Reliability Centered Maintenance

*Different Implementation Approaches*

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Civil Engineering, masters level
2016

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RCM

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Luleå/Sweden 2016

Master of Science in Engineering Technology
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PREFACE AND ACKNOWLEDGEMENT

This research presented in this thesis has been carried out in the subject area of Operation and Maintenance Engineering at Luleå University of Technology (LTU), Luleå, Sweden. I would like to thank my supervisor Behzad Ghodrati (Associated Professor in the Division of Operation and Maintenance Engineering at LTU) for providing support and resources for my master thesis. I would also like to thank Associated Professor Alireza Ahmadi, Dr Hussan Al-Chalabi, Dr Ahmed Al-Rubaei, and all my teachers and friends in LTU.

Special thanks for Khalid Habibi Alredha and Ali Badi for supporting me during my studying at the university. I would also like to thank all my teachers in the municipality adult education in Nordanstig commune, in Hälssningland (Annelie Nyrén, Magnus Danchwardt), and my friends from Netherlands (Frans, Christine, and David).

Special thanks to my family (my wife, my brother and sisters) for supporting during my life and for continues supporting. Special thanks to my beloved parents; my father Teacher Ahmad Al Haiany and my mother Teacher Iman Al Haiany for supporting and teaching me and for continues helping.

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Luleå, Sweden

August 2016
ABSTRACT

Mining equipment are becoming very sophisticated and complex. At the same time, mining companies modernise its operation by increased mechanisation and automation (Dhillon, 2008). That requires well-developed and planned maintenance strategy. A proper maintenance strategy and appropriate maintenance actions, are essential to keep equipment safe & reliable, decrease the overall costs, and it helps to eliminate workplace hazards.

Maintenance strategies and maintenance actions, in turn, are changed and developed more than any technology (Moubray, 1997). Changing and developing of the maintenance can be due to many factors, perhaps due to the complexity of the systems or due to the development of the technology. One of the best research (developed technology) that has been done in this area is the research by Nowlan and Heap about Reliability Centered Maintenance (RCM) in 1978.

RCM is defined as, “a zero-based, structured process used to identify the failure management strategies required to ensure an asset meets its mission requirements in its operational environment in the safest and cost – effective manner” (Regan, 2012). The RCM is one of the best powerful asset management strategies. RCM can be applied to any asset, nuclear power plant, aeroplane, or truck ship. According to (Nowlan & Heap, 1978), the main goal of implementation an RCM process is to provide the stated function of the facility with required reliability and availability at the lowest cost.

In this master thesis, an RCM analysis process has been described in details. Moreover, two types of implementation approaches of an RCM analysis process have also been described. The intention of describing these two approaches is to see what the differences between them are and which one can be recommended for using in mining. The first approach is according to (Hinchcliffe & Smith, 2004) and the second approach is according to (Regan, 2012). Moreover, in this master thesis, there are also two case studies that have been analysed. The intention of analysing these two case-studies is to see how the RCM has been implemented.

As a result of the research carried out in this master thesis, some basic streamline RCM analysis process has been recommended for using in mining. This recommended RCM analysis process could be applicable to be used in every industry section. The result of this work can be summarised that RCM is an applicable tool which can be used in mining for selecting the right maintenance approach for different equipment, systems or subsystem.

RCM analysis process is discussed from different perspective. In the discussion, the misconceptions about the implementation of an RCM analysis process have been discussed. Altogether, Reliability Centered Maintenance is one of the most powerful asset management strategies that can be used in every industry section. If the RCM is applied by right people and by the right way, the result can be profitable for the mining companies.

Keywords: Reliability Centered Maintenance, RCM, Implementation of RCM, RCM Analysis Process, RCM Implementation methodology.
SAMMANFATTNING

Gruvutrustning och maskiner har blivit mycket sofistikerade och komplexa under de senaste åren. Samtidigt håller gruvföretagen på att modernisera sina verksmaheter genom ökad mekanisering och automatisering (Dhillon, 2008). Detta kräver en väl utvecklad och planerad underhållsstrategi. En riktig underhållsstrategi och en lämplig underhållsåtgärd är viktigt för att hålla utrustning säker och pålitlig samtidigt minskar de totala kostnaderna och bidrar till att risker på arbetsplatsen elimineras.

Underhållsstrategier och underhållsåtgärder, i sin tur, har förändrats och utvecklats mer än någon annan teknik. Förändringen och utvecklingen kan bero på många faktorer, möjligtvis på grund av komplexiteten i de nya systemen eller på grund av utvecklingen av tekniken (Moubray, 1997). En av de bästa forskningarna (utvecklad teknik) som har gjorts på detta område är forskningen av Nowlan och Heap om Reliability Centered Maintenance (RCM) år 1978.


I resultat av detta examensarbete, kan man se en rekommenderad RCM-metod som kan användas för tillämplig av RCM i gruvdrift. Denna rekommenderade RCM-metod skulle kunna tillämpas för användning inom alla branscher. Resultatet av detta examensarbete kan också sammanfattas genom att bekräfta att RCM är ett tillämpligt verktyg som kan användas i gruvdrift för att välja rätt underhållsstrategi för olika utrustning, system eller delsystem.

Sist men inte minst har RCM analysprocessen diskuterats utifrån olika perspektiv. I diskussionen har missuppfattningar om genomförandet av en RCM analysprocess diskuterats. Sammantaget är Reliability Centered Maintenance en av de mest kraftfulla förvaltningsstrategier som kan användas inom alla branscher. Om RCM tillämpas av rätt personer och på rätt sätt kan resultatet bli lönsamt för gruvföretagen.

Nyckelord: Reliability Centered Maintenance, RCM, Genomförande av RCM, RCM analysprocessen, RCM genomförandemetod.
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<td>A</td>
<td>Availability</td>
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<td>CA</td>
<td>Criticality Analysis</td>
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<td>CBM</td>
<td>Condition Based Maintenance</td>
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<td>CM</td>
<td>Corrective Maintenance</td>
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<td>CMMS</td>
<td>Computerized Maintenance Management System</td>
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<td>D</td>
<td>Detection</td>
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<td>FMEA</td>
<td>Failure Mode and Effects Analysis</td>
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<td>FMECA</td>
<td>Failure Mode, Effects and Criticality Analysis</td>
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<td>IPP</td>
<td>Impact per Publication</td>
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<td>LCC</td>
<td>Life Cycle Cost</td>
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<tr>
<td>LCP</td>
<td>Life Cycle Profit</td>
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<td>LTA</td>
<td>Logic Tree Analysis</td>
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<tr>
<td>MTBF</td>
<td>Mean-Time-Between-Failure</td>
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<td>MTTF</td>
<td>Mean-Time-To-Failure</td>
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<tr>
<td>MTTR</td>
<td>Mean-Time-To-Repair</td>
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<td>OEM</td>
<td>Original Equipment Manufacturing</td>
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<td>OCC</td>
<td>Occurrence</td>
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<td>PaM</td>
<td>Proactive Maintenance</td>
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<td>PdM</td>
<td>Predictive Maintenance</td>
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<td>PM</td>
<td>Preventive maintenance</td>
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<td>RCA</td>
<td>Root-Cause Analysis</td>
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<td>RCM</td>
<td>Reliability-Centered Maintenance</td>
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<td>RM</td>
<td>Risk Management</td>
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<td>Risk Priority Number</td>
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<td>RTF</td>
<td>Run to Failure</td>
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<td>S</td>
<td>Safety</td>
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<td>SEV</td>
<td>Severity</td>
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<td>TPM</td>
<td>Total Productive Maintenance</td>
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1 INTRODUCTION

