)*

Origins of the RCM are in the aircraft industry in the 1960's. By the late 1950s, the cost of maintenance activities in this industry became high enough to permit a special investigation of the effectiveness. Henceforth, a task force formed consisting of representatives of the airlines and the FAA (Federal Aviation Administration) to investigate the capabilities of PM in the 1960s. Foundings of the task force led to the development of a series of guidelines for aircraft manufacturers to use. (NASA, 2000)

In 1974, the US Department of Defense commissioned United Airlines to make a report of the used processes in the civil aviation industry, which to help the development of maintenance programs for aircraft (Mainsaver, 2018:1-2). Authors Stan Nowlan and Howard Heap published the report in 1978, entitled Reliability Maintenance, which became the report that all subsequent RCM approaches have been based on. Mr's Nowlan and Heap found many types of failures, which some of them could not be prevented even maintenance activities are as intensive as possible (Nowlan & Heap, 1978:3-4; Mainsaver, 2018:2-3).

It was also discovered that for multiple items the chance of failure did not increase with age (Nowlan & Heap, 1978:43-44). Consequently, a maintenance program based on age will have little, if any effect on the failure rate with the age-reliability patterns (NASA, 2000). This will be further explained in the chapter 4.4.7 especially with figure 25. Later RCM adjusted to several other industries and military branches (Rausand & Vatn, 2008:80). Maintenance generations are defined and explained in the following block process (Figure 15.) by Moubray (1997:1-3):

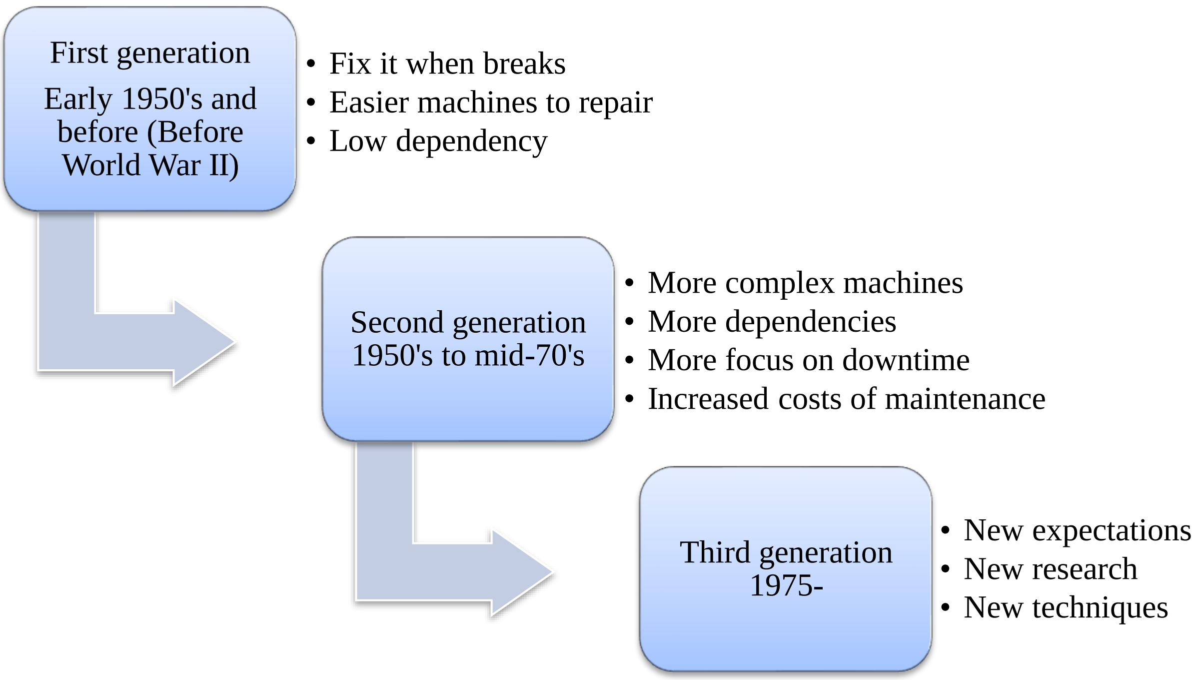


Figure 15. Maintenance generations illustration by Moubray (1997:1-3)

Through the ages, the method of RCM has developed, and there exist several theories about RCM. Common aim for the different theories is to develop optimized maintenance strategy and plan (Moubray, 1997:33). Creating a maintenance strategy reduces costs, and the focus is on maintaining the functions of the systems or assets (Moubray, 1997:312).

4.2. Standards

There are different types of maintenance standards, which are intended for different purposes. It appears that there are almost as many product and process variations as there are individual structures (Marsh, 2010:19). Therefore, formulating industry standards and qualification routes could be difficult. However, in this thesis, the focus is on the following standards and guidelines, since the original documents need to be presented for officials when the maintenance process is executed in other ways than in manual that is following official standards and guidelines. There are two standards that are most commonly followed when executing the RCM process: IEC 60300-3-11 and SAE JA1011.

4.2.1. IEC 60300-3-11

IEC 60300-3-11:2009 for dependability management. This standard is an application guide for the development of failure management policies for equipment and structures using RCM analysis techniques (NSAI Standards, 2009). IEC 60300-3-11 is an extension of standards IEC 60300-3-10, IEC 60300-3-12 and IEC 60300-3-14. Maintenance activities are recommended to follow all three standards, which relate to PM and could be implemented using IEC 60300-3-11 standard. The standard is limited to the application of RCM techniques, and it does not include maintenance support aspects, which are covered by standards mentioned above or other dependability and safety standards. (Finnish Electrotechnical Standards Association (SFS), 2001:46)

According to standard IEC 60300-3-11, normative structures of maintenance program development trails the following instructions (Finnish Electrotechnical Standards Association (SFS), 2001:47):

- Structures are classified into one of two categories, depending on the consequences of their failure on safety: Primary category includes a structurally significant item (SSI) that has any detail, element or assembly, which contributes significantly to carry operating, aerodynamic, gravity, ground, hydrodynamic, pressure or control loads, and whose failure could affect the safety critical structure of the equipment and structures; secondary category is another structure, which is judged not to be a structurally significant item. Both defined externally and internally within specified zonal boundaries.
- The aim for the maintenance of the scheduled structures is dependent on the design philosophy of the member being analyzed: safe life or damage-tolerant. The principal objective for a safe life structural member is to prevent the first failure. The principal objective for a damage-tolerant member is to detect incipient failures. SSIs are always safety critical because the major load-carrying element failures will have a direct disadvantageous on safety. A separate logic is followed for SSIs. Therefore, this logic identifies structural inspection requirements, based on whether the SSI design philosophy is safe life or damage-tolerant.

Safe life structural members have a safe usable life. A single failure with this type of structure can be catastrophic. Safety is achieved in two ways: by building the structure with a large margin of strength above the expected loads; or by limiting the structure usage to a “safe life”, which is less than the time it was tested in the laboratory. A failure symptom cannot be detected, e.g. the crack propagation rate is too fast to allow for multiple inspections before failure. For these reasons, safe life structural members are replaced or modified before the age that failures are expected to occur. (Finnish Electrotechnical Standards Association (SFS), 2001:47)

The damage-tolerant design concept requires the following two rules, which are needed to take into account: (1) Fail safe – when one or more elements crack or fail completely, the rest of the structure should be capable of withstanding a given static load; and (2)

Slow crack growth – the rate at which a fatigue crack in an element grows should be slow enough to give a sufficient period of time for detection before it reaches a critical crack length. After a single primary structural failure, the equipment should withstand 80% of its design loading without catastrophic failure. Reliability for a damage-tolerant structure is achieved by (1) using multiple paths, safety assured by preserving the capability of load carrying through redundancy; (2) choosing materials that exhibit slow crack growth, safety assured by the ability for inspecting and discovering damage before complete failure; and (3) using a crack-arresting design, cracks are inhibited from reaching a critical size. (Finnish Electrotechnical Standards Association (SFS), 2001:49)

The assessment of structure should consider the following damage sources (Figure 16.) for the selection of maintenance tasks. Damage sources are divided into three different categories: Accidental and fatigue damages, and environmental deterioration.

Damage sources		
Accidental damage (AD)	Environmental deterioration (ED)	Fatigue damage (FD)

• Random discrete event
• Can reduce the inherent level of residual strength
• Sources of such damage can include:
  • Maintenance and servicing equipment
  • Erosion from rain, hail, lightning etc.
  • Debris
  • Human error during equipment manufacturing, operation or maintenance
	• Structural deterioration caused by an adverse environment
	• Assesments required to cover corrosion, stress corrosion and deterioration of non-metallic materials
	• Corrosion can be result from a breakdown with age or randomly occuring discrete event - can or cannot be time or usage dependent
	• Stress corrosion cracking primarly caused by heat treatment, forming, welding, machining, installation, fit up or misalignment
		• Initiation of a crack or cracks due to cyclic loading and subsequent propagation
		• Cumulative process with respect to equipment operating hours or cycles
		• May be affected by irradiation

Figure 16. Damage sources of structures in maintenance program development (Finnish Electrotechnical Standards Association (SFS), 2001:49)

Structural inspection program procedure consists of 21 different factos (from “a” to “u”), described by a series of process steps (P1, P2, P3, etc.) and decision steps (D1, D2, D3, etc.) as follows (Finnish Electrotechnical Standards Association (SFS), 2001:51-53):

a. The structural maintenance program includes all equipment structure. (P1) The designer subdivides them into items.
b. (D1) The designer categorizes each item as a (P2) SSI or (P3) other structure, using the basis of the consequences of item failure or malfunction on equipment safety.
c. (P3) Comparing items, which are categorized as other structure, (D2) to similar structural items on existing equipment and structure. (P4) Developing maintenance recommendations with the knowledge of personnel that has operating experience and good judgment, together with accurate data for similar items. Also considering (P5) designer’s advice for the items that are not similar to others (e.g. new materials and design concepts). (P4) All selected tasks are included in the (P8) preliminary maintenance plan.
d. Repeating the steps “a” to “c” until all structural items are categorized.
e. (P6) Determining inspection requirements for timely detection of AD or ED for all SSIs. These are all divided as individual SSIs or SSI-groups, which are each suitable for comparative assessments based on their location, inspection access, boundaries, analysis breakdown, etc.
f. (P7) Determining inspection requirements with the designer’s rating systems to assure timely detection of AD, corrosion and stress corrosion, for all SSIs.
g. Including all selected inspection tasks to (P8) preliminary maintenance plan.
h. Requirements for assuring timely detection or prevention of FD to all SSIs are also determined by using the Logic Tree Analysis (LTA). This step is the beginning of the third decision (D3).
i. (D3) Categorizing each SSI as damage-tolerant or safe life by the designer.
j. (P9) The designer determines the safe life limit for all the items categorized as safe life, with a description of the SSI, in the equipment safe operation limitations manual. (P10) Scheduled fatigue related inspection program is not required to assure continuous safe operations.

k. (P11) Remaining SSIs are damage tolerant. (D4) The designer determines if timely detection of fatigue damage is dependent on scheduled inspections.
l. (P12, P10) SSI design does not require a scheduled fatigue related inspection program to carry the required load with the damage that will be readily detectable during routine operation of the equipment or is indicated by a safe function failure.
m. The scheduled inspection program is required for the remaining SSIs, to assure timely detection of FD. (D5) Determination, if scheduled fatigue related SSI inspections are required, is estimated by the designer.
n. (D6, D7) Proper inspection tasks are determined when scheduled fatigue related inspections are required, e.g. can FD be detected by (D6) visual inspections or by (D7) Non-Destructive Inspection (NDI) at practical intervals. Tasks are generally based on the designer's damage tolerance evaluation, where the timing and order for determining the fatigue inspection tasks will mainly depend on the availability of the required technical data. In some industries, by industry-wide steering committees and appropriate regulatory authorities, the schedule for completing the FD detection evaluations may be subject to approval.
o. (D6) Providing the necessary fatigue damage detection opportunities are performed, when applicable and effective, by visual inspections during proper scheduled maintenance checks.
p. (D7) In addition, providing necessary fatigue damage detection opportunities when visual inspections are inadequate during proper scheduled maintenance checks, applicable NDI methods are used.
q. (P13) If practical and effective visual and/or NDIs are not available, improved inspection access and/or SSIs redesign could be required. The SSI should be categorized as safe life if the designer does not find this action feasible.
r. (D8) Together with accurate data, knowledgeable personnel use good judgment and operating experience to review the details of the fatigue inspection requirements to determine if the details are feasible. D8 procedure in P13 is used if visual inspection and/or NDI is not feasible.
s. (P8) The preliminary maintenance plan includes selected fatigue inspection requirements.
t. The FD analysis procedure is repeated for all SSIs

u. (P14) Inspection tasks from AD, ED and FD analyses are overlaid and consolidated. Reviewing, approving and including the resulting inspection requirements for all SSIs and the maintenance tasks for other structure in the maintenance program proposal.

4.2.2. SAE JA1011

Society of Automotive Engineers, SAE International, is a classification society that has created a standard JA1011, which consist of evaluation criteria for RCM processes. This SAE standard for RCM is intended for use by any organization that has or makes use of physical assets or systems, which the organization wishes to manage responsibly (SAE international, 2009).

Standard JA1011 contains requirements for a process, to be called as RCM process. These requirements can be summarized in the following seven questions that need to be answered satisfactorily to reach the RCM process title (SAE international, 2009):

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

SAE JA1011 addresses specifics for every one of these seven basic questions. Answers for the previous questions (SAE international, 2009):

1. The operating context of the asset need to be defined, all the functions of the system need to be identified (incl. primary and secondary), all function statements needs to contain a verb, an object, and a performance standard, and performance

standards in function statements needs to be on the level of performance desired by the owner or user of the system in its operating context.

2. With the functional failures, all the failed states associated with each function need to be identified.
3. All failure modes reasonably likely to cause each functional failure should be identified. The method is used to decide what constitutes a “reasonably likely” failure mode should be acceptable to the owner or user of the asset. Also, the failure modes have to be identified at a level of causation, which makes it possible to identify an appropriate failure management policy. In addition, the lists of failure modes need to include failure modes that have (1) happened before; are (2) being prevented by existing maintenance programs currently; and those that (3) have not yet happened but that are thought to be reasonably likely in the operating context. 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, except a human error is addressed by analytical processes apart from RCM, should also include in the lists of failure modes.
4. Failure effects should describe what would happen if no specific task is executed to anticipate, prevent, or detect the failure. Failure effects includes all the needed information to support the evaluation of consequences of the failure, such as: (1) evidence (if any) that the failure occurred (if hidden functions – what happens when multiple failures occurred); (2) what it does (if anything) to injure or even kill someone, or to have an adverse effect on the environment; (3) what it does (if anything) to have an adverse effect on production or operations; (4) physical damage (if any) is caused by the failure; what must be done (if anything) to restore the function of the system after the failure.
5. The consequences of every failure mode should be formally categorized, where the categorization process separates hidden failure from evident failure modes. The consequence categorization process should clearly distinguish events that have safety and/or environmental consequences from those that only have economic consequences (operation and non-operational). The assessment of failure consequences should be carried out as if no specific task is currently being done to anticipate, prevent, or detect the failure.

6. The failure management selection process should consider that the conditional probability of some failure modes will increase with age, or exposure to stress, for others the conditional probability will not change, or it could even decrease with age. All scheduled tasks should be technically feasible and worth doing (i.e. applicable and effective). How this requirement will be satisfied is set out in the next (7^{th}) paragraph. When there are more than two proposed failure management policies that are applicable and effective, the most cost-effective policy is going to be selected. The selection of failure management policies should be carried out as if no specific task is under work to anticipate, prevent or detect the failure.
7. Failure management policies for all scheduled tasks should comply with the following criteria. In the case of (1) an evident failure mode that has safety or environmental consequences, the task reduces the probability of the failure mode to a level that is tolerable to the owner or user of the asset; (2) a hidden failure mode where the associated multiple failures have safety or environmental consequences and the task 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) an evident failure mode that does not have safety or environmental consequences, the direct and indirect costs of doing the task should be less than the direct and indirect costs of the failure mode when measured over comparable periods of time; (4) a hidden failure mode where the associated multiple failures does not have safety or environmental consequences, the direct and indirect costs of doing the task should be less than the direct and indirect costs of the multiple failure with the cost of repairing the hidden failure mode when measured over comparable periods of time.

On-condition tasks are defined in the standard SAE JA1011. Any on-condition, predictive, condition-based or condition monitoring task that is selected should meet with additional criteria, such as: (1) existing a clearly defined potential failure; (2) existing an identifiable P-F interval (potential-to-functional failure) or failure development period; (3) the task interval should be less than the shortest likely P-F interval; (4) it should be physically possible to do the task at intervals less than the P-F interval; and also (5) the shortest time between the discovery of a potential failure and the occurrence of the functional failure (the P-F interval without the task interval) should be long enough for predetermined action to be taken to avoid, eliminate, or minimize the consequences of the failure mode. In addition, scheduled discard tasks, scheduled restoration tasks, and failure-finding tasks are handled in the JA1011 standards in the on-condition task list. (SAE international, 2009)

JA1011 standard also deals with failure management policies – One-time changes and RTF policies. SAE JA1011 is considered as a living program since the standard recognizes that “a lot of the data used in the initial analysis are inherently imprecise and that more precise data will become available in time”. It also states that “the way in which the asset is used, together with associated performance expectations, will also change with time, and that the maintenance technology continues to evolve”. Any of the used mathematical and statistical formulae in the application of the process should be logically robust, available and approved by the owner (or user) of the asset. (SAE international, 2009)

4.3. RCM principles

There are four main principles known as pillars for RCM philosophy (Smith & Hinchcliffe, 2004:66-69). Any maintenance analysis process to be labeled RCM must contain all the following four pillars:

1. Preserve system function. The most important feature of RCM. Enables user to systematically decide what equipment relates to what functions in later stages of the process. Every item of equipment is not equally important. Answers to the questions: what to maintain and how to do it? (Smith & Hinchcliffe, 2004:67).
2. Identify failure modes that can defeat the functions. Functional failures are different sizes and shapes, and it is not always simple to know if there is a failure or not. Answers to the question: which specific failure modes in the hardware could potentially produce the unwanted functional failures? (Smith & Hinchcliffe, 2004:67).
3. Prioritize function need via failure modes. All functions are not created equal, which means all functional failures and their related components and failure

modes are not created equal. Preparing a plan for carrying out the identified maintenance tasks at optimal intervals and evaluating all the founded tasks with cost-benefit analysis (CBA) helps to prioritize. Timing is important in the efficient process (Rausand & Vatn, 2008:80). Answers to the question: what priority customer wishes to assign in allocating budgets and resources? (Smith & Hinchcliffe, 2004:68).

4. Select appropriate and effective PM tasks for high priority failure modes. An outcome of first three RCM pillars formulates a systematic road map which illustrates where (component), what (failure mode), and the priority that is used to proceed to establish specific PM tasks. All the potential PM tasks in the RCM process need to be judged as appropriate and effective. (Smith & Hinchcliffe, 2004:68-69).

Major advantages of the RCM analysis are a traceable and structured approach to determine the optimal type of preventive maintenance (PM). Optimal PM achieved through a detailed analysis of failure modes and failure causes. Although the main objective of RCM is to determine PM, the results from the analysis can also be used in relation to corrective maintenance strategies, spare part optimization, and logistic consideration. RCM also has a vital role in overall system safety management. (Rausand & Vatn, 2008:79; Moubray, 1997:102).

Moubray (1997:102) states that the RCM process stipulates if failure could affect safety or the environment, and therefore it needs to be prevented. Failure modes that have safety or environmental consequences are only worth doing a proactive task if it reduces the probability of the failure to a tolerably low level (Moubray, 1997:102). When properly conducted, the RCM analysis process should answer the following seven questions (Rausand & Vatn, 2008:79-80; Moubray, 1997:7):

1. What are the system functions and the associated performance standards?
2. How the system would fail to fulfill these functions?
3. What may be the cause of a functional failure?
4. If a failure occurs, what will happen?
5. What are the consequences after the failure occurs?

6. How to notice and then avoid the failure?
7. What should do when cannot found a suitable preventive task?

The main objectives to get of an RCM analysis process are (1) effective maintenance tasks identified; (2) these tasks evaluated by some CBA; and (3) a plan for carrying out the identified maintenance tasks at optimal intervals prepared (Rausand & Vatn, 2008:80).

4.4. RCM procedures

Carrying out the RCM procedures, there is a certain sequence of activities to take care of. Some of the activities, in other words, steps, overlap in time sequence. The steps are used to define the required information to finalize the maintenance programming. These steps provide a baseline definition of preferred PM tasks on each system and they are explained in more details in the following subsections. The seven RCM steps to describe the systematic approach are defined in the following process flow chart (Figure 17.) (Nowlan & Heap, 1978:6-9; Smith & Hinchcliffe, 2004:337; Hoseinie & Kumar, 2016:26):

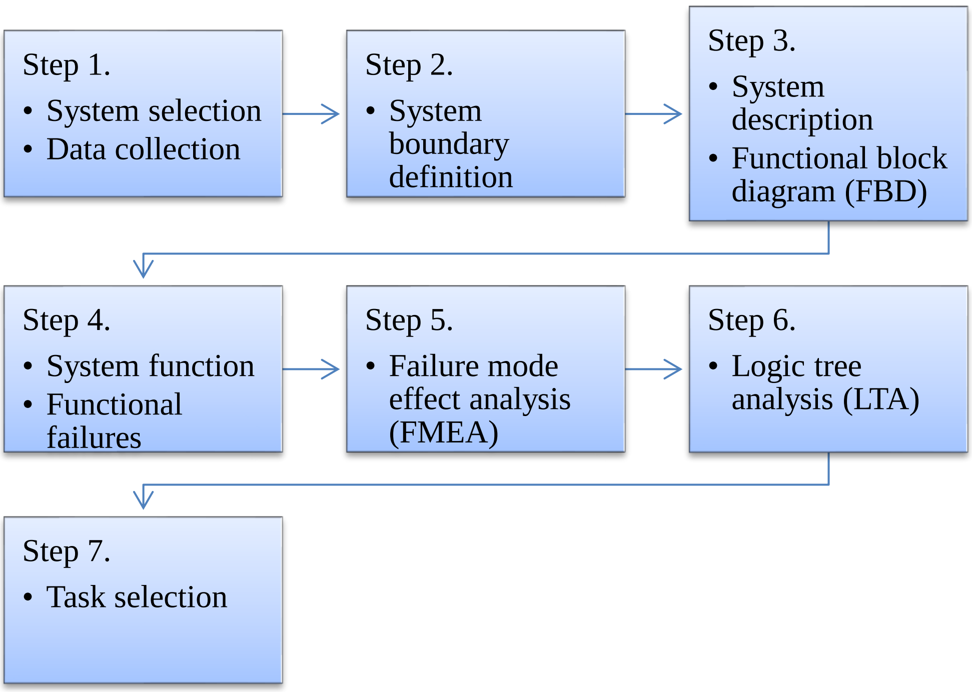


Figure 17. RCM process procedures (Hoseinie & Kumar, 2016:26)

4.4.1. Step 1: System selection and data collection

A level where component, system or plant should be conducted in the analysis:

- Part or piece of a part should be conducted in the lowest level, where equipment is possible to disassemble without damaging or causing a destruction of the item. (Hoseinie & Kumar, 2016:26).
- Conducting components or black boxes; a grouping or collections of piece parts into some package that performs at least one significant function as a stand-alone item. In addition, groupings such as modules, circuit boards, and subassemblies, should be performed in the intermediate buildup levels between parts and components. (Hoseinie & Kumar, 2016:26)
- A system conducting as a logical grouping of components that performs a series of key functions that plant, or facility requires (Nowlan & Heap, 1978:7; Hoseinie & Kumar, 2016:26).
- When conducting plant or facility analysis, logical grouping of systems that function together to provide an output (e.g. electricity) or product (e.g. mineral, ore) by processing and manipulating various input raw materials and feedback (e.g. oil, LNG, water) (Hoseinie & Kumar, 2016:26).

Selection making if the entire plant or facility is not taking a part in the process: According to the research of Hoseinie and Kumar (2016), the most efficient and meaningful function list for RCM analysis is at the system level, when approaching PM planning from the point of view of function. The defining significance of functions and functional failures at the component level becomes difficult. Performing meaningful priority rankings of failure modes competing for limited PM resources is sometimes impossible. (Hoseinie & Kumar, 2016:27).

4.4.2. Step 2. System boundary definition

Precise system boundary definition is important in the RCM analysis process for two reasons: (1) there has to be precise knowledge of what has or has not been included in the system so an accurate list of components can be identified or, on the other hand, so that the identified components will not overlap with components in an adjacent system; (2) both system interfaces (IN and OUT) includes to boundary definition, as well as interactions that establish inputs and outputs of a system. An accurate definition of IN and OUT interfaces is a requirement for fulfilling the following steps 3 and 4. (Hoseinie & Kumar, 2016:27)

4.4.3. Step 3. System description and Functional Block Diagram

Purpose of system description and Functional Block Diagram (FBD) is to identify and document the systems essential details, which are required to perform the remaining steps in a thorough and technically correct method. RCM process step 3 must establish the five following details (Hoseinie & Kumar, 2016:29):

1. System description
2. Functional block diagram
3. IN/OUT interfaces
4. System work breakdown structure
5. Equipment history

In this point of the analysis, a lot of vital information is collected about how the system is composed and how does it operate (Hoseinie & Kumar, 2016:29). The aim is to get the process through the FBD, which is a top-level representation of the major functions performed by the system. That is why the blocks are labeled as functional subsystems. The block diagram is composed only of functions, which does not include components or equipment titles. The FBD is used for defining the failure as the inability to deliver the function (Narayan, 2004:189), where systems should be represented by five or less major functions (Smith & Hinchcliffe, 2004:90).

Smith & Hinchliffe (2004:139) states that the number of functional subsystems should be limited. In addition, the FBD together with the boundary overview provides a valuable description of the initial phase of the system analysis process. The best timing for this step is immediately after the system boundary overview. That is how reaching an early agreement, whether tackle the entire system or only some individual subsystems, is possible. (Smith & Hinchcliffe, 2004:139)

An engine and a power plant consist of many systems, sub-systems, and equipment items. These may be in series, parallel, or some combination of a reliability point of view. In a series system, failure of any component will result in a system failure. For example, in the following chart (Figure 18.) all three components (A, B and C) must work for the system to work. The figure is represented in Boolean notation by using AND gates to link the components. For example, in a functioning engine: A could be a piston, B - cooling system, and C could be oil pump. (Smith & Hinchcliffe, 2004:90, Hoseinie & Kumar, 2016:30)

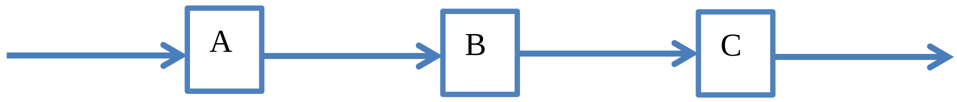


Figure 18. Reliability Block Diagram of a series system

To function properly, engines pistons, cooling system, and oil pumps need to be in good shape. Making simplifying assumption that each of the systems' failures represented by an exponential distribution, the overall engine reliability is the outcome of the individual systems' reliability. (Narayan, 2004:13-14)

When the number of components in series increases, the system reliability falls. Therefore, complex systems might be unreliable. Some components could be very reliable, but the overall system weakens when there are plenty of different components. Not just weakening the productivity level, but also becoming dangerous in the worst-case scenario. So-called KISS (keep it simple, stupid) principle should not be forgotten in terms of the reliability block diagram (RBD). (Narayan, 2004:14)

In addition to the series system, RBD may be utilized with parallel elements as well. For example, in the following chart (Figure 19.) components (A, B and C) are in the parallel relation. In the parallel case, only one of the components (A, B or C) needs to work for the system to be effective. This type of arrangement works with for example fire detection systems with voting logic, and standby equipment in a one out of two (1oo2) or two out of three (2oo3) or similar configuration. The figure is represented in Boolean notation by using OR gates to link the components. (Narayan, 2004:14)

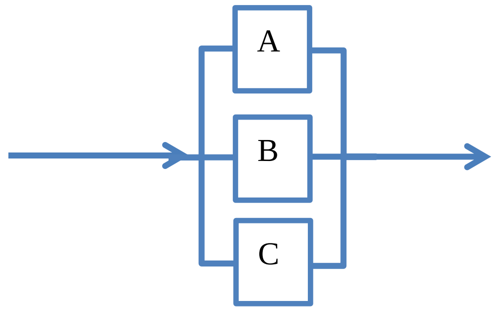


Figure 19. Reliability Block Diagram of a parallel system

Contrastingly to RBD in series elements, with parallel elements, the system reliability increases rapidly with the level of redundancy. With the high level of redundancy is possible to tolerate low component reliability levels. Each of the blocks represents the individual system that determines how effective the whole plant will be in meeting its functional objectives, in terms of the configuration reliability and capacity rating. Certain systems are more critical than others, since the impact of the loss of function may be bigger than some other systems. (Hoseinie & Kumar, 2016:29-30)

4.4.4. Step 4. System functions and functional failures

RCM system functions and performance standards for functional failures consists of two steps: (1) functions and associated performance standards of the asset in its present operating context, and (2) ways that the system can fail to fulfill its functions.

First step: Functions and associated performance standards of the asset in its present operating context. SAE international (2011) lists four key concepts about the functions for the system or asset:

- Operating Context
- Primary and secondary functions
- Function statement
- Performance standard

The operating context transacts with the environment, which under the asset or system are supposed to operate. The operating context will affect the analysis further, so it should be as specific as possible. Every asset or system has its own intended function, the reason for its existence.

The functions can be divided into two; primary and secondary functions (SAE International, 2011; Moubray, 1997:47). Primary functions are the main reason for the asset or system existence, and that is why those need to be defined as specific as possible. The secondary functions are the functions in addition to the primary functions. The secondary functions are usually not as easy to discover as the primary functions, since a list of secondary functions may result in a very long list. Therefore, should always consider the relevance of the listed functions according to the analysis. (Moubray, 1997:47-48)

Function statement is in use to describe the functions. Statement typically contains an object, a verb, and a performance standard (Moubray, 1997). An example of a functional statement would be following: maintain the piston in two hours. This example consists of an object the piston, a verb to maintain, and the performance standard is the time-period of two hours.

The performance standard states how the system should operate and what is required. The performance standard can be defined in two ways: desired performance, and built-in capability. It signifies what the owner wants it to do when the built-in capability stands for what it is (actually) capable to do.

Second step: Ways that the system can fail to fulfill its functions. After completing the first step, the second step takes place. SAE International (2011) defines functional failure as “a state in which a physical asset or system is unable to perform a specific function to a desired level of performance”. This definition means that the second step deals with failures of the functions that were stated in the first step. As the definition mentioned, functional failure is a state, but it does not answer how the functional failure occurred.

The second step is a part of the analysis that identifies all the possible states at which the asset or system failure. (SAE International, 2011)

The system may have a total failure, which indicates that the asset or system will not work at all. Another kind of failure state is a partial failure. These two scenarios are easier to understand through an example: When cylinder output of the LNG engine is 480kW, engine speed is 720rpm. This cylinder has two potential functional failures:

TOTAL FAILURE	PARTIAL FAILURE
→ Cylinder stops working	→ Cylinder is not working correctly
→ Engine speed is 0 rpm	→ Engine speed is under 720 rpm

The first functional failure represents a total failure of the cylinder, causing by small particles scoring surface, cylinder seizing, overheating, or the cylinder breaking in pieces. The second functional failure represents a partial failure that could be caused by very small particles scoring surface or light overheating.

4.4.5. Step 5. FMEA & FMECA

Identify failure modes that can defeat the functions. Combination of letters FMEA stands for Failure Mode and Effects Analysis. FMEA is a bottom-up (hardware) approach to risk assessment. It is an inductive analytical method, performed at either the functional or the piece-part level. Failure modes are the ways in which a process can fail. Effects in the analysis are the ways that these failures can lead to waste, defects or harmful outcomes for the customer. To clarify, the qualitative tool FMEA explores “what-if scenarios”, it is designed to identify, prioritize and limit these failure modes. In addition, it is closely related to tool FMECA. (Moubray, 1997:48-50)

An important task in FMEA is identifying known and potential failure modes (Narayan, 2004:190). With the help of data and knowledge of the process or equipment, each potential failure mode and effect is rated. There are three factors for rating these potential failure modes: (1) *Severity* is the consequence for the failure when it occurs; (2)

O*ccurrence* is the probability or frequency of the failure occurring; and (3) D*etection* defines the probability of the failure being detected before the impact of the effects is realized (Moubray, 1997:91; Hoseinie & Kumar, 2016:33).

Letter combination FMECA signifies Failure Mode, Effects and Criticality Analysis, which is a bottom-up (hardware) or top-down (functional) approach to risk assessment. FMECA consists of two activities: first, create the FMEA; then perform the Criticality Analysis. FMECA is inductive or data-driven, linking elements of the failure chain as an effect of failure (Quality-One, 2015). Both tools, FMEA and FMECA, identifies and then resolves the failure modes, which potentially causes product or process failures.

The effect of failure duplicates the experience of user/customer, and after is translated into the technical failure description or failure mode. The technical failure description introduces causes that result in the failure mode. (Narayan, 2004:189). Quality-One (2015) states that “each failure mode has a probability assigned and each cause has a failure rate assigned”. When data is not available, the probability of occurrence assigned as well. The failure data source -documents are the source for counting the probability, which are are all utilized in the FMECA. The technical failure description answers the question “why”, as well as introduces causes that result in the failure mode (Quality-One, 2015).