This chapter deals with the background of mining equipment maintenance, development of maintenance and maintenance strategies. It is aimed to introduce the Reliability Centered Maintenance which in turn will be described in details in chapter three. This chapter also deals with the statement of the problems, purpose of the thesis, and the research questions. By the end of this chapter, the delimitations will also be defined.

1.1 Background

There are many people are working in mining industries throughout the world. Only in the USA, there are more than 675,000 peoples are employed in the natural resources and mining sector (Dhillon, 2008). Each year, many billions of dollars are spent on manufacturing different types of equipment for use by the mining industries around the world.

By the time, mining equipment is becoming very sophisticated and complex. That leads to, increasing of operation- and maintenance costs. Besides, governments and organisations require that mining equipment must be safer for the operator and environment-friendly. Mining companies need also modernise its operation by increased mechanisation and automation (Dhillon, 2008).

Therefore, a proper maintenance is essential to keep equipment safe and reliable and it helps to eliminate workplace hazards. It is important, a proper maintenance program is in the place and all maintenance work is risk assessed before beginning the work. Then, the cost of maintenance must be plausible in order to mining companies meets the goals in their business strategy.

Without proper maintenance, the workplace will not be safe and mining equipment will suffer and the cost of maintenance will increase. Therefore, it is needed to maintain the equipment as it needs and continuously improve the maintenance methods. According to (Dhillon, 2008), the following facts are related directly or indirectly to mining equipment maintenance;

1- Over 25% of the accidents in underground coal mining occur during maintenance activity.
2- The total annual cost of engineering maintenance is approx. $450 million in the Australian underground coal mining industry.
3- Approximately 10% of production time is lost by unplanned maintenance in Australian underground coal mining industry.
4- Usually, the cost of maintenance in the mining industry varies from 40% to 50% of the equipment operating cost.
5- Equipment maintenance costs range from 20% to over 35% of total mine operating costs.
6- According to civilian and military studies, it is possible to reduce preventive maintenance and corrective maintenance tasks times by 40% to 70% with planned maintainability design efforts.
In specific point of view or from the production perspective, mining equipment is essential and critical. In underground mining process cycle, there are many types of equipment that are in the drift, figure (1-1) illustrates a typical mining operation cycle. To generate a continuous ore flow, there are different types of mining equipment such as:

1- Drill rigs for development and production.
2- Vehicles for charging holes.
3- LHDs for loading and transportation.
4- Scaling rigs and rigs for reinforcement and cable bolting.

Mining companies strive for high equipment availability in order to reduce the operational and capital costs. As mentioned previously, a proper maintenance of mining equipment can entirely reduce the overall cost and boost the productivity of the mining. As it well known in maintenance field, high availability of mining equipment requires high reliability and high maintainability. Therefore, high reliability is important for the mining companies especially in attempts to automate the production. Reliability Centered Maintenance as a maintenance technique increase the availability of the plant or the equipment by increasing the reliability and maintainability (redesign or modification) of the equipment.

1.1.1 The Development of Maintenance
Starting from sixty years ago, industrial maintenance has been developed in a different perspective. Maintenance has evolved from non-issue into a strategic concern. By other words, maintenance has evolved from inevitable part of production into an essential strategic element to reach the business objectives. Therefore, nowadays maintenance is considered as an internal or external partner of success (Khairy et al., 2008).

However, maintenance has been changed more than any management and technology. The changing can be due to many factors, perhaps due to the complexity of the systems or due to the development of the technology and the research that done in this field, (Moubray, 1997). One of the best research that has done in this area was the work that has been done by Nowlan and Heap about the RCM, Reliability Centered Maintenance in 1978. According to (Moubray, 1997), the evolution of maintenance can be traced through three generations, figure (1-2).
1.1.2 First Generation

According to (Moubray, 1997), up to the Second World War, the industries were not highly mechanised and the downtime in the production did not matter. Therefore, many managers around the world have not any desire to prevent equipment’s failure. That was because the equipment was simple, overdesigned and available (reliable and easy to maintain when it fails). That lets to no systematic maintenance was needed and the basic maintenance philosophy was, fix the problem when they occurred. Figure (1-3), illustrates the traditional thinking of failure occurrence which is the failure rate increase by the time.

1.1.3 Second Generation

After the Second World War, manufacturing of equipment and machines changed dramatically. New technology implemented on different equipment & machines and they began to be complex and more sophisticated, in comparison to the old one (Moubray, 1997). Dependence on the new equipment with new technology grew and led to some sharp focus on the downtime. Therefore, managers started to think about the different ways to prevent equipment’s failure. That resulted in the birth of the preventive maintenance concept. The cost of increasing maintenance work led in turn to maintenance planning and control systems. Figure (1-4), illustrates the traditional thinking of failure occurrence in this generation.
1.1.4 Third Generation

In this generation, the changes in industries have been gathered even greater momentum. It can be summarised in new expectations, new research and new techniques (Moubray, 1997). In 1960’s and 1970’s, the concept of just in time (JIT) manufacturing became in focus. That means, any stop of the production could interfere the operation of an entire facility. By other words, the downtime (planned or unplanned) has many effects on increasing operating costs, reducing output and affecting the customer service. Therefore, in this generation, the downtime is an issue that need detailed analysing.

The mechanisation and automation of the facilities have also become as issues in this generation. Therefore, reliability and availability are issues as diverse as health care, data processing, and telecommunications (Moubray, 1997). Another issue is the quality standards that are arising rapidly. Some failures have serious safety and environment consequences. These types of failure must be prevented of mitigated. All these issues, increase the dependence on the integrity of the physical asset. In this generation, it became evident to the research and maintenance engineers that there are different failure patterns figure (1-5). These different failure patterns will be explained later in chapter three.

![Third Generation Diagram](image)

According to (Moubray, 1997), during this generation, there are an amazing growth of maintenance concepts and techniques. The development includes:

1- Decision support tools such as hazard studies, failure mode and effect analysis
2- New techniques such as condition monitoring
3- Designing equipment with must greater emphasis on reliability and maintainability
4- A major shift in organisation thinking towards participation, team working and flexibility

However, the greatest challenge facing maintenance people nowadays is not how to learn the new maintenance techniques rather than how to decide which maintenance techniques must be applied in different organisations.
1.2 Maintenance Management and Strategy

The official definition of maintenance is the “combination of all technical, administrative and managerial actions carried out during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform its required function” (EN 13306, 2001).