The intent of the FMECA methodology is to increase knowledge of risk and prevent failure. Performing FMECA, instead of only performing FMEA, takes a place when desire is to have more quantitative risk determination. The FMECA requires completing the FMEA process worksheet first and then completing the FMECA criticality worksheet. Worksheet divided in two parts as follows (Figure 20.) (Quality-One, 2015):

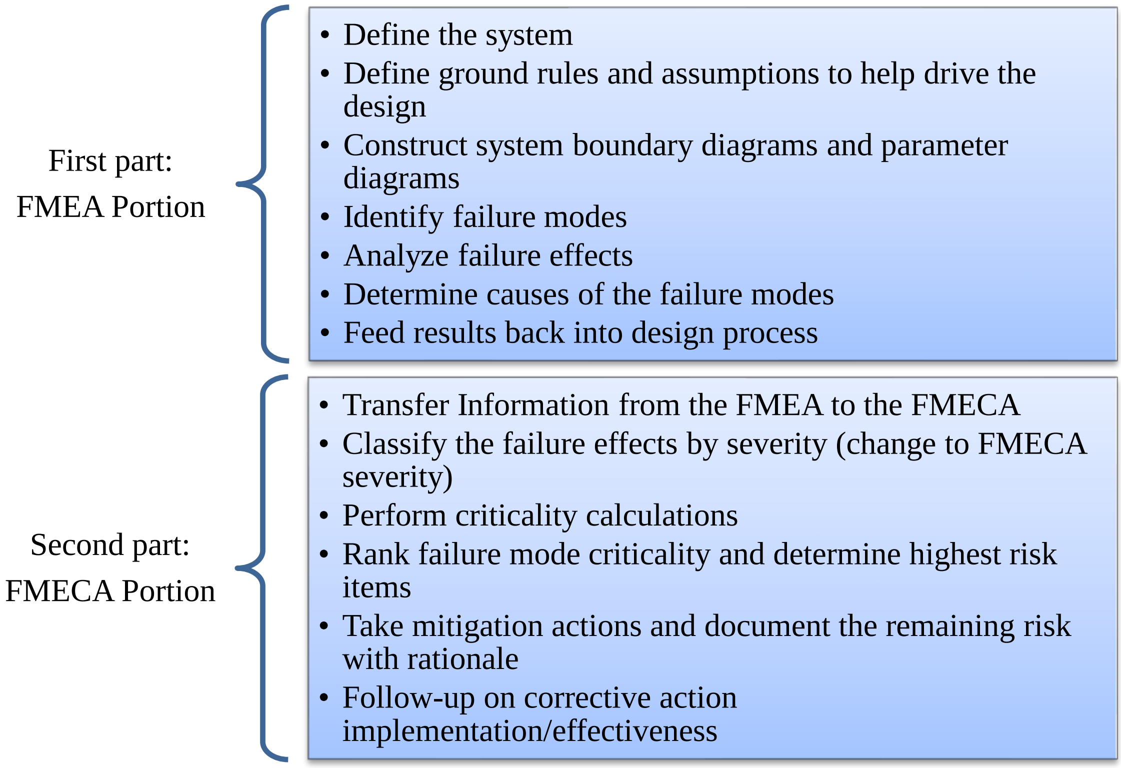


Figure 20. Two parts of FMECA worksheet (Quality-One, 2015)

After identifying functions for the asset or systems with its functional failures, the next step is to identify why the failures occur. FMECA is a tool of RCM analysis to identify those failures. FMECA analyzes risk, measured by criticality, which is a combination of severity and probability. By analyzing the risk, it is possible to act and thus provide an opportunity to reduce the possibility of failure. One of the most important objectives of FMECA is to identify the failure modes for the components in the system, the causes, and their effects. (Quality-One, 2015)

Procedures of the FMECA process is usually carried out in seven steps:

1. Plan and prepare
2. Carry out system breakdown and functional analysis
3. Identify failure modes and causes
4. Determine the consequences of the failure modes
5. Assess the risk
6. Suggest improvements
7. Report the analysis

Even though the procedures are performed on a component level, the effect of the failure is assessed on the asset. FMECA includes a unit of quantitative input taken from a source of known failure rates.

Executing FMECA process in practice, proceed as follows: (1) identify failure modes, including their causes; (2) asses the effects each of the failure modes has on the asset; (3) take care of criticality part, which includes safety, asset, availability, and environment; (4) include the MTBF (Mean Time Before Failure) for the components to the analysis, as well as MTTF (Mean Time to Failure). MTBF is used for repairable items, MTTF for non-repairable items. Consequently, MTBF is considered for both repairable and non-repairable components. (Quality-One, 2015)

The means for quantifying how important a system function is relative to the identified mission is provided by the criticality assesment. Following table (Table 1.) provides a method for ranking system criticality, with 10 categories of Criticality/Severity by NASA (2008). These categories can be explained or contracted to produce a site-specific listing. This system is adapted from the automotive industry (Pecht, 2009) and it is not the only method available.

Table 1. Criticality/Severity categories for failures (NASA, 2008)

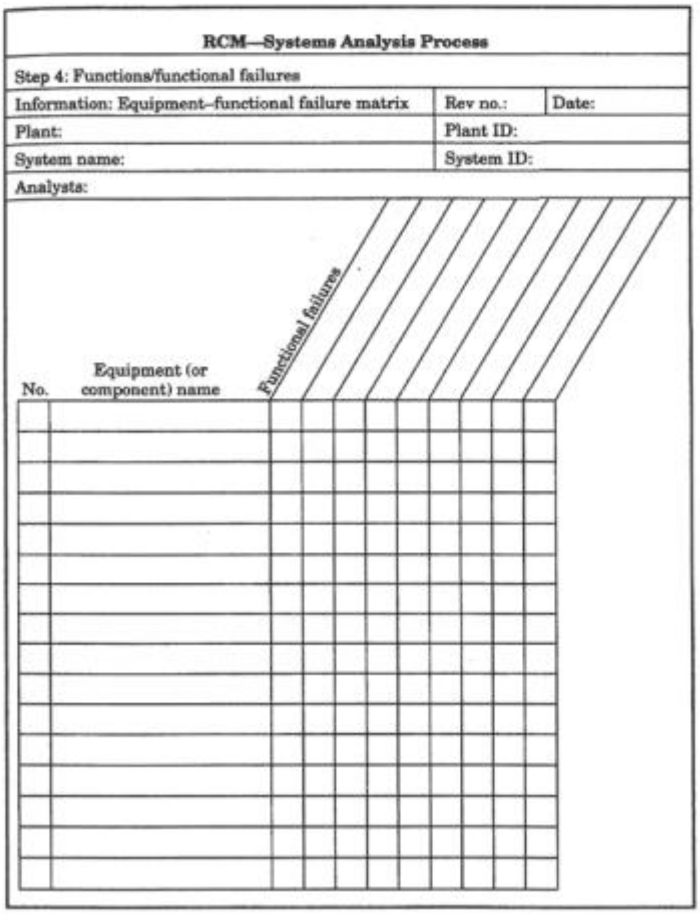
Ranking	Effect	Comment
1	None	No reason to expect failure to have any effect on safety, health, environment or mission.
2	Very Low	Minor disruption to facility function. Repair to failure can be accomplished during trouble call.
3	Low	Minor disruption to facility function. Repair to failure may be longer than trouble call but does not delay mission.
4	Low to Moderate	Moderate disruption to facility function. Some portion of mission may need to be reworked or process delayed.
5	Moderate	Moderate disruption to facility function. 100% of mission may need to be reworked or process delayed.
6	Moderate to High	Moderate disruption to facility function. Some portion of Mission is lost. Moderate delay in restoring function.
7	High	High disruption to facility function. Some portion of Mission is lost. Significant delay in restoring function.
8	Very High	High disruption to facility function. All of Mission is lost. Significant delay in restoring function.
9	Hazard	Potential Safety, Health, or Environmental issue. Failure will occur with warning.
10	Very Hazardous	Potential Safety, Health, or Environmental issue. Failure will occur without warning.

When finally turning the question of defining the required PM tasks, decisions are linked to these failure modes (Hoseinie & Kumar, 2016:34). This means that none of the failure modes leads to RCM without PM task (August, 2004:19). Failure modes are generally described in four or fewer words, and for clarifying things, the following list (Table 2.) of typical descriptors for failure modes demonstrates the used terms by Smith & Hinchcliffe (2004):

RCM-Systems Analysis Process (Figure 21.) is a typical form for equipment-functional failure matrix (Smith & Hinchcliffe, 2004). It is generally considered as “connecting tissue” between function and hardware. Vertical and horizontal elements are the component list based on Step 3 (chapter 4.4.3.), and the functional failure list based respectively on Step 4 (chapter 4.4.4.).

Table 2. List of typical descriptors for failure modes (Hoseinie & Kumar, 2016:34; Smith & Hinchcliffe, 2004)

abrasion	clogged	disintegrated	lack of...	overstress	shorted
arcing	collapsed	ductile	leak	overpressure	split
backward	cut	embrittlement	loose	overspeed	sticking
out of balance	contaminated	eroded	lost	pitted	torn
bent	corroded	exploded	melted	plugged	twisted
binding	cracked	false indication	missing	punctured	unbounded
blown	damaged	fatigue	nicked	ruptured	unstable
broken	defective	fluctuates	notched	scored	wrapped
buckled	delaminated	frayed	open	scratched	worn
burned	deteriorated	intermittent	overheat	separated	
chafed	disconnected	incorrect	over-temp	shattered	
chipped	dirty	jammed	overload	sheared	


RCM—Systems Analysis Process

Step 4: Functions/functional failures

Information: Equipment–functional failure matrix | Rev no.: | Date:

Plant: | Plant ID:

System name: | System ID:

Analysts:

No. | Equipment (or component) name | Functional failures

Figure 21. Equipment-functional failure matrix example (Smith & Hinchcliffe, 2004)

4.4.6. Step 6. Logic Tree Analysis

Logic (decision) Tree Analysis (LTA) prioritizes function need via failure modes. The decision tree structure is created to identify each failure mode in one of three distinct areas, so-called bins, in the basic LTA (Hoseinie & Kumar, 2016:34-35):

- Safety-related
- Outage-related
- Economics-related

Each failure mode is entered to the top box of the tree and then answers the questions. For example, in the normal course of the daily duties, does the operator know that something abnormal or harmful has occurred? The operator does not necessarily have to know exactly what is wrong, but the question is for establishing those so-called hidden failure modes. The traditional hidden failures occur in standby systems or components and are difficult to discover before it is too late. (Hoseinie & Kumar, 2016:35)

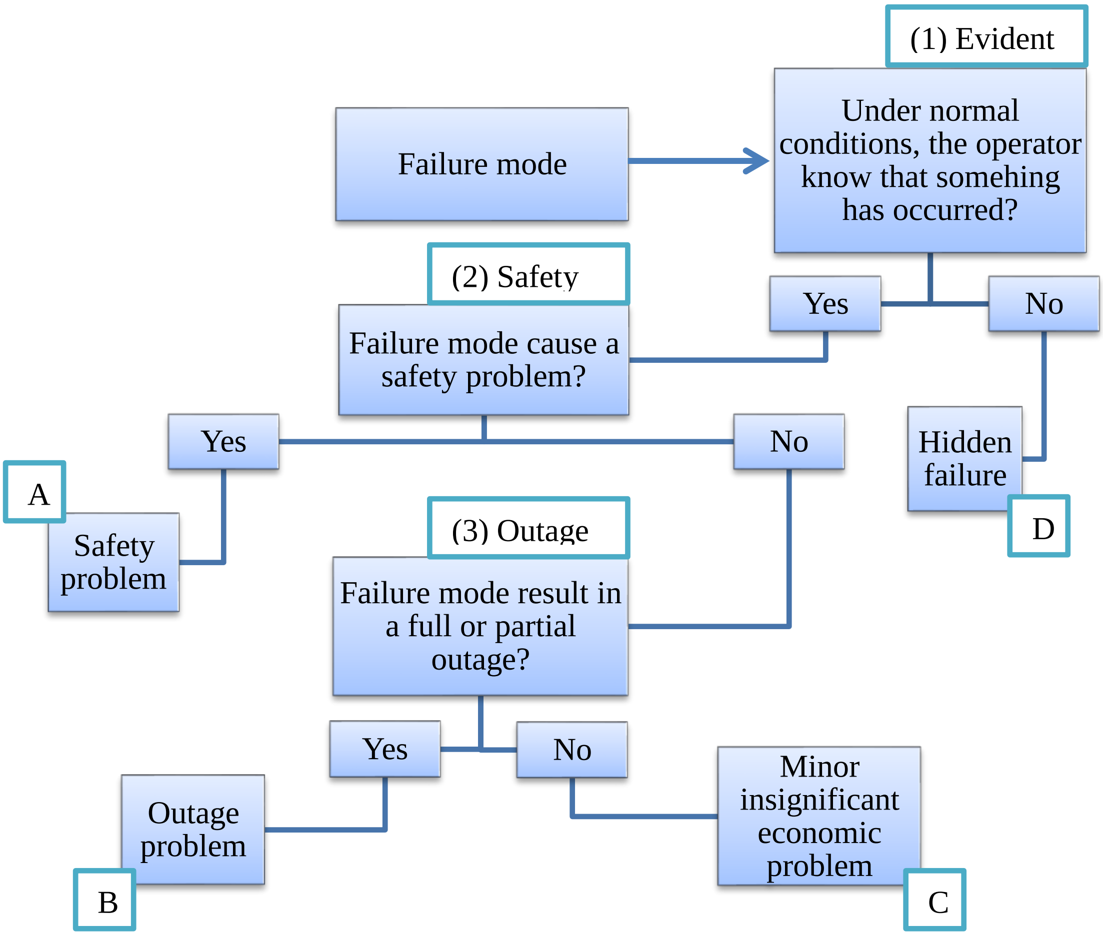


Figure 22. LTA structure (Rausand, 1998)

When all failure modes are identified, both evident and hidden, the second concern is whether these failure modes lead to a safety problem or not. Safety basically refers to person death or injury, either on-site or off-site. In basic RCM process definition of safety is limited to injury or death, even though equipment damage is sometimes included to safety part. (Hoseinie & Kumar, 2016:35)

If there is no safety issue, the remaining concern of interest is the economics of a facility. The economic issue is measured by focusing on facility failure or loss of productivity. Measuring whether the failure mode result is a full failure or partial failure, where the partial failure mode result, in a loss of output, would be for example >5%. The edge value of 5% depends on several variables, so the analyst should adjust this value to suit the situation. Meaning that answer “Yes” in question A moves the analysis to bin B, which represents outage and significant loss of income. If the answer to A is “No”, economic loss is small and places analysis to bin C. Bin C signifies that failure mode is tolerable until the next opportunity to restore the equipment to its full specified performance. Examples for C-type bin failure modes would be small leaks and degraded heat transfer. (Hoseinie & Kumar, 2016:35-36)

After finishing the LTA process, every failure mode is classified as A, B, C, D/A, D/B or D/C. The most common way to address PM priorities as follows (Hoseinie & Kumar, 2016:36):

1. A or D/A
2. B or D/B
3. C or D/C

The evidence is rather strong; therefore, the C-bin should be relegated to the run-to-failure (RTF) list. It is also recommended that all failure modes from C-bin would be designated as RTF and changed only if they do not pass the check in the final Step 7. In this type of case, only classifications A or B failure modes are passed on. (Hoseinie & Kumar, 2016:36)

Logic Tree is an effective way to screen maintenance tasks, which provides a consistent approach to the maintenance of all equipment. The following figure is an example of

RCM Logic Tree that NASA (2008) is implementing (Figure 23.) as a part of their RCM guide for facilities and collateral equipment.

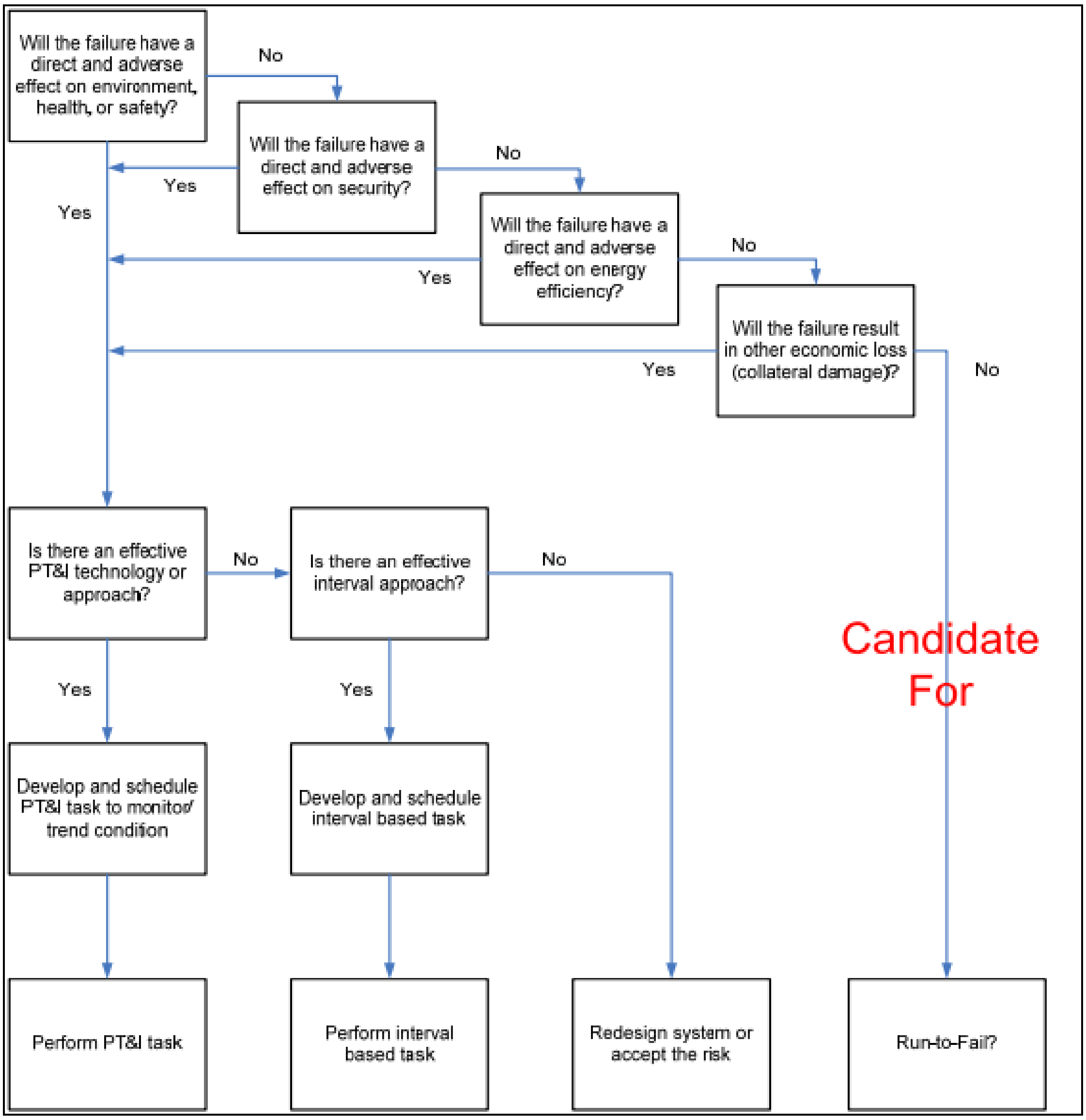


Figure 23. RCM tree logic by NASA (2008)

4.4.7. Step 7. Maintenance task selection

Select only applicable and effective PM tasks. PM task selection provides the maintenance solutions based on the, in the previous chapters mentioned, six steps. The RCM process requires each task to complete the effective and applicable test, which both has following requirements (Smith & Hinchliffe, 2004:242):

- Effective: the task is the most cost-effective option among the competing candidates
- Applicable: the task will prevent or mitigate the failure, detect an onset of failure, or discover a hidden failure

RTF is the only option if there is no applicable task, or in the situation where the cost of an applicable PM task exceeds the cumulative costs associated with failure. Exceptions are situations where design modification in A-bin or safety-related failure mode is mandatory. (Hoseinie & Kumar, 2016:36; Smith & Hinchliffe, 2004:155)

Maintenance staff should be involved in task selection to gain the benefit of their experience and to ensure their buy-in to the RCM process. This is especially relevant if predictive maintenance and performance monitoring options are introduced. Following flowchart (Figure 24.) of maintenance task selection in the RCM process is especially useful to develop PM tasks for each selected and targeted failure mode. (Hoseinie & Kumar, 2016:36)

Following task selection road map (Figure 24.) is defined by Smith & Hinchcliffe (2004:112), where the first question is about the age-reliability relationship. When the road map continues with “yes” or “partial” answers, following questions deal with time-dependent (T.D.), condition-dependent (C.D.), and failure-finding (F.F.) tasks. The result of the task selection road map is categorized into three different possibilities: (1) specify T.D./C.D./F.F. tasks; (2) accept failure risks; and (3) modification of the design.

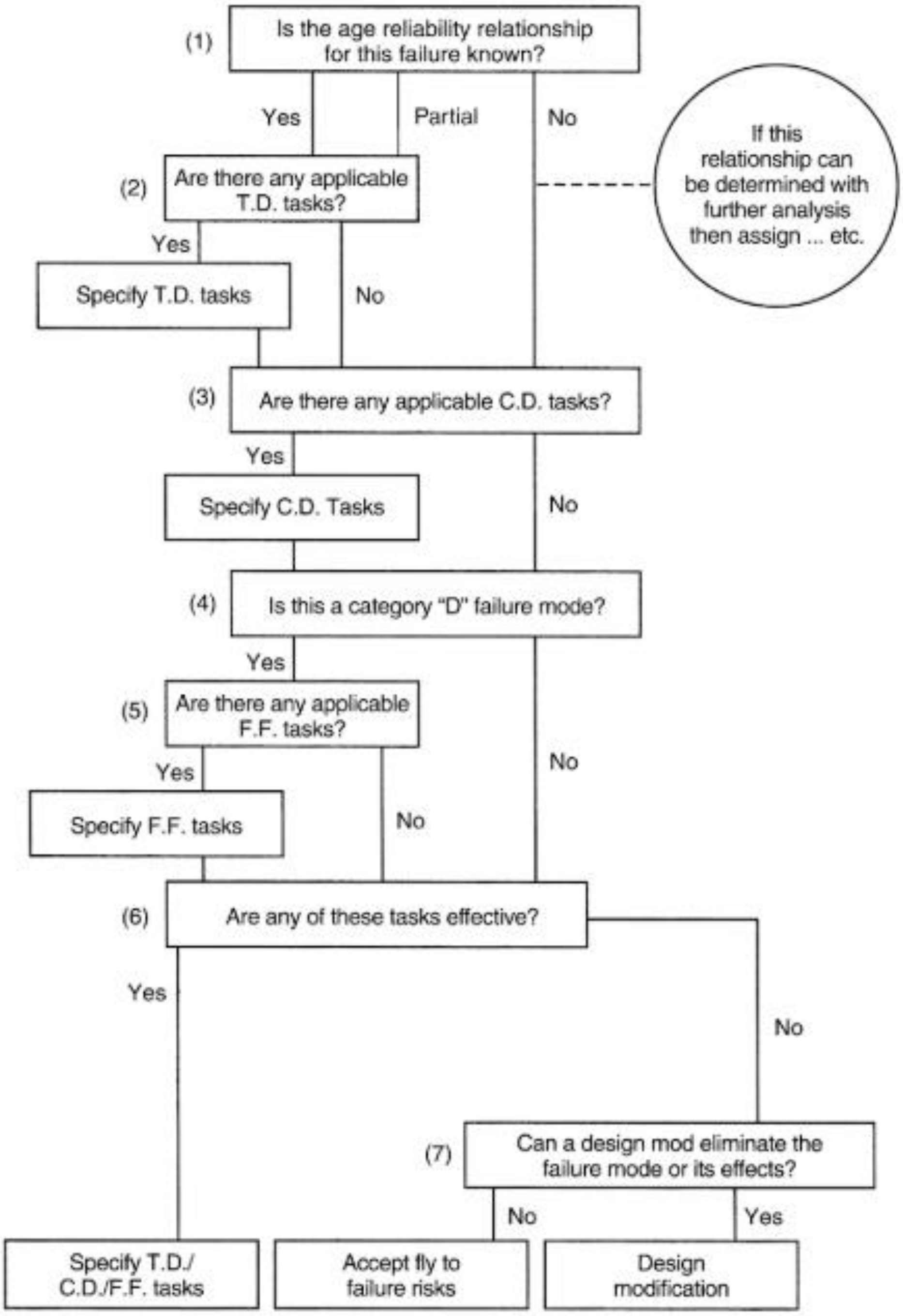


Figure 24. Task selection road map (Smith & Hinchliffe, 2004:112)

Nowlan & Heap (1978:46) discusses patterns of the age-reliability relationships, whether there are age-related effects in the failure rate or not. Statistics are collected from the United Airlines during the years (note: source is from the 1978 so its validity is not optimum). Study (Figure 25.) visualizes the age reliability relationship (Nowlan & Heap, 1978:46).

In the following chart (Figure 25.) of the age-reliability patterns, the vertical axis represents the conditional probability of failure and the horizontal axis represents operating age since manufacture, overhaul, or repair. The percentages indicate the percentage of items studied that well into each of the basic patterns. (Nowlan & Heap, 1978:46)

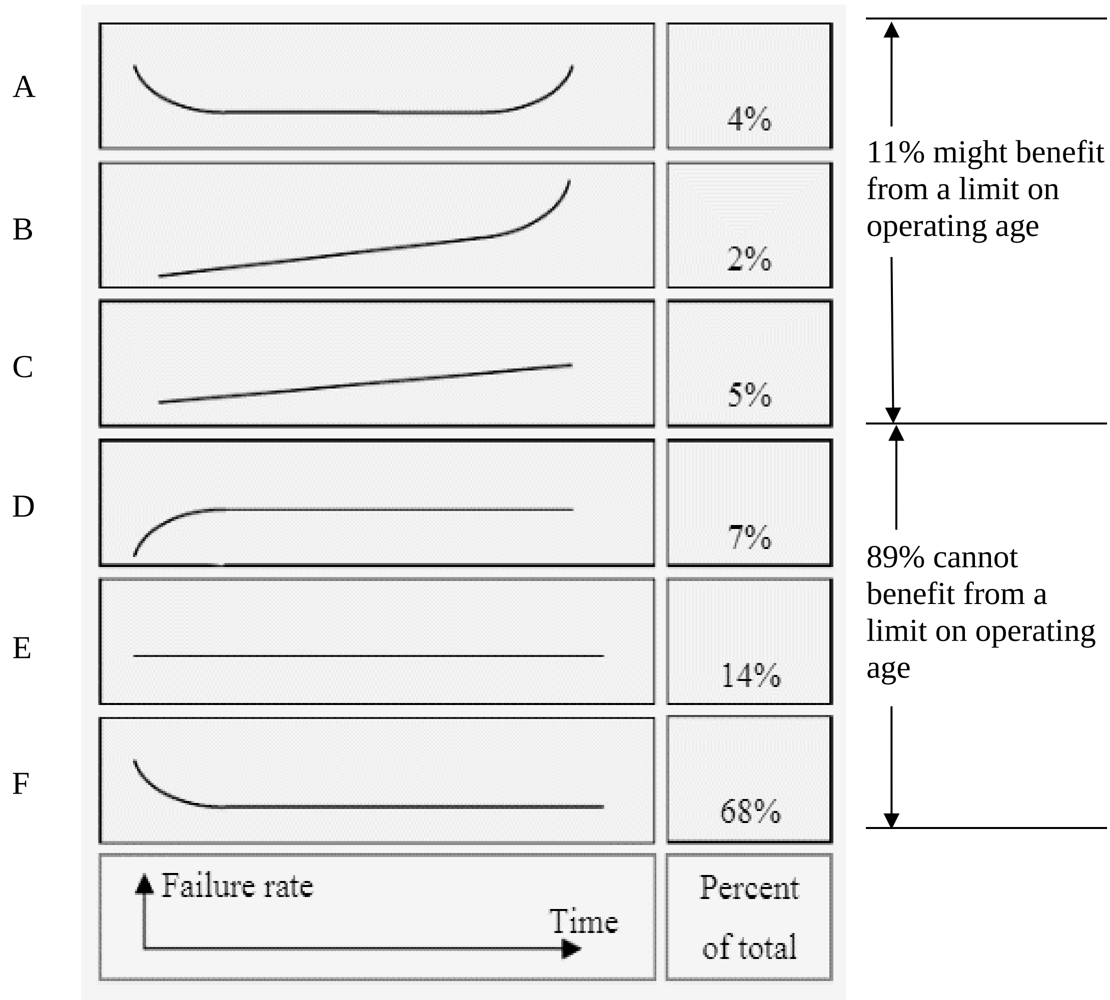


Figure 25. Age-reliability patterns as aircraft failure characteristics (Nowlan & Heap, 1978:46; Siddiqui, 2009:399)

Explaining the curves of the previous chart (Figure 25.) (Nowlan & Heap, 1978:46):

A. “The bathtub curve”: infant mortality, followed first by a constant or gradually increasing failure probability and then pronounced as a *wearout* region. Wearout defined as a situation in which a product can no longer be used because it has become damaged after having been used for a certain time (Cambridge dictionary, cited 11.12.2018). An age limit may be desirable, provided many units survive to the age which wearout begins.

B. Constant or gradually increasing failure probability: followed by a pronounced wearout region. Also, in curve B an age limit may be desirable (B curve is characteristic of aircraft reciprocating engines).
C. Gradually increasing failure probability: but with no identifiable wearout age. It is usually not desirable to impose an age limit in such cases (this curve is characteristic of aircraft turbine engines).
D. Low failure probability: when the item is new or just out of the shop, followed by a quick increase to a constant level.
E. Random: a constant probability of failure at all ages (exponential survival distribution).
F. Infant mortality: followed by a constant or very slowly increasing failure probability (particularly applicable to electronic equipment).

4.5. Fault Tree Analysis – Developing the RCM process

Fault Tree Analysis (FTA) is a tool for managing the RAMS. In this case, FTA is used for developing the RCM procedures by including the analysis. Instead of using traditional FMECA analysis as a risk assessment tool in the RCM process, FTA is one option for optimizing the RCM in practice. Modeling and making a risk analysis of complex systems with FTA is easier and more practical than with FMECA. For example, results of FMECA include only failure rate, not any costs of the failure nor how the failure modes are in relation with each other. FTA aims to improve the system most efficiently, by processing data into information and progressively to knowledge about these vital factors to make rational decisions. (Penttinen & Lehtinen, 2016:471)

Explicit understanding of risk related system quality attributes, such as reliability, availability, maintainability, and safety, are required to verify quality and to assess (identify, analyze & evaluate) the risks of the system. The alternatives can be compared in the design phase by creating and analyzing a model that describes the features of the system under design. The modeling enables predicting the overall effect of purposed modifications when taking already existing systems into account. The performance of the current system can be improved without any major modifications and investments by the maintenance spare part policy optimization. (Penttinen & Lehtinen, 2016:471-472)

The overall risk identification process (i.e. risk assessment) includes three different stages: risk identification, analysis, and evaluation (ISO Guide 73, 2009). ISO Guide 73 (2009) defines risk as an effect of uncertainty of objectives. Finding, recognizing and describing risks is the first step, which basically means collecting the available information to a comprehensive model. Risk analysis aims to comprehend the nature and to determine the risk level, which is done with stochastic (i.e. random) discrete event simulation of the model (Penttinen & Lehtinen, 2016:472). Risk evaluation compares the results with risk criteria to determine whether the risk and its magnitude are acceptable or tolerable (Penttinen & Lehtinen, 2016:472-473). Risk assessment process as a part of risk management and systems engineering is illustrated in the following chart of relations (Figure 26.).