Maintenance management is defined as “all activities of the management that determine the maintenance objectives, strategies, and responsibilities and implement them by means such as maintenance planning, maintenance control and supervision, improvement of methods in the organisation including economic aspects” (EN 13306, 2001).

Maintenance strategy, in turn, is also defined as “management method used in order to achieve the maintenance objectives” (EN 13306, 2001). By other words, maintenance strategy lets the responsible managers know how to plan to reach where they want to be from where they are at that moment. Maintenance strategy also allows the responsible managers to focus on all relevant improvement initiatives, and also to align all objectives with that of business goals. According to (Kelly, 1997), a well-developed maintenance strategy is required by other to:

1- To evolve the maintenance time plan
2- For concentrated planning and efforts
3- For consistent pattern of decision making
4- For persuasiveness and motivation
5- To achieve the business objectives

According to European Standard (EN 13306, 2001) and Figure (1-6), maintenance can be divided into two major groups. Preventive Maintenance which is before the occurrence of a failure, and corrective maintenance which is after the occurrence of a failure.

![Figure 1-6 Maintenance overview chart according to (EN 13 306, 2001)](image-url)
1.2.1 Preventive Maintenance PM

Preventive maintenance (PM) is a proactive maintenance approach. PM is in turn subdivided into two groups: condition based maintenance or pre-determined maintenance, time-based maintenance and usage-based maintenance. It is defined as “a maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item” (EN 13306, 2001).

1.2.2 Corrective Maintenance CM

Corrective maintenance (CM) is a reactive maintenance approach. CM is also subdivided into two groups: deferred or immediate. It is defined as “a maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function” (EN 13306, 2001).

1.2.3 Reliability Centered Maintenance RCM

The title above consists of three essential terms, reliability, centered, and maintenance. The first term is the reliability which can be defined as “ability of an item to perform a required function under given conditions for a given time interval” (EN 13306, 2001). This definition of reliability requires a description of the functional failure (what does the failure mean to the user or to the repairer). The definition of the reliability also requires a description of the operating’s condition (e.g. car or home environment). The time interval must also be specified (at which time e.g. 10 days, 12 months, or 3 years, etc.).

The second term is “Centered” which means that an RCM analysis process focuses on the target. The target can be determined before initiating an RCM analysis process. The third term is Maintenance, which has been defined before.

Many authors have identified RCM. However, the original definition of RCM is “a logical discipline for the development of scheduled maintenance programs” (Nowlan and Heap, 1978). The another definition of RCM is according to Regan (2012) which is “a zero-based, structured process used to identify the failure management strategies required to ensure an asset meets its mission requirements in its operational environment in the safest and cost effective manner”. In this definition, there are three important terms;

1- Zero-Based. It means that failure modes and failure effects are written assuming that nothing is being done to prevent or predict the failure mode. That leads to failure consequences are assessed, and solutions are formulated without mentions to what is currently being done.

2- Failure Management Strategies. It means that RCM analysis process is carried out to identify the failure management strategies, not maintenance tasks.

3- Operational Environment. It means that when solutions for an asset are formulated, some different issues regarding the operational environment are considered. That will be explained in details later in chapter three.

6
1.3 Statement of the Problem
This master thesis describes different implementation approaches of an RCM analysis process. Various methods are used when RCM analysis process is performed. RCM analysis process can be performed in different phases of equipment life cycle. RCM analysis process is often conducted in the design phase of equipment, but it can also be performed for an existed equipment or system.

In this thesis, two different implementation approaches are explained in details. These two different implementation approaches can be used for new equipment (design phase) or for an existed equipment.

1.4 Purpose of the Research
The primary purpose of this thesis is to illustrate the methodologies or implementation approaches of Reliability Centered Maintenance. The secondary purpose of this thesis is to illustrate how an RCM analysis process can be performed in a basic way for an existed mining equipment.

1.5 Research Questions and Objectives
1- What is an RCM analysis process and how it can be performed?
2- What are the benefits and goals of implementation an RCM analysis process?
3- What are the principles or key features of an RCM analysis process?
4- What are the difference between two implementation approaches of an RCM analysis process?
5- What are the difference between the described approaches?
6- Analysing different case-studies where an RCM analysis process is implemented

1.6 Delamination
Reliability Centered Maintenance is a hard topic which requires a holistic & comprehensive view and enormous research about the intended implementation area. Therefore, this master thesis is delimitated to describe only the different implementation approaches and answer the research questions. Moreover, the analysed case-studies are included in this thesis only to show how an RCM analysis process are used in real case-studies and what the difficulties are?
2 METHODOLOGY

This chapter describes the methodology and the procedure, used for writing this thesis. This chapter describes the work that has been done in this master thesis from the desire through the idea and choice of the case studies. However, the procedure of implementation the RCM will be described lightly or simply due to it will be explained in details later on in chapter three.

2.1 Phase 1: Self-study and finding

After two years’ studies at Luleå University of Technology LTU, a desire created to do the last course namely, the master thesis in the operation and maintenance which has been the most favourable subject. The operation and maintenance is a big area and development in this field is going on in a different perspective. However, to choose a specific area for doing the research has been not difficult because there is a huge desire to work with operation and maintenance. Phase 1 figure (2-1) consists of three parts, explained here to give a holistic illustration of the work that has been done in this phase.

The desire is to apply the mathematical and theoretical knowledge (what is learned about operation and maintenance, studied in different courses at the Luleå University of Technology) in the operation and maintenance section. The desire started by attending mine automation course D7001B at LTU. The idea arises which is to fill the knowledge gaps, to do something which could be expected by the university or by the companies. After some genuine research, it has become evident that there are many things in the maintenance field, need to be developed and optimised. One of the most interesting research areas is, developing the preventive maintenance and optimising the condition-based maintenance.

Among the studied areas, the RCM analysis process has been chosen as a research subject (choice). RCM as a maintenance strategy is one of the most robust and credible maintenance strategy. It optimises and develops the preventive maintenance and choose the right maintenance task for each system of subsystem in equipment. RCM analysis process is extremely difficult and requires an enormous research and entire knowledge of how it can be implemented.

![Figure 2-1 Phase 1-1: desire, idea and choice](image)
To gather the required knowledge about operation and maintenance, different courses were studied. As mentioned before, the desire was started by reading the Mine Automation course D7001B at LTU. Attending this course, gave the fundamentals of mine automation and the required knowledge were gathered.