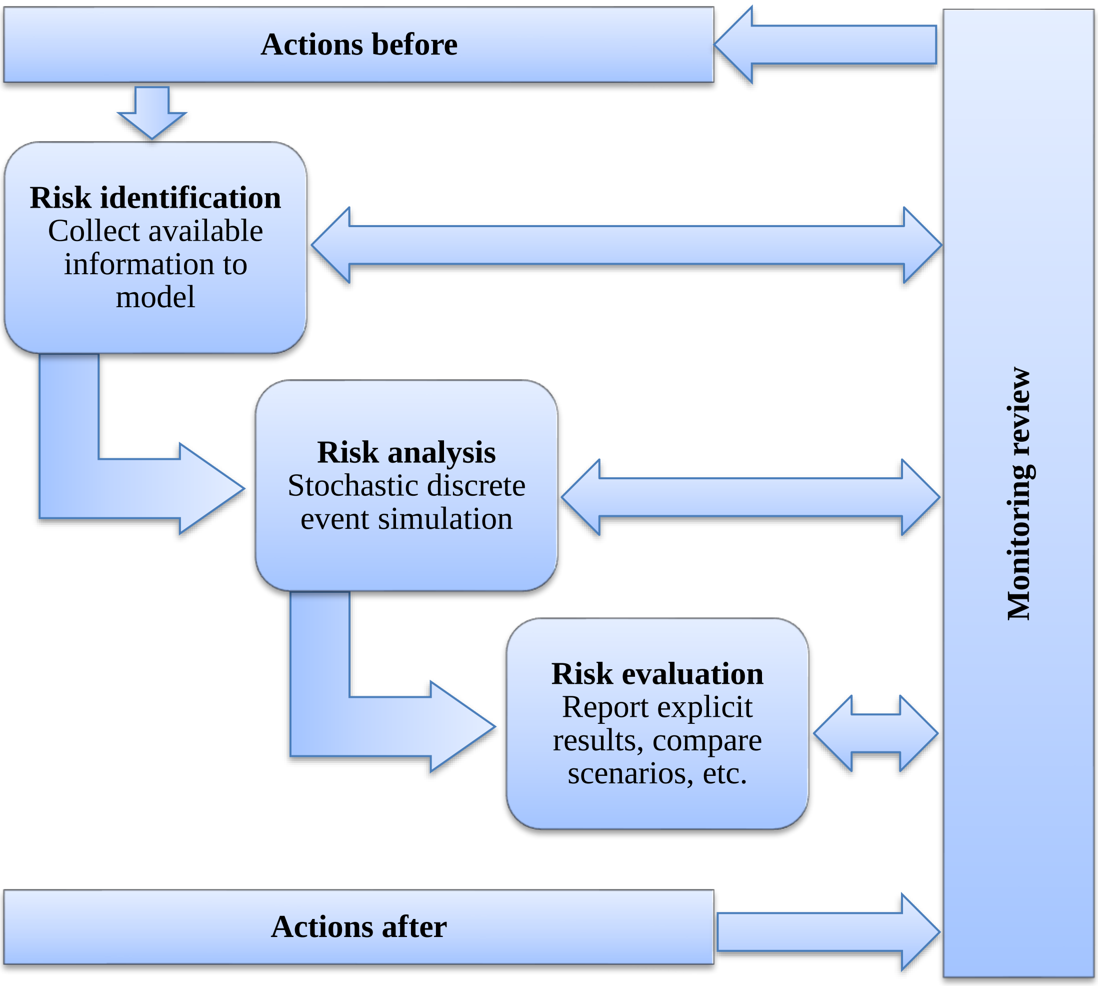


Figure 26. Risk management process (Penttinen & Lehtinen, 2016:473)

In addition, Smith & Hinchcliffe (2004:29) ponders if there are new procedures or modifications to existing procedures required. Rausand & Vatn (2008:80) adds five steps to the mentioned seven steps of RCM process (Figure 27.), where also occurs some changes in the time sequence. In addition, the structuring is slightly different than in the various standards, guidelines, and textbooks (Rausand & Vatn, 2008:80).

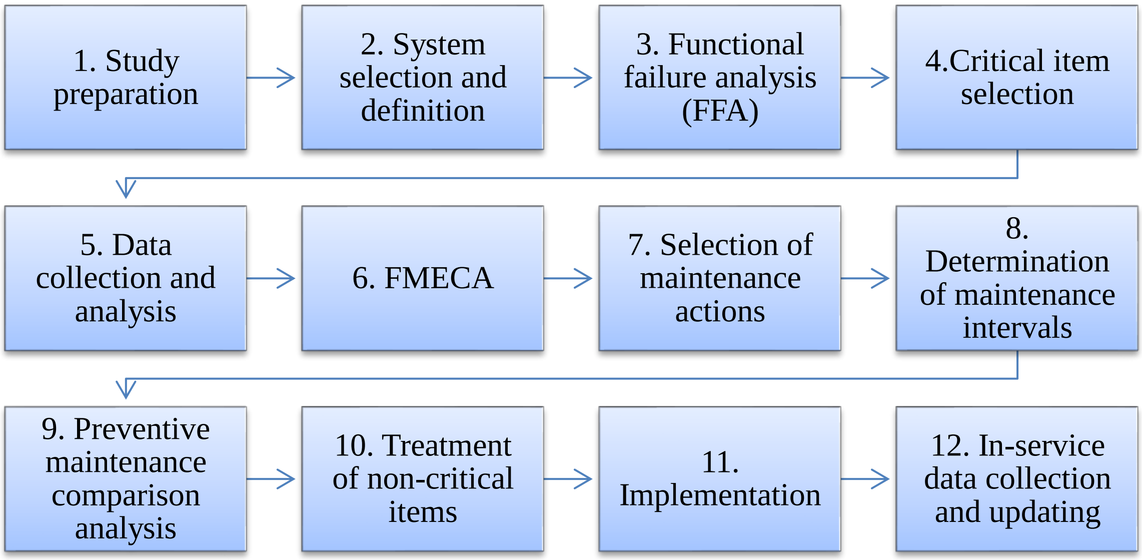


Figure 27. Modified RCM process procedures (Rausand & Vatn, 2008:80; Mainsaver 2008:2-4)

5. RESEARCH CASE: WÄRTSILÄ SERVICES

5.1. Wärtsilä Services in numbers

Wärtsilä is a global leader in smart technologies and complete life cycle solutions for the marine and energy markets. Wärtsilä maximizes the environmental and economic performance of the vessels and power plants of its customers, by emphasizing sustainable innovation, total efficiency, and data analytics. The company has operations in over 200 locations in more than 80 countries around the world, with approximately 18,000 employees on the company's payroll (Wärtsilä Factsheet, 2018). Wärtsilä was listed on NASDAQ Helsinki (stock exchange) on the first of September 1915, meaning the company has been listed for more than 100 years (Wärtsilä celebrating-100-years-as-stock-listed-company, 2018). The following caption is Wärtsilä stock price historic development on January 15, 2019.

Figure 28. Wärtsilä Oyj Abp stock (Google finance, cited 15.1.2019)

In 2017 Wärtsilä's net sales reached 4,923 billion euros, increasing 3% from 2016. Target is to grow constantly faster than the global gross domestic product (GDP) and to reach this target Wärtsilä focuses on strengthening position in strategic growth markets. In addition to improving its financial performance, the company also creates added value for its stakeholders and society. (Wärtsilä targets and achievements, 2018)

Wärtsiläs net sales by business groups in 2017 including three main business areas: Services, Energy solutions, and Marine solutions. Percentages of the business net sales divided as follows (Figure 29.):

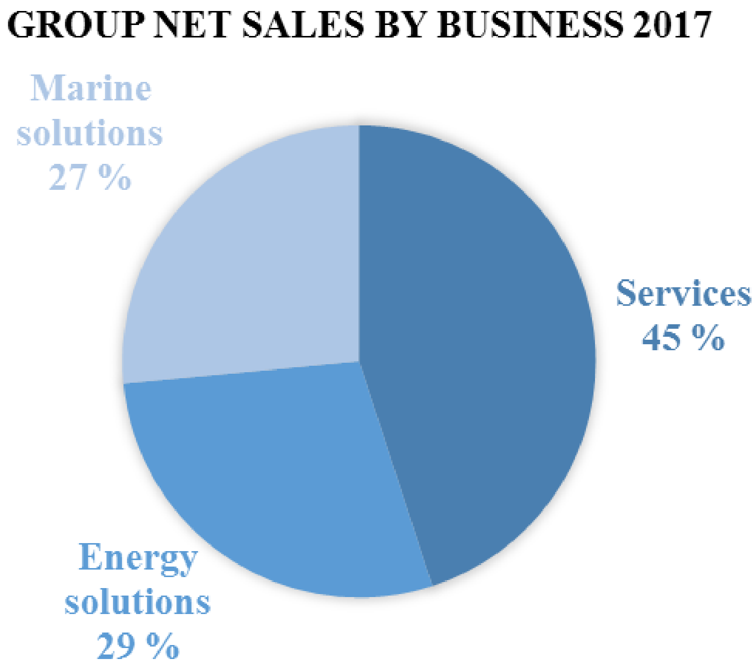


Figure 29. Wärtsilä net sales by business in 2017 (Wärtsilä Factsheet, 2018)

Wärtsilä Services is a crucial part of its business entirety: Service is 45%, of total EUR 4,9 billion net sales, signifies more than EUR 2,2 billion shares of the whole Wärtsilä's net sales. Services business covers both the marine solutions and the energy solutions businesses in their service portfolio. As a long-term partner for its customers, the main market driver is a life cycle efficiency for which the availability, reliability and economic viability take the biggest roles. The marine service business is strongly driven by existing, as well as new, environmental regulations. Wärtsilä service agreements ensure reliable performance from receiving of fuel to supplying energy. In addition, lower operating costs, the need for enhanced safety, and the need to outsource the operations and management of power plants, complete the service portfolio. (Wärtsilä's markets, 2018)

5.2. Services as a source of stable cash flow

Long-term contracts and service agreements are the best resources to earn a stable cash flow to the company (Dechow, 1992). Vessel engines and power plants are produced by make-to-order (MTO) method, therefore Marine and Energy solutions net sales are based on project-related income. As a result, long-term contracts are stabilizing Wärtsilä's annual source of revenue, even if the Marine and Energy solutions sales would undershoot their targets.

Wärtsilä Services Catalogue offers seven different solution types to choose from (Wärtsilä Services Catalogue for Marines, 2018):

1. Upgrading solutions to improve performance, efficiency, uptime, safety, and operational costs.
2. Parts solutions to ensure always having high-quality spare parts ready at anytime and anywhere as customer needs them.
3. Life cycle solutions ensuring equipment performance with solutions covering servicing, maintenance, and operation.
4. Analytics & monitoring solutions prevent the unexpected with continuous monitoring and analysis.
5. Maintenance & repair services guarantee that equipment is performing at its best and keep unplanned downtime to a minimum.
6. Expertise services improve the performance or solve problems with expert analysis and recommendations based on equipment data and information gathered during inspection visits.
7. Training services on a wide range of topics by Wärtsilä experts, including management, operation, maintenance, and safety.

To execute the servitization model in solution business, Wärtsilä must develop and perform their model continuously. In this thesis, the focus is to develop a maintenance analysis process for life cycle solutions for preventing the unexpected failures as a part of the RCM process, explained in the fourth chapter. Monitoring, collecting and processing data is a key factor to success. Condition monitoring and collecting data is performed by IoT solutions and data processing by bid data analysis.

5.3. Research target

Current maintenance planning for the service agreement includes a standard plan, which is not always the most appropriate way to take customers' asset and business into account. In addition, production losses and installation configurations do not cause any changes in the maintenance plan, and the spare parts policy follows the standard plan. Maintenance tasks are mainly executed by periodic overhauls, counted from the operating time e.g. every 10000 running hours. In periodic overhaul concept, the timing for the maintenance tasks depends on engine type and its total meter reading. Some maintenance intervals have been specified depending on the installation's average load or amount of fuel spent.

The standard maintenance plan is not optimal for every installation, since some customers are taking availability into account already at the installation planning phase, and some are running installation only with one main engine. Therefore, customers are demanding more advanced and tailored services, and thus creating individualized and optimized maintenance plans are the aim for maintenance planning.

Research target is to develop a systematic method to analyze customers' asset and business to optimize maintenance plan for long term service agreement, i.e. maintenance analysis process for service plan optimization. In addition, engaging discussions about Wärtsilä reaching Approval of Service Supplier notation for RCM concept. An outcome of the research will be a developed and documented streamlined RCM process for Wärtsilä Services to create tailored maintenance plans of customers' assets considering installation configuration and customer's business needs. Constraints are limited to power generation systems, and the focus is on maintenance management.

In Wärtsilä Services, RCM process does not have a notable role in the maintenance management. Therefore, there is not enough measurable data to formulate facts and uncover patterns as required in quantitative research. Also, it is not useful to have group discussions or multiple individual interviews to uncover trends and opinions for digging deeper into the problem as qualitative research requires (Newman & Ridenour, 1998). However, interactive discussions with the Specialist from Wärtsilä Marine Business Asset Management Services, and Reliability Specialist from Ramentor Oy, was performed to collect some qualitative data. Results of discussions included transformative knowledge of developing RCM method for the case study. In addition, to have adequate research data, a methodology of design science (DS) research is taking a place in this thesis.

5.4. Research methodology & Dataset

"Whereas natural sciences and social sciences try to understand reality, design science attempts to create things that serve human purposes" (Peffers, et al., 2007).

Design science (DS) research methodology is an information technology-based outcome of research. DS offers guidelines for evaluation and iteration within research projects and focuses on the development and performance of designed items, with the intention of improving its functional performance. DS creates and evaluates information systems as an intention to solve identified organizational problems. (Peffers, et al., 2007)

DS involves a comprehensive and rigorous process to design items to solve discovered problems, to make research contributions, to evaluate the designs, and to communicate the results to appropriate audiences. These items may consist of models, constructs, methods, and installations, as well as social innovations or new properties of technical, social, or informational resources (Hevner, March & Park, 2004). Shortly, the definition of DS would be any designed object with an embedded solution to an understood research problem (Peffers, et al., 2007).

To develop the maintenance analysis process for service plan optimization, design science method together with a qualitative method, interviewing subject specialists, are composing comprehensive research results. Interviewed persons are: A specialist from Wärtsilä Marine Business Asset Management Services, and Reliability Specialist from Ramentor Oy. Interviews do not follow predefined open-ended question list, instead, having a comprehensive discussion about considered topics.

The discussed topics:

1. A content of the traditional RCM process, standards, and guidelines
2. Possibility to modify the RCM process procedures
3. Possibility to replace FMEA and FMECA with FTA
4. A structure of the FTA in the modified RCM process
5. FTA software, an introduction of ELMAS
6. RCM-based LTA to Wärtsilä Services environment

The reliability specialist Lehtinen have years of experience about the RCM process. Lehtinen emphasizes that the fault tree analysis is a more accurate method for indicating time intervals between failures, failure recovery time, and maintenance costs, than the FMECA. A discussion, if a bottom-up or top-down method should be practiced in the Wärtsilä -case, ended in consensus within the bottom-up method.

During the research, some of the case company's failure data archives were analyzed to make conclusions of the maintenance plan possibilities and requirements. Failure data and engine information are also used to create an ELMAS -model for testing the FTA software's operability.

The research results are presented further in the modified and streamlined RCM process (chapter 5.6.) since the research discussions handled mainly of developing the RCM process for Wärtsilä Services environment. An analyzing tool for the FTA is presented with screenshots in the 5th step (chapter 5.6.5). FTA software that is used in this thesis, ELMAS, is created by Ramentor Oy.

5.5. Launching the RCM process for the case company

Launching the RCM process is started by identifying requirements from related specialists (i.e. subject matter experts). Requirements for launching are:

1. Plan
2. Measure
3. Train
4. Perform
5. Implement
6. Complete

Taking advantage of engine experts and their extensive practical experience is the best way to identify these requirements. Next step is evaluating the available experience and the need for external expertise, along with possibility and need for training requirements. In this phase also deciding if internal or external RCM facilitator is going to be used. In the pilot stage, an external specialist can be used to gather expertise in facilitating. When the streamlined RCM process is up and running, the aim is to use internal facilitators for constant actions.

The traditional RCM method is not always the most optimal concept to launch as a maintenance management tool. By blindly following the steps of traditional RCM (incl. FMECA and standards etc.) step-by-step and top-down, the result might be purely too simple, and there is a bigger risk that the process is misunderstood or used wrong. The traditional process cannot manage to re-plan, modify or develop the process if the logic tree analysis causes the process to end. Challenge for the traditional RCM is its launching for the existing processes. Generally, RCM is launched in an early stage of a process life cycle.

RCM process will be customized to suit the business environment of the case company but will not be strictly following on precise standards. Nevertheless, applicable standards IEC 60300-3-11 and SAE JA1011 are considered in the process execution to ensure its progress. Theory part explained comprehensively what these standards contain, but the execution phase is modified for the case company's requirements. Also, DNV GL guidelines are followed as a base of the research. Hence, the RCM process will not blindly follow RCM decision logic as theory part suggests. In RCM theory the process stops at the first applicable service task, instead of that, all the potential service task types will be gone through, starting from the most critical failure modes.

Traditional RCM process is based on going through all the failure modes, which is not always the most suitable way. The following chapters explain how the RCM process should be modified, and why not all the failure modes are gone through, depending on their criticality. As the Pareto –principle proposes: 20% of failure modes cause 80% of costs of production losses (Fenton & Ohlsson, 2000:800), which is a good point in modifying traditional RCM process. In the Wärtsilä case, the percentages in production losses costs could be even 15/85 or even with a higher difference. In this case study, the focus is in the component level, not in every different failure mode of each component.

The process is going to utilize input from the standard maintenance manual as a base of process planning. The engine experts define how current condition monitoring could be improved to better detect failure symptoms and what symptoms each failure might show. This is done for each relevant failure mode one by one. Experts also assist in recognizing failure or failure symptoms to quickly react on them and thereby increase installations availability. Similarly, expert knowledge and experience are used to recognize failure intervals in different operating conditions, according to their own experiences. Also defining how much quicker recovery time the component has after the failure when a proper condition monitoring system is installed.

5.6. Modified and streamlined RCM process

Usually the traditional RCM method is executed to company's manufacturing process, but in this case, Wärtsilä's aim is to offer services that are modified to each customers' needs. Modified and streamlined RCM process for the case company includes the following procedures, which consist of seven steps as a part of its structure:

5.6.1. Step 1. Planning the execution of the streamlined RCM process

The first step follows the traditional RCM process: system selection and data collection. Decide the scale what is measured, which in this case is engines systems and their subsystems. Reviewing what are the current and planned maintenance tasks. Modified RCM execution utilizes the bottom-up method, which means going through all the components in the system that the experts consider to be necessary, in bottom-up order. Starting from the most critical ones and figuring out how they and their failure modes affect in a higher level of the process.

5.6.2. Step 2. System boundary definition

Defining the system boundaries for RCM analysis is needed, since an installation may include many on-board and out-board instruments. Facilitating system analysis and ensuring better maintenance management is achieved by defining system boundaries for equipment and on-board components. The off-board and communication components, such as the navigation network, are not included to system boundary definition.

Not all the installations are the same, thus defining the system boundaries need to be done individually for each installation. For example, system X may have control statistics in an engine control room physically separated from it (off-board), but the analyst believe it is a good idea to include those control room instruments in an analysis of the system X. If the control room is later analyzed as a separate system, the previously established boundary for system X will tell the analyst not to include those instruments in the control room boundary definition (on-board).

Therefore, dividing installation into clear subsystems and the boundaries of target systems, defined with clear IN and OUT interfaces, will help to find the failure modes and effects of each unit in a system and to follow 80/20 rules. Some elements (signals, heat, fluids, gases, etc.) come IN across the boundary; others move OUT to support other systems. OUT interfaces represent what the system produces.

5.6.3. Step 3. System description and functional block diagram

Basically, Step 3 aims to identify and document the essential details of the system that are required to perform the remaining steps in a systematic and technically correct way. In the third step of RCM process, the following details should be established: (1) system description; (2) FBDs; (3) IN/OUT interfaces; (4) system work breakdown structure; and (5) the equipment history. In Wärtsilä case, this is the step where adding all the engines, their systems, and subsystems to the “master program”, and then defining which systems affects with each other and how.

At this point of the analysis process, there has already been collected a big amount of information about what constitutes the system, and how does it operate. Continuing the process through the FBD, which is a top-level representation of the major functions performed by the system. Hence, the blocks are considered as functional subsystems. The FBD is composed only of functions, not component or equipment titles appear in it. Boundary overview and the FBD together provides a valuable description of the initial phase of the systems analysis process.

The intention of the Step 3 is to reach understanding how the components effects in the systems. Functional block diagrams are used to help to describe if the systems or subsystems are in a relationship with each other. In addition, some of the subsystems that have no effect on the process can be deleted from the process. All the necessary components will be gone through, defining what are their effects in the upper level, in bottom-up order.

Following FBD (Figure 30.) demonstrates that not all the system functions, e.g. auxiliary system, affect in every engine of the installation. If the auxiliary system does not get enough fuel pumped, only engines 1 and 2 goes to failure mode, since the auxiliary system does not affect in engines 3 and 4. The figure is the highest level of the FBD and will include a lot of components underneath.

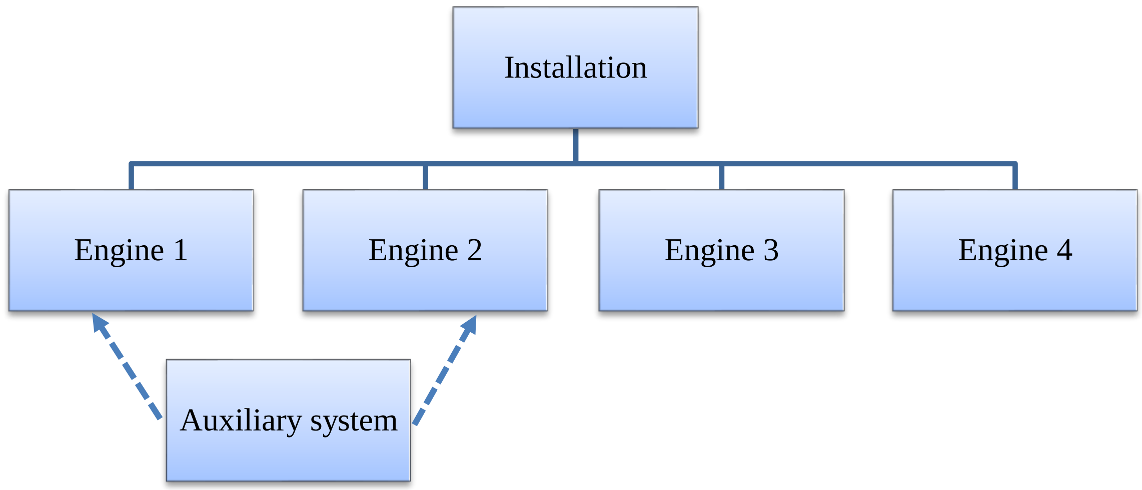


Figure 30. Functional block diagram demonstrating the system functions relations

5.6.4. Step 4. System functions and functional failures

This step defines how the component's failure affect the system. The focus is on the functional failure of an engine and how does it impact on the engine availability, rather than on performance of failures. Every system has its own intended function, the primary function, which is the reason for its existence. When the systems functional failure occurs, function statement should be done. The statement describes what is the object, what needs to be done, and what is a functional standard in its presenting context. The number of secondary functions can be a very long list. Considering the relevance of the listed functions according to analysis is important.

There are several different types that the system can fail to fulfill its functions. The system can fail totally: caused by small particles scoring surface, cylinder seizing, overheating, or the cylinder breaking in pieces; or it can fail partially: very small particles scoring surface or light overheating. Nevertheless, it is not effective to dig too deep into components functions while going further through the failure modes. It is accurate enough to recognize if the failure mode is a general failure or for example a leakage.

Taking care of the most common failures. Some failure modes are "normal failures" and some are more special. For example, in the process, there could be a component with five different failure modes, and with the further analysis, the outcome in all modes can be the same: replace the component with a new one. During the streamlined RCM process, these type of failure modes should be recognized, and no unnecessary effort should be made.

5.6.5. Step 5. FMEA & FMECA replaced by FTA

The fifth step makes a big difference. Existing failure mode, effects, and criticality analysis (FMECA) in traditional RCM process is used as supporting data when updating service actions for the most critical components. Fault tree analysis (FTA) will be replacing FMECA, to define relevant failure modes and their consequences for better support of quantitative criticality calculations. With the FTA method, time intervals between failures, failure recovery time, production losses, and maintenance costs are indicated. FTA answers how the failures impact in the process.

The previous (1-4) steps of the modified RCM process are reliable and needed source for creating FTA model for Wärtsilä's needs. With the help of the FTA, all the parts and items that need to be maintained are represented. In this step, FTA goes through all the hidden failures as well.

In a situation, such as nuclear power plant maintenance, there are many different items and small details, where the bottom-up version of the maintenance process is impossible to execute. However, in Wärtsilä Services scenario, bottom-up is completely fine to use. In the top-down method there would be a lot of work that would have a small effect on improving system operations. Some of the consequences of failure modes are the same, no matter how deep is delved, therefore some failure modes can be handled quickly. The analysis is defined by the best available experts from the Wärtsilä.

Modifying the existing maintenance plan and delivering the contract for the customer is a five-step process. Following five steps (Figure 31.) defines how the expert analysis is serving the customer at the basic level:

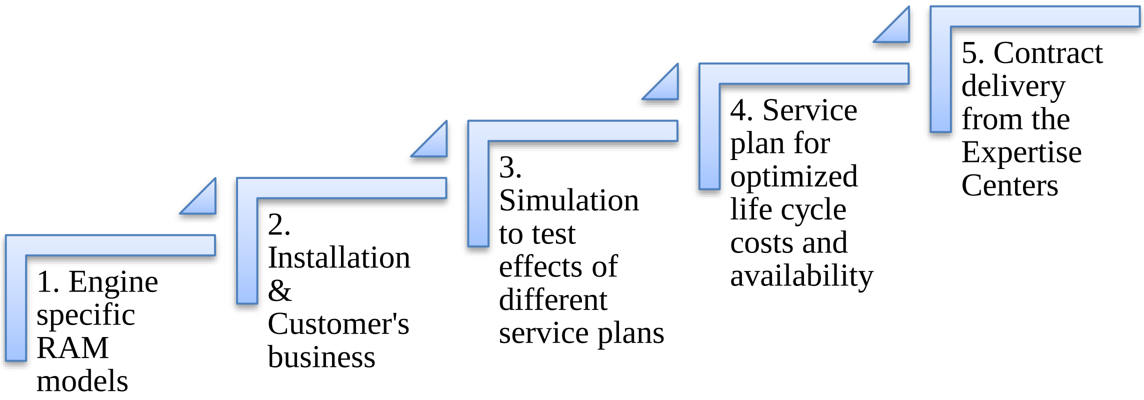


Figure 31. Steps to define how the expert analysis proceeds

Explaining the steps of the previous chart (Figure 31.):

1. Engine specific RAM models such as: failure modes, failure consequences for the engine, effective recovery time, and detectability, are being handled in the first step of the FTA process.
2. After the engine specific RAM models are defined, the installation and customer's business -step is taking place. In customer's point of view, this step includes some of the most crucial issues to be specified. These topics are customer needs, installation configuration, cost of downtime, cost of repairs, failure rates in customer operating environment, and installation-specific delays in recovery time.
3. Simulation for testing the effects of different service plans requires the following things being checked: spare parts availability, remote services, inspections, and maintenance schedules.
4. The service plan for optimized life cycle costs and availability requires a maintenance plan that is based on optimizing. The previous (3^{rd}) step simulates testing the effects of different service plans, and this (4^{th}) step is suggesting if the plan can actually be modified. Modifying could be prohibited if it increases the safety risk. Logic tree analysis, which is taken care in the RCM Process Step 6 (chapter 5.6.6.), prescribes the final decision of possibility of changes in the service plan.
5. Contract delivery from the Expertise Centers means that the installation is going to be maintained as the service contract defines. Contract delivery could consist

of maintenance planning, field service, spare part delivery, condition monitoring, engine operating, etc. Content depends on the scope of the service contract. In addition, continuous improvement and collecting statistical data are applicable services to improve maintenance plan.

The results of the fault tree analysis are identified risks, reliable conclusion of LCC, availability, and reliability. Instead of FMEA or FMECA, which both results only relative values (usually in a scale of 1 to 1000), FTA results in actual simulated LCC costs, availability, and reliability. Relative values will not provide any clear information about actual costs, availability or reliability, which FTA are able to find out. In maintenance management point of view, identified risks are in many cases depending on how much they cost.

Three critical factors taking part in the FTA method are (the same than in FMECA): severity, occurrence, and detection. Severity is a factor that explains how the failure modes effects on the system. Occurrence tells how often failure modes are occurring, and the detection answers to concern how to notice the failure mode in the system. This is a definition of detection as it is in theory part, but in the Wärtsilä case detection is more practical when defined as detecting component failures with operating engine systems before they lead into functional consequences. Also considering how effectively this detection is performed.

The focus in criticality phase is to result in reliable LCC and availability in numbers, as well as define how the failure modes effects on the system and with what costs. Safety and environmental factors are handled in the following step, not in the criticality phase. Next will be explained how to make the best out of the FTA process. Avoiding human errors in the FTA process is best achieved through the help of technology.

Ramentor is a Finnish company that created software Event Logic Modeling and Analysis Software (ELMAS), which is an analyzing tool for FTA. ELMAS is one option but analyzing tool could be any other FTA software as well. This chapter describes how the

FTA software is functioning in practice, clarified by using screenshots of an example installation 583 (Figure 32.) with four engines (584, 1062, 1540, 2018).

Figure 32. Screenshot of ELMAS in the highest FTA level

The engines have plenty of different causes that might lead to some failure mode. In this installation 583, three functioning engines are needed to keep the installation run effectively. Hence, if two out of four (2oo4) engines are in the failure mode, the installation is not functioning. Therefore, the port in the highest level is “voting” port, which means that failure mode will be resulting after 2oo4 engines fail. All the other ports are “or” types, and they describe how the component failures are affecting in the higher level in FTA.

As it is shown in the following screenshot (Figure 33.), engine (2018) has internal systems (2019) and external systems (2691). In this example, internal systems box is expanded, so the internal systems could be approached. Internal systems consist of different parts, such as engine components (2020), charge air and exhaust gas system (2338), cooling water system (2406), fuel oil system (2528), etc. Internal system n (2670) is an example system that is going to be clarifying FTA’s functioning in the level of system components (Figure 33.).

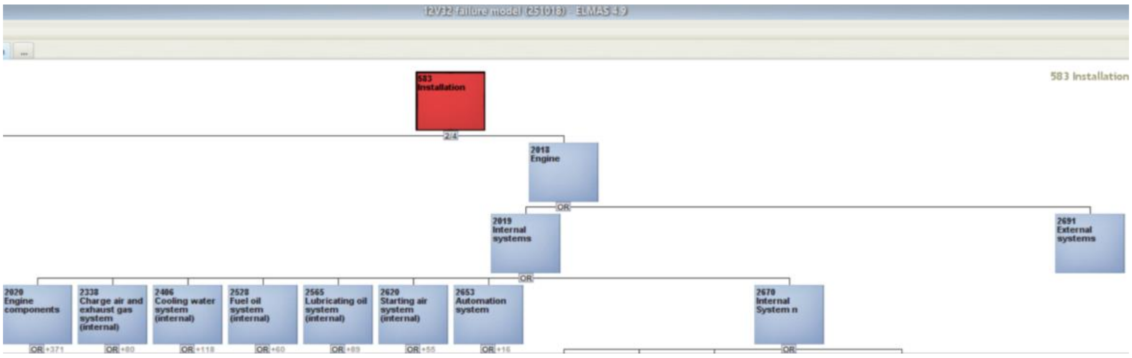


Figure 33. Screenshot of ELMAS in internal/external systems level

Expanding Internal system n (2670) leads to the component level of FTA (Figure 34.). This system n (2670) includes four different components: Component 1 (2671); Component 2 (2675); Component 3 (2679); and Component 4 (2683). Some of the systems may include hundreds of different components, so there are multiple variations to calculate for defining LCC and availability.

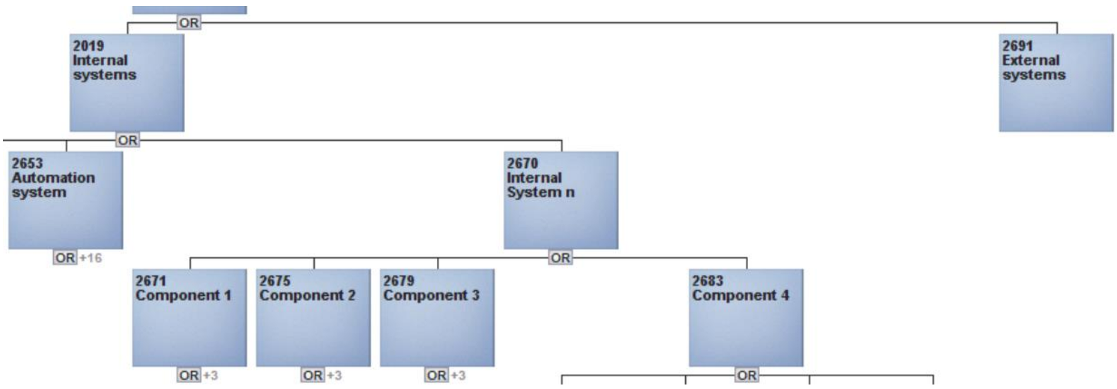


Figure 34. Screenshot of ELMAS in component level

Expanding one of the component boxes (Component 4 - 2683) leads to four different scenarios of how to carry out different failure modes. Each of the four different versions of failure modes (2684, 2687, 2688 & 2690) has its detailed and individual calculations of preventing the failure and causes of the failure (Figure 35.).