However, to collect the required knowledge about operation and maintenance in general and especially the necessary knowledge about RCM, two types of courses were studied figure (2-2). LTU courses that deals directly or indirectly with RCM:

1- Operation and MaintenanceD0002B.
2- Mine Automation D7001B.
3- Operation and Maintenance Engineering D7004B. This course described the RCM in details and gave all required knowledge about how RCM can be implemented.
4- Production Equipment Management D7002B.
5- Operation and Maintenance- Hydropower D0004B.

![Figure 2-2 Phase 1-2: The aid by university studies](image)

The online course is called Implementation of RCM. It is attended especially just to learn more about how RCM could be implemented in field in a real case study. This course is given by an Australian company which is called Lifetime Reliability Solution LRS.

2.2 Phase 2: Literature Study

As mentioned previously, to achieve the aim of the intended research, an enormous research has been done. Different books by different authors have been read. The RCM process, in general, is not a difficult, but it requires a detailed information about the equipment, ability to collect the required data and knowledge about the implementation of an RCM process.

Figure (2-3) illustrates how the literature study has been carried out. There are many science articles, published in international journals, shows how an RCM process can be implemented. These articles are read to understand how an RCM process is implemented.

However, the main book which has been read to implement the RCM process is *The RCM solution* by (Nancy Regan, 2012). This book is well written and it has a perfect description of the implementation of an RCM analysis process. It gives a practical guide for starting and maintaining a successful RCM program and how an RCM analyses process can be applied. However, there are other books have been read and they are listen in the reference.
2.3 Phase 3: RCM Implementation Approaches

One of the research questions, is to describe the difference between RCM implementation approaches. Implementation of an RCM analysis process can be carried out by different methods. However, there are many different RCM approaches created and written by different authors. The approaches that will be described are depicted in figure (2-4):

- According to Nancy Regan
  1- RCM Operating context
  2- RCM seven questions;
     - Q1: Functions
     - Q2: Functional Failure
     - Q3: Failure Mode
     - Q4: Failure Effect
     - Q5: Failure consequences
     - Q6: Proactive Maintenance and Intervals
     - Q7: Default Strategies

- According to Hinchcliffe and Smith
  1- System selection and information collection
  2- System boundary definition
  3- System description and functional block diagram
  4- System functions and functional failures – preserve functions
  5- Failure Mode and Effect Analysis (FMEA) – prioritize failure modes
  6- Logic Tree Analysis (LTA). Prioritize functions need via the failure modes
  7- Task selection – select only the applicable and effective PM tasks.
2.4 Phase 4: Selection Criteria for the Case Studies

The case studies for analysis, are selected by different methods. Figure (2-5), illustrates how the selection is carried out. The first priority is given to the case-studies that are published in an international journal which has a high impact factor (IPP, minimum is 0.5). The second priority is given to case-studies which have many citations, and the last priority is given to the case-studies which have an author that has high h-index (minimum h-index is 1). The databases that are used as aide for selecting case studies are:

1- Scopus: Reference database for scientific articles in all subjects
2- Web of science: Reference database that provides access to several databases and covers almost 10,000 leading journals of science, technology, social sciences, arts, and humanities and over 100,000 book-based and journal conference proceedings
3- Google scholar: Google Scholar searches academic publishers, professional societies and pre-print archives.
4- LTU library.

The keyword that are used when selecting the case-studies are:

1- Reliability Centered Maintenance
2- RCM
3- RCM Implementation
4- RMC Implementation in mining
5- RCM analysis process

Figure 2-5 Phase 4: Criteria for selection for the case studies
3 RELIABILITY CENTERED MAINTENANCE (RCM)

This chapter is written to give the reader an introduction to the Reliability Centered Maintenance (RCM). Moreover, this chapter describes the history and evolution of RCM, different types of RCM, the principles of RCM, and different implementations approaches according to different authors. However, this chapter includes also another important issues related to the RCM analysis process.

3.1 Introduction to RCM

Reliability-Centered Maintenance (RCM), identifies the functions of a system, equipment or an asset, which could be critical and then seeks to optimise their maintenance strategies. The most critical assets are those that are often likely to fail or those that have some hazard consequences in case failure (Regan, 2012). It is nearly impossible to prevent all failure but it is possible to develop a maintenance strategy that could prevent some failures. The essence of RCM is to manage the consequences of the failure, not necessarily preventing them.

One of the most beneficial products of an RCM analysis is the identification of the best proactive maintenance tasks such as on-condition maintenance, scheduled restoration & replacement, and scheduled discard tasks. With this maintenance tasks, possible failure modes and their consequences are identified while the function of the equipment is considered. The most effective techniques are then selected to improve the reliability of an asset.

According to (Regan, 2012), RCM is a process used to develop a proactive maintenance for an asset. However, an RCM analysis process can also be used to formulate scores of solutions that reach far beyond maintenance such as:

1- Design modifications.
2- Changes to a training program, and modifications to technical manuals.
3- Identification of new operating and emergency procedures.

An RCM analysis process examines the equipment as a series of functional systems, each of which has inputs and outputs. It is the reliability of the system, rather than the functionality that is considered. According to (SAE JA 1011, 2009), there are minimum criteria before any maintenance strategy can be called as RCM. The seven steps need to be done by order for each asset are:

1- What are the functions and desired performance standards of each asset?
2- How can each asset fail to fulfil its functions?
3- What are the failure modes for each functional failure?
4- What causes each of the failure modes?
5- What are the consequences of each failure?
6- What can and/or should be done to predict or prevent each failure?
7- What should be done if a suitable proactive task cannot be determined?
3.1.1 Definitions
The concept of RCM is defined by many authors who have been working with RCM or who have created the concept of RCM. According to Maintenance Steering Group (MSG-1), RCM is defined as a “logical discipline for the development of scheduled maintenance programs”. However, RCM is created by Nowlan and Heap in 1978 after enormous research of the failure patterns. Here are different definitions of RCM;

1- RCM is a disciplined logic or methodology used to identify preventive maintenance tasks to realize the inherent reliability of equipment at the least expenditures of resources (Nowlan and Heap, 1978).
2- RCM is a process used to determine the maintenance requirements of any physical asset in its operating context or a process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating context (Moubray, 1997).
3- A zero-based, structured process used to identify the failure management strategies required to ensure an asset meets its mission requirements in its operational environment in the safest and cost effective manner (Regan, 2012).
4- RCM is the best way to develop a maintenance improvement program (Hinchcliffe & Smith, 2004).
5- RCM is a process to identify components whose functional failures can cause unwanted consequences to one’s plant or facility (Bloom, 2006).
6- RCM is a specific process used to identify the policies which must be implemented to manage the failure modes which could cause the functional failure of any physical asset in a given operating context (SAE JA 1011, 2009).

3.1.2 Purpose
As mentioned previously by the definitions of RCM, the purpose can be summarised in two different points (NASA, 2008):

1- It is used to determine what the failure management strategies should be applied to ensure a system achieves the desired levels of safety, reliability, environmental soundness, an operational readiness in the most cost effective manner.
2- The implementation of an RCM process may eliminate unnecessary maintenance tasks, resulting in truly applicable and effective maintenance.