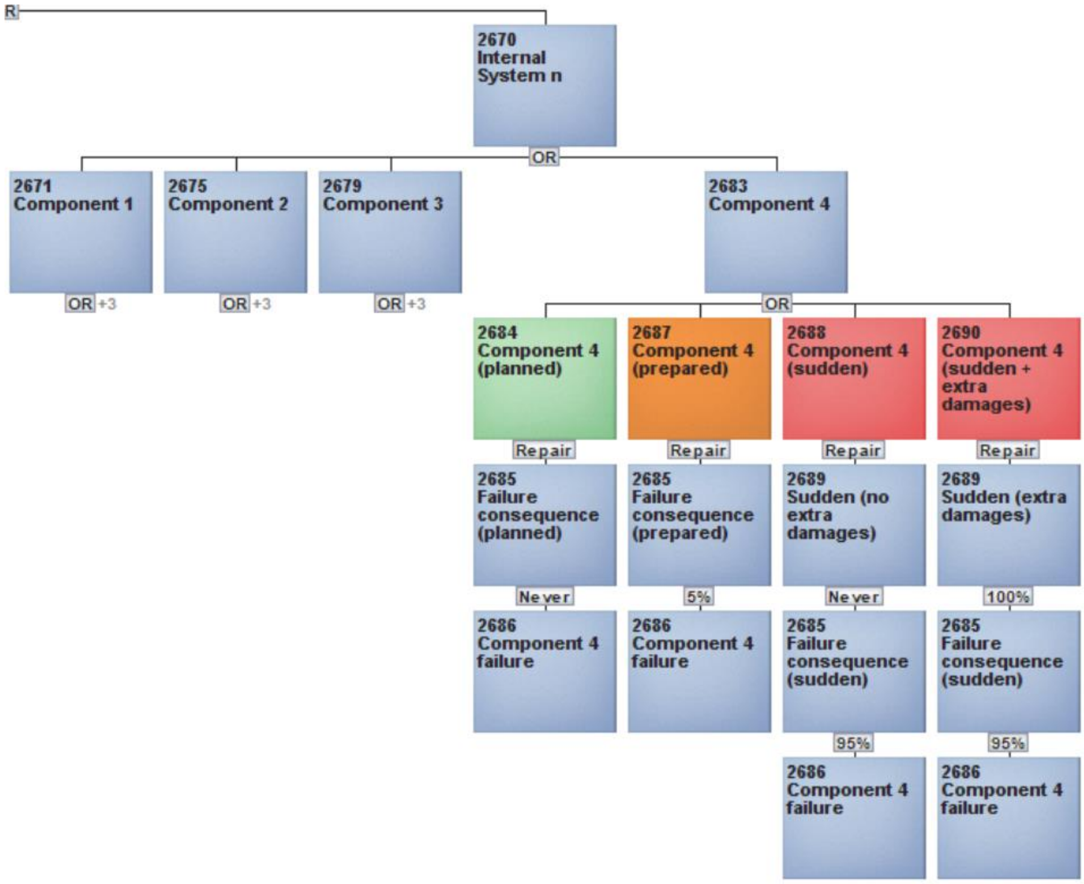


Figure 35. Screenshot of ELMAS in the lowest level of FTA - defining possibilities of different scenarios

The lowest level of FTA consists of four different scenarios of a component failure. Defining possibilities of different scenarios clarifies the most suitable ways to continue in the scenarios of planned (2684), prepared (2687), sudden (2688), and sudden with extra damages (2690) types of maintenance needs. Repairing time is determined by taking repairing delays into account, which are caused by tools and spare parts availability and their delivery time, maintenance staff's availability, and repairing costs (Figure 35.).

Component 4 (2683) repairing time and cost in different scenarios:

- Box 2684 (planned): No repairing time. An assumption is that the failure can be repaired in the next planned overhaul.
- Box 2687 (prepared): The best possible repairing time. The assumption is that the failure can be identified with the condition monitoring and that all the equipment

and spare parts are prepared for the repairing project. This scenario is applicable for all the same type of engines, no matter what installation.

- Box 2688 (sudden): Repairing time when the failure occurs suddenly but does not cause any extra damages, only to a certain component. Repairing time could be a lot longer than in prepared (2687) repair since the failure occurs suddenly. Therefore, there might be a situation where equipment, repairing staff or spare parts are not available as quickly as in the prepared failure. Recovery time will be considered by the case-by-case approach, depending on installation.
- Box 2690 (sudden with extra damages): The longest and the most expensive repairing process. Single component failure causes damage to multiple other components as well. In some cases, it is impossible to know how many components are actually broken before further inspection during the repairing. Also, some of the engine structures may have been damaged.

Following screenshot (Figure 36.) demonstrates what does the actual FTA looks when boxes from installation (583) to internal system n's Component 4 (2683) are expanded. FTA is explained Top-Down, but as mentioned, the FTA process is going to be executed in the Bottom-Up method.

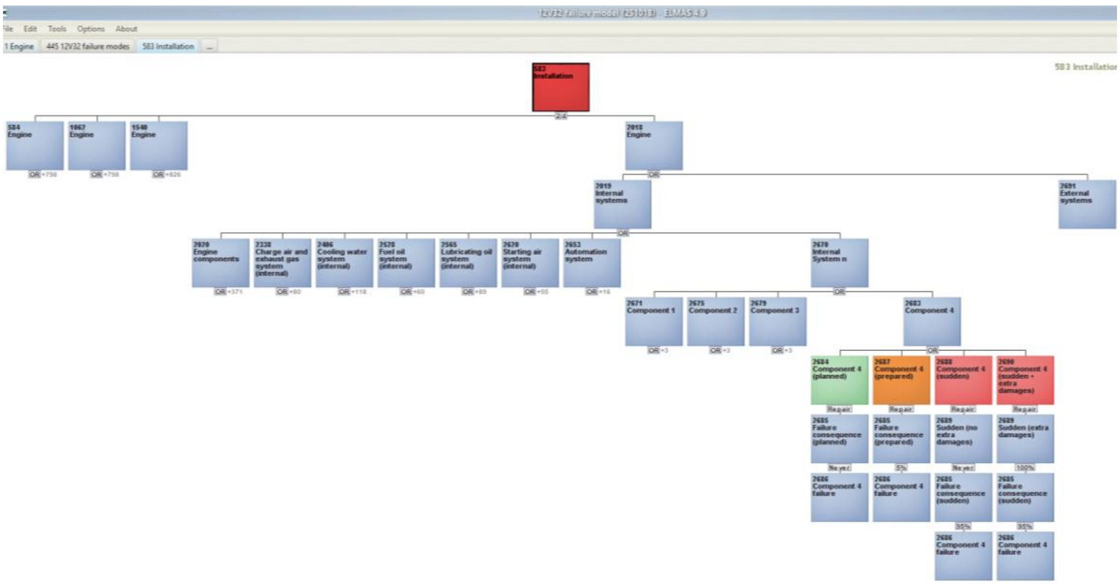


Figure 36. Screenshot of ELMAS

Summarizing the bottom-up method of FTA step by step:

1. The first and lowest level is component's failure box (2686), which is common to all four different paths. Failure rate, which in Wärtsilä case is MTTF, based on failure data and experts experience and knowledge, will be entered to the failure box (2686). Failure rate should also consider of operation profile and used fuel, since they effect on failure existence as well. For example, ship engine that is running by gas could not use heavy fuel oil using baseload power plant's MTTF.
2. Component level clarifies how to continue in the scenarios of planned (2684), prepared (2687), sudden (2688), and sudden with extra damages (2690) types of maintenance needs. This is the level where is calculated repairing time and cost in different scenarios.
3. The next step is to calculate probabilities in which path the failure is proceeding into Component 4 (2683) box. By changing percentage-values of the lowest level components (2685 and 2686), it is possible to impact in the path that the failure might proceed to the higher level. This simulation could be used to steer condition monitoring so that all the failures would be "planned", therefore sudden failures would not exist. The simulation takes also into account the repairing time, which is affected by the availability of spare parts, equipment and repairing staff, as well as those delivery time. Delivery time depends on installation case-by-case.
4. This model of FTA software (installation 583) could be improved by adding planned repair costs. Changing the costs in the model simulates how to, for example, lengthening periodic overhaul intervals affects in the LCC.

In practice, with the FTA software, it is possible to simulate what availability and reliability can be expected in the installation level and in the individual engines level. Availability is calculated from the relation of failure the amount and repair time, and reliability is calculated from amount of engine stopping failures. A result of simulation is components criticality rating, which is based on availability and reliability calculations. Also, calculating LCC is achievable when adding the real values of component costs, repairing costs, maintenance process costs, installation level costs of downtime, condition monitoring costs, and all the other installation specific costs.

With the FTA software, it is possible to simulate different scenarios for optimizing the maintenance plan to meet the customers' needs. Comparing maintenance costs of standard maintenance manual to components criticality rate in specific installation, it is possible to review how the used maintenance budget meet in different components according to their criticality rate. Thereby recognizing if the maintenance plan needs improvement actions. For example, some of the components could be over-maintained, which means that the overhaul costs are too much on the non-critical component. On the other hand, some of the components may be under-maintained, which means that there is too little attention in very critical components.

5.6.6. Step 6. LTA in business environment of Wärtsilä

LTA defines component level failure modes occurrence in safety-, outage- or economics-related areas. As mentioned in the previous chapter, the RCM process places each failure mode into one of four categories. First, need to be found out if the operator knows that something abnormal or harmful has occurred in the normal course of daily duties. After identifying the failure modes, both evident and hidden, and figuring out if these failure modes lead to a safety problem or not.

Failures in standby systems or components are often hidden failures and remain so unless deliberate action is taken to find them. Since these types of systems are not part of the operation in the normal life of an engine, there is no sign of degradation, malfunctioning or failure, unless those are set into operation. Thereby, the recognition and classification of such system failures are challenging even with the help of IoT devices.

Secondly, LTA of RCM asks if failures can lead to a safety problem. Considering if there is a chance for safety risk towards personnel (injury or death) or environment before changing the maintenance plan. During the LTA process, financial costs and components of which maintenance plan could be modified are identified. When identifying these factors, the question of the safety problem is asked. Safety concern includes both, personnel and environmental consequences.

Comparing to LTA in theory part, wherein the situation “is there evident” answer is yes, and then also positive answer for safety question, the analysis results “safety problem”. Not further analysis on how to manage the situation, nor how to continue. Hence, the results of the criticality analysis in the traditional model of RCM are not reliable or specific enough. RCM-based LTA in Wärtsilä’s business environment will figure out the safety problems cause, solve it, and then maintenance plan modification actions to best serve customers’ goals.

Since the maintenance program is already existing there is no need to define if there is planned condition-dependent (CD) or time-dependent (TD) maintenance tasks, instead of defining if those tasks are efficient and if they can be modified. The intention of this whole process is to serve the customers in the best possible way to help them reach their goals. Typically, customers’ aim is to optimize maintenance management processes by minimizing the life cycle costs (LCC) or maximizing availability, not defining if the maintenance should be done or not. The aim is to go through all the components that need to be modified, which is based on the fact, that there is already existing a maintenance plan and the intention is to modify it. Following chart (Figure 37.) simulates modified LTA process to the environment of Wärtsilä:

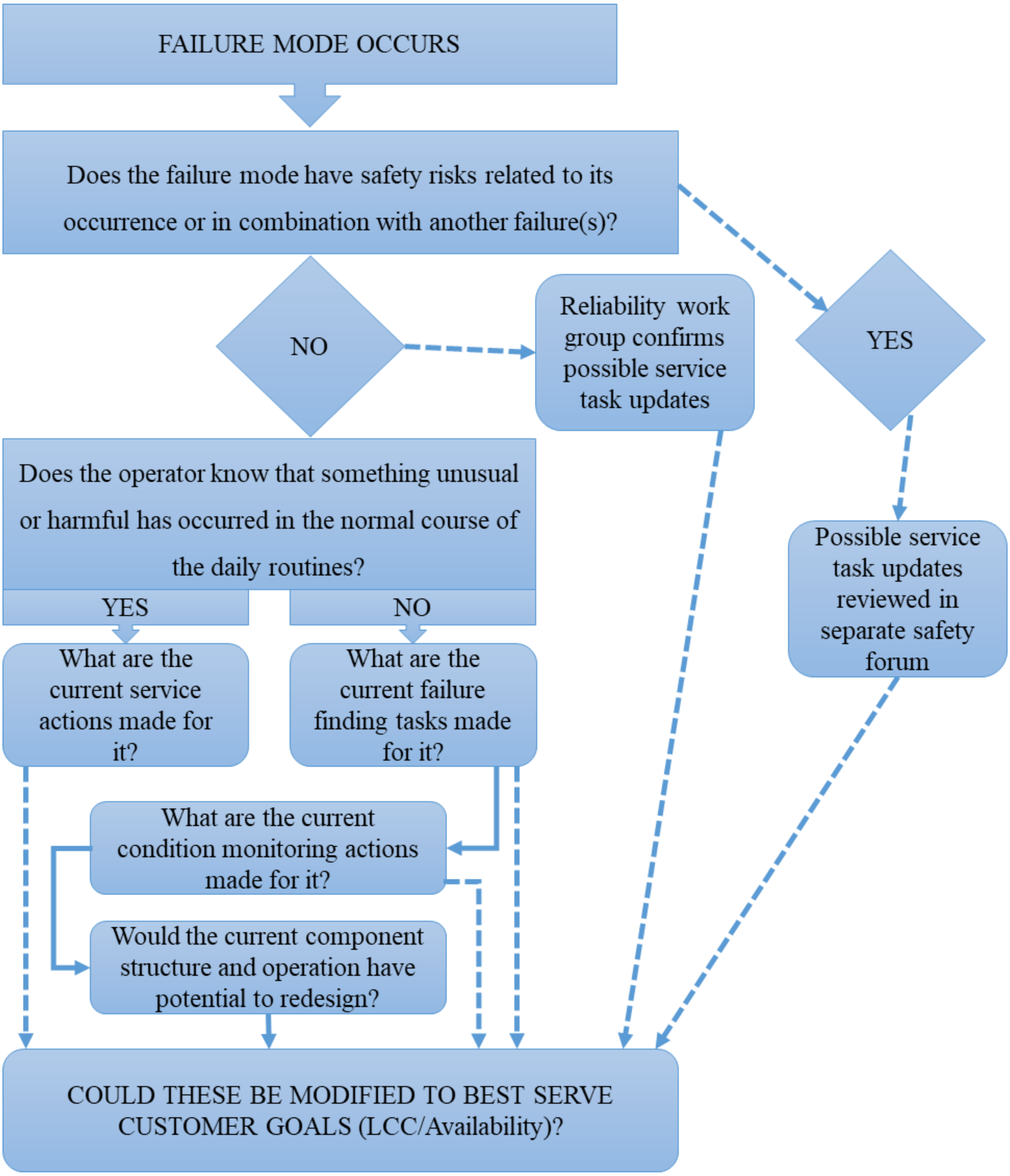


Figure 37. RCM-based LTA to Wärtsilä Services environment

5.6.7. Step 7. Maintenance task modification

In a modified and streamlined RCM process the fifth step simulates effects of the changes in the maintenance plan with the FTA process, and the sixth step goes through if the changes can be executed with the LTA process. The final (7^{th}) step specifies the tasks, which tasks are profitable to change according to FTA, and which tasks can be improved according to LTA.

Step 7 considers if the tasks are applicable and effective to modify and if those are adaptable in customers' environment. Going through the already existing maintenance plan with Wärtsilä specialists to define of which are the customers' needs for improvement. The focus could be minimizing the LCC costs, maximizing the availability and reliability, or optimizing all mentioned alternatives to the best-suited way. Modifications should not decrease the safety in any case.

As the theory part suggests, run-to-failure (RTF) option for some components could be the best suitable option. Whether there is no applicable PM task, even to be modified, or the cost of an applicable PM task exceeds the cost of RTF. However, the maintenance plan should include potential costs of a worst-case scenario, before letting any component run until the failure. Worst-case scenario, such as component breakdown that causes damage in a turbocharger, would increase the actual costs a lot. This type of worst-case scenarios can be avoided with suitable condition monitoring.

6. CONCLUSIONS

Research for this thesis was carried out in co-operation with Tuomas Kangas, Concept Manager in Wärtsilä Services, and Turkka Lehtinen, Senior Reliability Specialist in Ramentor Oy. Research results show that the RCM method is a suitable tool for developing the case company's maintenance management processes. However, it needs to be modified to merge in Wärtsilä's maintenance processes.

The thesis focuses on exploring and simulating potential advantages of RCM method in practice for the case company. The study first discusses the basic elements of RCM procedures and then in more advantageous to enable the streamlined and modified process to be performed for Wärtsilä's customers' needs.

Modified and streamlined RCM process that serves the best of Wärtsilä's customers' needs, should use the bottom-up method in failure tree analysis (FTA), which is replacing failure mode and effective analysis (FMEA & FMECA). Bottom-up method means finding and preventing failure modes begins from the lowest level of installation structure, the component level. In the component level, the most critical components should have the most attention from the beginning of the process, which means that the components that may cause the most repairing costs or the longest downtime should be taken care first. Experts knowledge and experience input has been used to recognize the components, which should be taken care of in the analysis, such as components repairing time, a chance for extra damage, etc.

FTA software, in this research ELMAS, is in the big role to make the RCM process easier to deal with. Human errors are minimized after all the necessary information is defined to the software. FTA software can calculate installations different possibilities of risks, actual costs of LCC, availability, and reliability, in different scenarios.