3.1.3 Benefits
It is a time-honoured, proven process that has been used the world around. The principles of RCM are versatile and powerful; therefore, the RCM has stood the test of time. The RCM is described as one of the best powerful asset management strategies. RCM can be applied to any asset, nuclear power plant, aeroplane, tuck ship and so on. However, an RCM process cannot be implemented on all equipment if there are not enough resources to do so.
3.1.4 Goals
According to (Nowlan & Heap, 1978), the main goal of implementation an RCM process is to provide the stated function of the facility with required reliability and availability at the lowest cost. However, there are other goals & objectives:

1- To ensure the realization of the inherent safety and reliability levels of the equipment.
2- To restore the equipment to these inherent levels when deterioration occurs.
3- To obtain the information necessary for design improvement of those items where their inherent reliability proves to be inadequate.
4- To accomplish these goals at minimum total costs, including maintenance costs, supports costs, an economic consequences of operational failures.

3.2 The History of RCM
According to (Nowlan & Heap, 1978), the RCM get its start in 1960’s. The cost of maintenance tasks in the aircraft industry in that time became very high due to the type of maintenance strategy. Therefore, it was needed to investigate the effectiveness of maintenance tasks in the applied maintenance strategy. The MSG (maintenance Steering Group) for civil aviation industry considered that it was necessary to re-examine the reliability aspects. Consequently, the representatives of aircraft companies decided to investigate the capabilities of the preventive maintenance to increase the reliability for the new airplanes.

As a result of that investigation, the research group provided the airlines and aircraft companies guidelines for their maintenance tasks. Indeed, it was some guidelines for better understanding about how they can decide the maintenance work. However, it led to MSG-1 that was used to develop the maintenance program for Boing 747 aircraft. MSg-1 became the first maintenance program to apply the RCM concept. The next revision of MSG-1 formulated as MSG-2, which introduced in 1970. It was used to develop the maintenance program for Lockheed L-1011 and the Douglas DC-10. These guidelines succeed by giving the best maintenance program by different ways.

In 1974, the department of defence in the USA asked United Airlines to provide them a detailed report about the maintenance process they used in the civil aviation industry. The report which sends to the department of defence in the USA was written by Stan Nowlan and Howard Heap, and it published in 1978. This report entitled the RCM and become the source for all books and report that used RCM. Nowlan and Heap found a vital thing about the maintenance strategy that was believed before. What they found can be summarized in the following issues:

1- All failures cannot be prevented even by the intensive maintenance tasks.
2- The probability of failure did not increase with operating age.
3- Reducing the replacement periods increases the repair cost without any benefits.
4- Maintenance program that is based on operating age have a minor effect on failure rate.
3.3 The Evolution of RCM

As mentioned, the RCM is a very powerful asset management process that can be employed nearly in any industry. However, this process should be done by right people and by the right way. The RCM is not a new process; it has been used in every industry throughout the world, and the application of the RCM spans four decades (Regan, 2012).

During the 1950s and before that, it was believed that all failures were directly related to the operating age. That means the failure occurs when it’s operating age increases. As it depicted in the figure (3-1), the probability of failure increases if the item remains in service.

Therefore, it was believed that the best thing to do was to replace the item before it reaches the end of its useful life. It was believed that the replacement of an item before reaching the end of its useful life, would prevent the failure. This mindset was embedded in the maintenance programs, and approximately 85% of aircraft components had a fixed interval for a replacement which led to the scheduled maintenance program was very high (Regan, 2012).

By 1959s, new airplanes were manufactured, and they contained advanced technology such as electronics, hydraulics, and turboprop engines. Those new airplanes required some advanced maintenance knowledge, and because they were new, there wasn’t any historical failure data or operational experience. Without the historical failure date and operational experience, it was difficult to know the useful life of the component in those new airplanes.

Early in the 1960s, the failure data were accumulated, and it showed that the crash rate was incredible, more than 60 crashes per million take-offs. The maintenance engineers could detect that two-thirds of these crashes were related to equipment failure (Regan, 2012). It was an issue for maintenance engineers, management and government and they were forced to solve this issue. They wanted to increase the reliability for the airplane’s systems. Therefore, they decided to shorten the replacement intervals of the component/systems in order to decrease the maintenance downtime. Figure (3-2) shows the attempt which was taken into increasing the reliability of the airplane’s component/system.

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The attempt into increasing the airplane reliability, gave an unexpected result which made the solution of the problem more difficult (Regan, 2012). The result of that attempt can be summarized as:

1- In very few cases things got better.
2- In very few cases things stayed the same.
3- But for the most part, things got worse.

This result made the reliability increasing for the airplane systems very difficult, and the responsible engineers felt unable. They started to think in details about the relation of operating reliability and the policy for the maintenance. They realize that such kind of maintenance strategy namely, replacement and overhauling of component before reaching the end of their useful life embedded two assumptions (Regan, 2012);

1- The assumption I: The likelihood of failure increases as operating age increases.
2- Assumption II: It is assumed that it is known when the failure will occur.

The responsible engineers did a lot of researches, and many parts of airplane components were analyzed. In fact, the result of that research gave the researcher the ability to detect that there were more than on failure pattern which could describe the behavior of the failure. However, they found that it was six failure patterns which describe how the failure behave. The figure below describes the six failure patterns as depicted in figure (3-3).

A. Bath Tub Curve.
B. Constant failure rate, then wear out zone.
C. Steady increase in the probability of failure.
D. Low when new, then increases to steady failure rate.
E. Random.
F. Infant Mortality, then random.

By looking at the figure (3-3), the six patterns can be divided into two groups. The first group are patterns A, B, and C which have a direct relationship between the likelihood of failure and the age. That mentioned before in assumption I, (the likelihood of failure increases as operating age increases). The second group are patterns D, E, and F which have no relationship to the operating age and the likelihood of failure. This group describes that failure which occurs randomly (Regan, 2012).

The important consideration in the engineering’s research was the percentages of failure mode that conformed to each failure pattern (Regan, 2012). Only 11% of airplane system’s failure
mode behaved according to the assumption I, failure patterns A, B, and C. But the remaining 89% of airplane system failure modes showed that failures occur randomly without any relationship to the operating age. Figure (3-4) illustrates failure patterns and their percentages.

![Figure 3-4 Percentages of Failure Modes that conformed to Failure Pattern (Regan, 2012)](image)

Contrary to what it was believed before (all failures were directly related to the operating age), the research of failure patterns made sense that only 2% of failure modes behaved according to the assumption I and failure pattern B, as depicted in figure (3-5). For this kind of failure mode, it would be possible to use replacement and overhauling as a maintenance strategy.

![Figure 3-5 Percentages of Failure Modes conformed to Failure Pattern B (Regan, 2012)](image)

Furthermore, the research showed in figure (3-6) that 68% of failure modes occurs randomly. That means this type of failure does not have any relationship to the assumption I, and replacement or overhauling of the item will not increase the reliability.

![Figure 3-6 Percentages of Failure Modes that conformed to Failure Pattern F (Regan, 2012)](image)

However, the important things were the infant mortality failures (i.e. someone forget a tool inside the equipment or poor operating procedure) had a significant role in the occurrence of a failure. That make the systems unreliable figure (3-7).

![Figure 3-7 Reintroducing infant mortality (Regan, 2012)](image)
As a result of an enormous amount of research which had been done, says that not all failures are related to the operating age. However, the replacement and overhauling is not an effective solution for increasing the reliability of an item. And the most important thing which has been considered as a result of the research is, most of the failure occurs randomly. Thereby, a new way to develop a scheduled maintenance tasks provided the first step of the RCM (Regan, 2012).

3.4 Different Types of RCM
During the years, the RCM as a maintenance technique has been modified by different experts such as John Moubray, Anthony M. Smith, Jack Nicolas and others who has been working with maintenance. However, there are different types of RCM approaches that differ in where they can be used. According to (NASA, 2008) there are two types of RCM approaches:

1- Rigorous RCM approach.
2- Intuitive RCM approach.

Although the two types of RCM approaches use the same principles, they are not identical. According to (NASA, 2008), the choice of which approach that will be used depends on;

1- Consequences of failure, and probability of failure.
2- Historical data, and risk tolerance.

3.4.1 Rigorous
Rigorous RCM approach or classical RCM is the first type. It is the first approach proposed and documented by Nowlan and Heap. Later on, it has been modified by John Moubray, Anthony M. Smith, Jack Nicolas and others. This approach is based on the FMEA and includes probabilities of failure and system reliability calculations. However, this type of approach provides completed documentation of an RCM analysis process. A formal Rigorous RCM analysis of each system, subsystem, and the component is normally performed on new, high-cost systems. However, this approach should be limited to the following situations (NASA, 2008);

1- The consequences of failure result in catastrophic risk regarding the environment, health, safety, or complete economic failure of the business unit.
2- The resultant reliability and associated maintenance cost are still unacceptable after performing and implementing a streamlined type FMEA (intuitive RCM approach).
3- The system or equipment is new to the organization and insufficient corporate maintenance, and operational knowledge exists on its function and functional failures.

3.4.2 Intuitive (streamlined)
The second type of RCM approaches is called Intuitive RCM approach (Streamlined). It is appropriate for facility systems due to many factors such as the high analysis cost of the rigorous
RCM approach, the relatively low impact of the failure of most facilities systems, and the amount of redundant system in place. An intuitive RCM approach should be applied in the following situations (NASA, 2008);

1- The function of the system/equipment is well understood.
2- Functional failure of the system or equipment will not result in loss of life, catastrophic impact on the environment, or economic failure of the business unit.

As mentioned, these two types of RCM approaches are not identical. However, they use the same principles, but Intuitive RCM approach recognizes that not all failure modes will be analyzed.

3.5 RCM Principles and Key Features
There are four features that are used to define concept of the Reliability Centered Maintenance. These four features according to (Hinchcliffe & Smith, 2004) and (Ben-Daya, 2009), are set apart from any other maintenance planning process that is used today.

- Feature 1: Preserve system function
The first and most important principal feature of the RCM process is to “preserve system function”. It must be stressed, as it forms a change in the typical view of equipment maintenance and changes it with the view of functional preservation. What is required to identify the desired system output and ensure availability of the same output level?”. So the first objective of an RCM process is to “Preserve System Functions”.

- Feature 2: Failure Mode Identification
The second principal feature of an RCM process is, “identifying the particular failure modes” that can potentially cause a functional failure. This information is crucial whether design or operational modification is required or a maintenance plan is to be determined.

- Feature 3: Prioritize function need (via failure modes)
The third principal feature of an RCM process is prioritizing the functional failures. An RCM process provides the opportunities to decide in a systematic way, just what order or priority to assigning in allocating budgets and resources.

- Feature 4: PM Task Selection
This principal feature of an RCM process is last in sequence but not least in importance than previous features. As described earlier, the purpose of prioritizing is to make an efficient and cost-effective use of the resources.
3.6 System Influencing Factors in Context of RCM

According to (Regan, 2012) there are many factors that affect directly or indirectly the performance of on an equipment. Some of these factors are:

1- Scheduled maintenance.
2- Operating procedures and technical publications.
3- Training programs and equipment design.
4- Emergency procedures.
5- Operational tempo & environment, and supply issues.

These factors affect the equipment performance. Therefore, they should be taken into consideration and should be well-analysed. If they are well-analysed, the equipment will provide its intended functions. However, if they are inappropriate or incorrect the equipment will suffer. An example on that, incomplete operating procedure or badly scheduled maintenance will affect the equipment negatively. Therefore, these factors, for this reason, are really important to be included in RCM analysis. RCM can give many products/solutions that which called default strategies that are beyond from development of scheduled maintenance program, (Regan 2012). Some of these solutions are:

1- Develop a proactive maintenance plan.
2- Give a new operating procedure and update the technical publication.
3- Modify the training program.
4- Enhance troubleshooting procedures and

As mentioned above, that one of the products that an RCM analysis process can yield is, a scheduled maintenance program but there are other solutions. However, in context of RCM, the default strategies, and scheduled maintenance program referred to as failure management strategies. The figure (3-8) below, shows the failure management strategies (Regan, 2012).

![Figure 3-8 Failure management strategies (Adapted from Regan, 2012)](image-url)
3.7 Equipment Criticality & Risk Analysis

The RCM recognizes that the consequence of a failure is the main driver in all maintenance decision, instead of the failure itself. The objectives of the maintenance tasks are detected by the consequence of the failure. Therefore, in the context of the RCM, the reason for doing any maintenance actions, is to avoid the consequences, or at least reduce them to an acceptable level. The title above, equipment criticality and risk analysis, includes some terms that need to be described in details before getting into describing the analyzing of the critical equipment.

- Critical equipment
Critical equipment is defined as equipment that stops the production, or that causes a huge production cost when it fails (Moubray, 1997).

- Criticality
The term criticality in the context of the RCM is defined as the priority rank of a failure mode, based on some assessment criteria, (Maintenance Resources, 2016).

- Risk
The risk is defined according to (Verma & Srividya & Karanki, 2010), as the chance of injury or loss resulting from exposure to a source of danger. Safety is defined as freedom from danger or hazards. The authors named above, point it out in their description of the risk, which in the technology world there is no activity that has zero risks.

However, the risk is defined as chance of loss. In the technical world, the terms chance & loss are converted to probability (p) and consequence (C). Therefore, the risk is defined as probability multiply consequences. Thus, risk combines of both the probability (failure rate) of particular event and the scale consequences.