RCM-based Logic Tree Analysis is modified for the Wärtsilä Services environment. Modified LTA differs from the traditional LTA in many ways. Traditional LTA, mentioned in theory part, suggests that the analyzing process could stop when the solution for failure mode cannot be found. Besides that, for the Wärtsilä environment modified LTA clarifies that (1) the relevant failures (evident and hidden) should be identified; (2) process should not stop if the solution is not found in the first place, rather the solution should be discovered in some alternative way; and that (3) aim is always to optimize customers' maintenance processes as intended to help them reach their goals. It is possible of trying to reach the lowest possible LCC or the best possible availability, but optimizing these alternatives helps the customer to find the best suitable maintenance process, the golden mean.

With the accurate knowledge of classification societies requirements for the Service Supplier notation, the documented process enables Wärtsilä to engage in discussions regarding approval for the streamlined RCM concept. Therefore, increasing the service portfolio and profitability is possible. In the future, modified and streamlined RCM process could be applied for other industries as well.

REFERENCES

Ahuja, I.P.S. & Khamba, J.S. (2008). Total productive maintenance: Literature review and directions, *International Journal of Quality & Reliability Management* 25:7, 709-756.

August, J. (2004). RCM Guidebook: Building a Reliable Plant Maintenance Program. ISBN 1-59370-007-5.

Ballantyne, D., Frow, P., Varey, R.J. & Payne, A. (2011). Value propositions as communication practice: Aaking a wider view, *Industrial Marketing Management*, 40:2, 202-210.

BSI Standards Publication, (2010). BS EN 13306:2010. *European standard*, 31. ISBN 978 0 580 64184 8.

Conachey & Montgomery, (2003). Application of Reliability-centered Maintenance Techniques to the Marine Industry, *Abs Technical Papers 2003*. Pages 39-60.

Davies, A. (1998). Handbook of Condition Monitoring: Techniques and Methodology. First ed. ISBN: 978-94-010-6065-3.

Dechow, P.M. (1994). Accounting earnings and cash flows as measures of firm performance. *Journal of Accounting and Economics*, 18:1, 3-42.

Denzin, N.K., & Lincoln, Y.S. (1994). Handbook of qualitative research. Thousand Oaks, CA, US: Sage Publications, Inc.

Det Norske Veritas. (2010). Offshore Service Specification DNV-OSS-309: Verification, Certification and Classification of Gas Export and Receiving Terminals, 6, 22-23.

DNV GL AS, (2018). DNV GL approval of service supplier scheme, Class programme: DNVGL-CP-0484. Available in: <https://rules.dnvgl.com/docs/pdf/DNVGL/CP/2018-03/DNVGL-CP-0484.pdf>

DNV GL, (2018). DNV GL.com, Maritime: Services: Approval of service suppliers. Available in <https://www.dnvgl.com/services/approval-of-service-suppliers-2851>

DNVGL-RU-SHIP, (2018). Rules for classification: Ships, 1:1. Available in: http://www.dnvgl.com, is the officially binding version.

Escobar, A., López-Gutiérrez, J.S., Esteban, M.D. & Negro, V. (2018). A modified method for assessing hydrodynamic loads in the design of gravity-based structures for offshore wind energy. *Journal of Coastal Research*, 85, 931–935.

EU (2017). EU Citizenship report: factsheet. [Cited 20.12.2017]. Available in: <http://ec.europa.eu /newsroom/document.cfm?doc_id=40722>

European Comission, (2014). High-Level Group on Business Services, Final Report April 2014, EU for Business.

Feijóo C., Gómez-Barroso J-L. & Aggarwal, S. (2016). Economics of big data. *Handbook on the Economics of the Internet*, 25, 510-526.

Fenton, N.E. & Ohlsson, N. (2000). Quantitative analysis of faults and failures in a complex software system. *IEEE Transactions on Software Engineering*, 26:8, 797-814.

Gandomi, A. & Haider, M. (2015). Beyond the hype: Big data concepts, methods, and analytics. *International Journal of Information Management*, vol.35, pp.137-144.

Grönroos, C. & Ravald, A. (2011). Service as business logic: Implications for value creation and marketing. *Journal of Service Management*, 22:1, 5-22.

Gubbi, J., Buyya, R., Marusic, S. & Palasiwani, M. (2013). Internet of Thins (IoT): a vision, architectural elements, and future directions. *Future Gener*, 26:7, 1645-1660.

Gunter, L. (2014). Servitization in Industry: Eight challenges to Mastering the Service Innovation Process in Manufacturing Firms. Springer, 182-183. ISBN: 978-3-319-06935-7 (eBook).

Gustafson, A., Schunnesson, H., Galar, D. & Kumar, U. (2013). Production and maintenance performance analysis: Manual versus semi-automatic LHDs. *Journal of Quality in Maintenance Engineering*, 19, 74-88.

Harkins, S. S., & Reid, M. W. (2002). SQL Grammar: Access to SQL Server, 69-82. ISBN: 978-1-893115-30-9.

Hevner, A.R., March, S.T., & Park, J. (2004). Design research in information systems research. *MIS Quarterly*, 28:1, 75–105.

Hojnik, Janja. (2016). The servitization of industry: EU law implications and challenges. *Common Market Law Review*, 53, 1575.

Horn, K. (2017). Consumer Values and Product Perception: Consumer Perception of Product Risks and Benefits. 283-299. ISBN: 978-3-319-50528-2.

Hoseinie, S.H. & Kumar, U. (2016). Project report: Reliability Centered Maintenance

(RCM) for Automated Mining Machinery. Luleå University of Technology. ISBN: 978-91-7583-556-3.

ISO Guide 73, (2009). Risk management Vocabulary. International Organization for Standardization. Available in: <https://www.iso.org/standard/44651.html>.

Knutsen, K.E., Manno, G. & Vartdal, B.J. (2014). Beyond Condition Monitoring In The Maritime Industry: DNV GL Strategic Research & Innovation. Available in: <https://www.dnvgl.com/news/dnv-gl-beyond-condition-monitoring-in-the-maritime-industry-7685>.

Dnvgl.com, (2018). About DNV GL: in brief our history. Available in <https://www.dnvgl.com/about/in-brief/our-history.html>

Kobbacy, K.A.H. & Murthy, D.N.P. (2008). Complex System Maintenance Handbook. *Springer Series in Reliability Engineering*, 657. ISBN: 978-1-84800-010-0.

Lai, A.W. (1995). Consumer Values, Product Benefits and Customer Value: A Consumption Behavior Approach. *Advances in Consumer Research*, 22, 381-388.

Lanning, M. & Michaels, E. (1988). A business is a value delivery system. *McKinsey Staff Paper*, 41.

Mäenpää, Antti (2014). Methodology and research design: The Ostrobothnian Model of Smart Specialization. *Proceedings of the University of Vaasa*, 196, 49–65.

Mainsaver, (2018). ODF: What is Reliability Centered Maintenance? Available in: <https://www.mainsaver.com/pdf/Reliability_Centered_Maintenance_White_Paper.pdf>. [Cited 10.11.2018].

Maritime Reporter, (2005). ABS Introduces SafeShip. New Wave Media. [Cited: 3.1.2019]. Available in <https://magazines.marinelink.com/Magazines/MaritimeReporter/200007/content/abs-introduces-safeship-207365>.

Marsh, G. (2010). Reinforced Plastics: Marine composites - drawbacks and successes. 54:4, 18-22. ISSN 0034-3617.

McClelland, C. (2019). What is IoT? - A Simple Explanation of the Internet of Things. [Cited 23.1.2019]. Available in: <https://www.iotforall.com/what-is-iot-simple-explanation/>.

Michael, K. & Miller, K. W. (2013). Big Data: New Opportunities and New Challenges. *Computer*, 46:6, 22-24.

Morison, J. R., O'Brian, H.P., Johnson, J.W. & Schaaf, S.A. (1950). The Force Exerted by Surface Waves on Piles. *Journal of Petroleum Technology,* 2:5, 1-6.

Moubray, J. (1997). Reliability-Centered Maintenance. Oxford: Butterworth-Heinemann, ed. 2. ISBN: 978-0831131463.

Narayan, V. (2004). Effective Maintenance Management: Risk and Reliability Strategies for Optimizing Performance, *Industrial Press Inc.*, 1, 246. ISBN: 0-8311-3178-0.

NASA, (2008). RCM Guide. Reliability-Centered Maintenance Guide for Facilities and Collateral Equipment. *National Aeronautics and Space Administration*. Available: <https://fred.hq.nasa.gov/Assets/Docs/2015/NASA_RCMGuide.pdf>

Newman, I., & Ridenour, C. (1998). Qualitative-quantitative research methodology: Exploring the interactive continuum. *Educational Leadership Faculty Publications*, 122, 1-12. ISBN: 0809321505.

Ngatchou, P.N., Fox, W.L.J. & El-Sharkawi, M.A. (2006). Multiobjective Multistatic Sonar Sensor Placement. *IEEE International Conference on Evolutionary Computation*, 2713-2719. ISBN: 0-7803-9487-9.

Nowlan F.S., & Heap, H.F. (1978). Reliability Centered Maintenance. *National Technical Information Service (NTIS)*, United Airlines, San Francisco International Airport, 476.

NSAI Standards, (2009). Dependability management: Reliability centred maintenance. *Application guide (IEC 60300-3-11:2009 (EQV))*, 3:11.

Oskouei F.S. & Pourgol-Mohammad M. (2015). Optimal Sensor Placement for Efficient Fault Diagnosis in Condition Monitoring Process; A Case Study on Steam Turbine Monitoring. *Lecture Notes in Mechanical Engineering*, 83-97. ISBN: 978-3-319-23596-7.

PdMA, (2014). PdMA Corporation: Tip of the week: TPM and RCM. [Cited 24.1.2018] Available in: <http://www.pdma.com/pdfs/tips/2014/5_26_2014.pdf>.

Pecht, M. (2009). Product reliability, maintainability, and supportability handbook. CRC Press, 2, 480. ISBN 978-0-8493-9879-7.

Peffers, K., Tuunanen, T., Rothenberger, M.A. & Chatterjee S. (2007). A Design Science Research Methodology for Information Systems Research. *Journal of Management Information Systems,* 24:3, 45-77.

Penttinen, J-P., & Lehtinen, T. (2016). Advanced Fault Tree Analysis for Improved Quality and Risk Assessment. Part of K.T. Koskinen et al. (eds.), Proceedings of the 10th World Congress on Engineering Asset Management (WCEAM 2015), *Lecture Notes in Mechanical Engineering*, 471-478.

Peshkin, D.G. & Hoerner, T.E. (2004). Optimal Timing of Pavement Preventive Maintenance Treatment Applications. *National Cooperate Highway Research Program (NCHRP)*, 523, 1-10. ISBN: 0-309-08811-9.

Pintelon, L. & Van Puyvelde, F. (2006). Maintenance Decision Making. Voorburg, 1, 272. ISBN: 90-334-6251-6.

Quality-one, (2015). Quality-One international discover the value: Failure mode, effects & criticality analysis (FMECA) Available in <https://quality-one.com/fmeca/#What>

Rausand M. & Vatn J. (2008). Complex System Maintenance Handbook: Reliability Centred Maintenance. *Springer Series in Reliability Engineering*, 79-108. ISBN: 978-1-84800-010-0.

Rausand, M. (1998). Reliability-Centered Maintenance. *Reliability Engineering and System Safety*, 60:2, 79-108; 121-132.

Rausand, M. & Hoyland, A. (2004). System Reliability Theory: Models, Statistical Methods, and Applications. *Wiley series in probability and statistics*, Wiley-Interscience, 2. ISBN: 0-471-47133-X.

NASA, (2000). Reliability Centered Maintenance Guide for Facilities and Collateral Equipment, *The National Aeronautics and Space Administration*, Washington D.C. Available in: <https://www.hq.nasa.gov/office/codej/codejx/Assets/Docs/RCMGuideMar2000.pdf>.

Russom, P. (2011). Executive Summary: Big Data Analysis. *TDWI best practices report*, Q4/2011.

Rymaszewska, A., Helo, P. & Gunasekaran, A. (2017). IoT powered servitization of manufacturing: an exploratory case study. *International Journal of Production Economics,* 192, 92-105.

SAE International, (2009). Evaluation Criteria for Reliability-Centered Maintenance (RCM) Processes: JA1011_200908. [Cited 3.12.2018]. Available in: <http://www.barringer1.com/mil_files/NAVAIR-RCM-VS-SAE-JA1011-Comparison.pdf>

SAE International, (2011). A guide to the Reliability-Centered Maintenance (RCM) standard. *Society of Automotive Engineers*, Warrendale.

Samui, P., Chakraborty, S. & Kim, D. (2017). Modeling and Simulation Techniques in Structural Engineering. Advances in Civil and Industrial Engineering, 130-131. ISBN: 1522505881.

Siddiqui, A. (2009). Reliability Centered Maintenance. *Handbook of Maintenance Management and Engineering,* 397-415. ISBN: 978-1-84882-471-3.

Smith, A.M., & Hinchcliffe, G.R. (2004). RCM - Gateway to World Class Maintenance. Elsevier, USA, 337. ISBN: 9780750674614.

Stapelberg, R.F. (2009). Handbook of reliability, availability, maintainability and safety in engineering design. *Springer Science & Business Media*. ISBN: 978-1-84800-174-9.

Finnish Electrotechnical Standards Association (SFS), (2001). Standard SFS-IEC 60300-3-11: Dependability management. *Application guide. Reliability centred maintenance.* 3-11.

Therivel, R., & Ross, B. (2007). Cumulative effects assessment: Does scale matter? *Environmental Impact Assessment Review*, 27(5), 365-385.

Tistel J., Eiksund, G., NTNU, Kvaerner, H.J., Bye, A. & Corneliu, A. (2015). Gravity-Based Structure Foundation Design and Optimization Opportunities. 772-779. ISBN: 978-1-880653-89-0.

Vandermerwe, S., & Rada, J. (1988). Servitization of business: Adding value by adding services. *European Management Journal*, 6:4, 314-324. ISSN 0263-2373.

Vargo, S.L. & Lusch, R.F. (2006). Service-dominant logic: What it is, what it is not, what it might be. *The Service-Dominant Logic of Marketing: Dialog, Debate, and Directions*, 43-55.

Vargo, S.L. & Lusch, R.F. (2004). Evolving to a new dominant logic for marketing. *Journal of Marketing*, 68:1, 1-17.

Veldman J., Klingenberg, W. & Wortmann, H. (2011). Managing condition-based maintenance technology: A multiple case study in the process industry. *Journal of Quality in Maintenance Engineering,* 17:1, 40-62.

Wang, H. (2002). A survey of maintenance policies of deteriorating systems. *European Journal of Operational Research*, 139:3, 469-489.

Wärtsilä celebrating-100-years-as-stock-listed-company (2018). Available in: <https://

www.wartsila.com/resources/articles/wartsila-celebrating-100-years-as-stock-listed-company>

Wärtsilä Factsheet (2018). Available in: <https://www.wartsila.com/investors/wartsila-as-an-investment/factsheet>

Wärtsilä Services Catalogue for Marines (2018). Available in <https://www.wartsila.com/services/areas-of-expertise/services-catalogue#/marine>.

Wärtsilä targets and achievements, 2018. Available in: <https://www.wartsila.com/about/strategy/financial-targets>.

Wärtsilä's markets (2018). Available in: <https://www.wartsila.com/investors/markets>

Wortmann, F. & Flüchter, K. (2015). Internet of Things: Technology and Value Added. *Business & Information Systems Engineering*, 57:3, 221–224.

Ylimäki, J. & Vesalainen, J. (2015). Relational development of a service concept: dialogue meets efficiency. *Journal of Business & Industrial Marketing*, 30:8, 939-950.

Yu, W., Liang, F., He, X., Hatcher, W., Lu, C., Lin, J. & Yang, X. (2018). A survey on the edge computing for the Internet of Things. *IEEE Access*, 6, 6900–6919. ISSN: 2169-3536.

Appendix 1: Terminology

Availability: Aspect of system reliability that considers equipment maintainability. Designing requires an evaluation of the consequences of unsuccessful operation or performance of integrated systems. The critical requirements necessary to restore operation or performance to design expectations. (Stapelberg, 2009:5)

Co-creation: A business strategy focusing on customer experience and interactive relationships. Co-creation allows and encourages a more active involvement from the customer to create a value rich experience. (Business Dictionary, cited 12.12.2018)

Failure: No success, the fact of someone or something not succeeding (Cambridge Dictionary, cited 7.12.2018)

Maintainability: Aspect of maintenance that considers downtime of the systems. Designing requires an evaluation of the accessibility and repairability (i.e. ability to repair) of the inherent systemsand their related equipment in the failure event. Also integrated systems shutdown during planned maintenance is required in designing maintainability (Stapelberg, 2009:5-6)

Reliability: Regarded as the probability of successful operation of performance of systems and their related equipment, with minimum risk of loss/disaster or system failure. Designing requires an evaluation of the effects of failure of the inherent systems and equipment. (Stapelberg, 2009:5)

Safety: Classified to three categories: relating to personal protection; to equipment protection; and to environmental protection. Defined also as not involving risk. (Stapelberg, 2009:6)