Risk (R) = Probability (P) \times Consequence (C)

Risk analysis consists of risk assessment, risk management, and risk communication. However, risk assessment figure (3-9), in general, has three basic steps that must be carried out professionally in order to estimate the magnitude and the potential losses of a failure.

Figure 3-9 Risk Assessment
Risk assessment can be done by different methods but in this report, only the first method (Failure Mode and Effects Analysis) will be described. However, the following methods are available and commonly used in the risk assessment (Dhillon, 2008);

1- Failure Mode and Effects Analysis, FMEA.
2- Failure Mode and Effects Criticality Analysis, FMECA
3- Fault Tree Analysis, FTA.
4- Hazard and Operation Analysis.

Risk can be assessed quantitatively or qualitatively. Quantitative risk assessment uses the risk formula or equipment criticality formula. Equipment criticality starts by using the risk formula. The consequences of an event may come in many forms. Therefore, the set of consequence dimensions that apply to different organizations or systems vary but in the context of the RCM there are three types of consequences namely;

1- Safety & Environmental,
2- Operational Costs,
3- Non-Operational Costs

Consequence dimensions are associated directly with the mission and level of service required of the organization or systems, not the events being considered. There are some important factors that must be known to the group who assess the equipment criticality. Some of these factors that assessments group must be familiar with are:

1- The impact on production of losing the equipment
2- Equipment operation.
3- Equipment design.
4- Operator manuals and maintenance manuals.

### 3.7.1 Risk Priority Number (RPN)

According to (Moubray, 1997) the concept of Risk Priority Number (RPN) is defined as a measure used when assessing the risk. RPN is used to identify the critical failure modes associated with a design or a process. By other words, it is a numerical ranking of the risks of each failure mode or failure cause. The RPN value ranges from 1 to 10 depending on the risk matrix estimated in the company. RPN is calculated as (Moubray, 1997):

\[
\text{RPN} = \text{Severity} \times \text{Occurrence} \times \text{Detection}
\]

\[
\text{Criticality assessment} = \text{Consequence} \times \text{Probability of Occurrence}
\]

RPN is an essential part of FMECA and it is widely used specially in automotive industries. It is often wrongly believed that the high RPN is always the critical one. That is not true because some failure mode has high occurrence and high detection but low severity. Therefore, it is extremely important that some focus and detailed analysis must be done when assigning risks.
3.8 Failure Modes and Effect Criticality Analysis (FMEA & FMECA)

This is one of the main used methods for performing the reliability analysis. FMEA starts usually in early phase of system design. FMEA can be done as separate or in an RCM analysis process. However, it is really important to describe the FMEA because it is an essential part of an RCM analysis process. In RCM Implementation approach, according to (Smith, 2004), FMEA is defined in step five. In the other approaches (Moubray and Regan), FMEA is an essential part of the analysis and consists of the first four steps.

- Definition

FMEA stands for Failure Mode and Effect Analysis. Each of the named terms is defined in Appendix 1. However, the definition of FMEA is an analysis used to determine what parts fail, why they usually fail, and what effect their failure has on the systems in total. It is an element of Reliability Centered Maintenance (NASA, 2008).

- Purpose

By FMEA or FMECA it could be possible to list all potential failures and identify the severity of their effects in an early stage of the design phase, select the most suitable design with a high reliability and high safety potential during the design phase, and create documentation for future designs and redesigns (Moubray, 1997).

The FMEA or FMECA can be used without implementation of an RCM analysis process. Many companies try to do the FMECA in order to illustrate the most critical failure mode. According to (Dhillon, 2008), there are many important applications of FMECA such as:

1- To identify weak spots in design,
2- To choose design alternatives during the early stages,
3- To serve as a basis for doing design improvement actions,
4- To identify weak areas in design,
5- To recommend appropriate test programs.

- Types

Failure Mode and Effects Analysis can be used in different stages. However, there are four different types of FMEA which are; design FMEA, system FMEA, process FMEA, and Service FMEA. The first two types can be explained in basic level as;

Design FMEA, an analysis of the system’s technical design taking account all types of failure modes Remove failures in the design process, (Moubray, 1997).

System FMEA, used for analyzing systems and subsystems in the early concept and design stage. A system FMEA Focuses on potential failure modes between the functions of the system caused by system deficiencies, (Moubray, 1997).
3.9 RCM Implementation, Hinchcliffe & Smith Approach

The first approach of RCM implementation is according to (Hinchcliffe & Smith, 2004). There are seven steps that are used to finalize an RCM analysis process. The following steps are defined in details to illustrate the methodology that is used in this approach. The following is an excerpt of the book "RCM gateway to world class maintenance” by (Hinchcliffe & Smith, 2004).

3.9.1 Step 1: System selection and information collection

The first step for RCM analysis process is to select a critical asset (equipment, system or a component). The critical asset is the asset that gives most pain to the company. It could be critical due to its effect on safety, environment, operations, its previous costs of repair and previous costs of preventive maintenance.

- System selection

An RCM analysis process can be applied on different levels, e.g. part or piece of a subsystem, sub-system- or a system of an equipment, or on the whole facility. However, it depends on the specific situation (what is required and needed). When the PM planning is approached from function, the most efficient function list for RCM analysis is at the system- or subsystem level. According to (Hinchcliffe and Smith, 2004), at system or subsystem level it could be possible to define the significance of functions.

- Information Collection

Information collection requires multidisciplinary research. However, the RCM analysis process depending on which approach (Intuitive or Rigorous) and implementation of RCM in design phase or on a used asset, needs all information about the previous maintenance and operation. So, there are several documents that are required to be collected such as;

1- System schematic and/or block diagrams: facilitate a good understanding of the main equipment and function features of the system.
2- Individual vendor manuals for the equipment in the system: contain potentially valuable information on the design and operation of the equipment for use in Step 5 (FMEA).
3- Equipment history files: list the actual failures and corrective maintenance actions that have occurred in the facility for documentation in
4- System operation manuals: provide valuable details on how the system is intended to function, how it relates to other systems, and what operational limits and ground rules are employed.

Summary: 1- Selection of a critical asset.
          2- Information and data Collection.
3.9.2 **Step 2: System boundary definition**

After the previous step, the system (or part, component or the facility) boundaries should be determined. This step is really important in the RCM analysis process. According to (Hinchcliffe and Smith, 2004), the precise system boundary definition is essentially important for two reasons;

1- There must be precise knowledge of what has or has not been included in the system, so an accurate list of components can be identified or, conversely, so the identified components will not overlap with components in an adjacent system.

2- Boundary definition includes system interfaces (both IN and OUT interfaces) and interactions that establish inputs and outputs of a system.

However, the system can be large or small, but the function/functions of the system and its inputs and outputs should be known.

**Summary:**

1- Boundary overview.
2- Boundary details.

3.9.3 **Step 3: System description and functional block diagram**

This step depends totally on the previous steps. After selecting the system and collecting the information regarding the first system, the essential details of the selected system should be identified and documented. The required document and information is needed to perform the remaining steps.

**Summary:**

1- System description.
2- Functional block diagram.
3- Equipment history.

3.9.4 **Step 4: System Functions and Functional Failure**

In this step, for the intended system (or subsystem), the functions and functional failure will be written. There are different types of functions;

1- Primary functions
2- Secondary Functions

These types of functions will be described in details later on in RCM implementation approach according to Regan in section 3.12. After writing the functions, the Functional Failures will be written. Functional Failure is also defined and described in section 3.12.

**Summary:**

1- System Functions
2- Functional Failure
3.9.5 Step 5: Failure Mode and Effects Analysis, FMEA
In this step, the Failure Mode that potentially could produce unwanted functional failure will be identified. By other words, FMEA will be used to identify the potential failure mode or failure cause and illustrates their effects. This step satisfies the principle features of an RCM analysis process, feature 2.

**Summary:** 1- Determine the Failure Mode and Effect Analysis, FMEA.

3.9.6 Step 6: Logic tree analysis; prioritize function need via failure modes
In this step, the failure modes are further classified in a qualitative process, called logic tree or decision tree analysis (LTA) figure (3-10). The purpose of this step is to prioritise the resources that could be devoted to each failure mode. However, this step satisfies feature three of an RCM analysis process.

![Logic Tree Analysis Diagram](Adapted from Hinchcliffe & Smith, 2004)

**Summary:** 1- Each failure mode is further classified as:
- A or D/A
- B or D/B
- C or D/C

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3.9.7 Step 7: Task selection

After completing the previous six steps, the most appropriate maintenance task for each failure mode is determined. The maintenance task which is selected must be technically appropriate (applicable) and worth done (cost effective).

1- Applicable tasks are these tasks that:
   - Prevent or mitigate failure,
   - Detect the onset of failure, or
   - Discover a hidden failure.

2- Cost Effective tasks are these tasks that are the most cost-effective option among the competing tasks.

For classic RCM, different maintenance policies and actions can be applied and selected for each selected failure mode. Appendix 10 (task selection road map), illustrates the procedure that is used to select the most appropriate PM tasks for each selected failure mode. However, if it is difficult or impossible to assign an applicable- and a cost effective PM task, the only option is to let the equipment run until it will fail, Run-To-Failure (RTF).

Preventive maintenance PM, is widely used in different maintenance concepts. However, PM is the core of an RCM process philosophy. In the context of RCM, there are four categories of PM that can be assign for each selected failure mode;

1- Time-Based Maintenance (TBM). The main reason for doing for this kind of maintenance task is to prevent or mitigate failure mode.
2- Condition-Based Maintenance (CBM). The main reason for doing this kind of maintenance task is to detect onset of failure mode.
3- Failure-Finding (FF). The main reason for doing this kind of maintenance task is to discover hidden failure mode.
4- Run-To-Failure (RTF). Failure mode that was not identified as being critical in step 6 may be identified as suitable candidates for a run-to-failure maintenance schedule.

Summary: 1- Selection of the most appropriate maintenance task for each selected failure mode.

All steps in this approach are illustrated in Appendix 9. This approach is widely used in different companies. It presents the essence of RCM in another way of the original way that has been established by Nowlan and Heap. However, this approach is one of the best approaches that describes the procedure for assigning different maintenance tasks for each defined failure mode. The author who establishes this approach has been working in different companies and has an extensive knowledge of the implementation of an RCM analysis process.
3.10 RCM implementation, Regan Approach

The second approach of RCM implementation is according to (Regan, 2012). The author has written one of the best books, about the implementation of RCM. The book is called “The RCM Solution” written in 2012. As mentioned, it is one of the best books written about the implementation of an RCM analysis process. This approach is explained in details and all information about this approach is according to (Regan, 2012). According to the (Regan, 2012), implementation of an RCM analysis process can be divided into two main parts;

1- An RCM operating context.
2- RCM implementation seven steps, see Appendix three.

3.10.1 RCM Operating Context

Before starting an RCM analysis process, there are different questions must be answered. A typical question could be; what is the equipment? How the organisation wants it to perform? Moreover, in what environment the equipment expected to operate? These questions are important before starting an RCM analysis process.

An RCM operating context is “a storybook identification of the system to be analysed”. It is a living document that includes technical information relevant to the RCM analysis process. Moreover, it is acting as a centreline tool to orient working group members as an analysis begins.

The technical information regarding the equipment must be sought in a different document and in sometimes, it requires an enormous research. However, an RCM operating context is typically drafted by the planner (facilitator or coordinator) before analysing starts. The planner also has to review the operating context to the group before the seven steps of an RCM analysis process. In the original way of implementation of an RCM analysis process, the operating context includes different types of documents such as;

- General information about the asset

General information about the equipment or the system is required to be collected. Therefore, this section first of all, describes the intended equipment which later will be analyzed. General information about the equipment or the system could be;

1- A description of the organization and the equipment.
2- The role which the equipment has in the organization. Why is it needed?
3- A number of equipment in inventory.
4- How long has the equipment been in operation? (That is if the equipment is not a new).
5- Description of the operating environment.
6- The operating tempo (24-hour operation or another tempo).
7- The consequences of failure and how they affect the organization?
- **Scope of Analysis**
It should be clearly defined what is included in the analysis. In the facility or an equipment, the analysed system may have a connection to other systems. Therefore, the boundary of the system should be clearly determined. Another important thing to mention is, the analysis may have delimitation (the equipment has many critical subsystems but the analysis is done to develop PM only for one critical subsystem). The time of analysis must also be determined. Goals and objectives may also be included in the scope of analysis. However, the scope of analysis is crucial because there are many things may arise up during the analysis. The intention of analysis may disappear if the working group do not follow the plan.

- **Theory of Operation**
It is important to describe how equipment is operated and what the organisation expects of equipment to do. However, is important to consider what the organisation requires from the equipment rather the design specifications. Theory of operation includes some parameters such as the operating pressures and temperatures. These kinds of parameters must be included because they are needed later in the analysis.

- **Equipment/System Description**
An equipment may have many assemblies and subsystems figure (3-11). The subsystems in turn may have also many components. All these parts must be included and documented in the operating context. The figure bellow illustrated typical system dividing into different levels.

![Figure 3-11 System description](image)

- **Protective Devices**
Some equipment or systems have protective devices intended to protect peoples, organization or the equipment itself. These types of devices should be included and listed in the operating context. There are other things should be included in the operating context.
3.10.2 RCM Seven Questions

RCM Seven Steps is the second part of an RCM analysis process and it depends extremely on the previous part, RCM operating context. If the RCM operating context has inappropriate data and information or may it is incomplete, the result of the implementation of an RCM can be counterproductive or wholly wrong. Therefore, it is important that much time should be given to the first part to achieve the best result of the implementation. The RCM seven steps will be explained in details and in order.

3.10.2.1 Functions

The best way to learn about component in a system is to tear it apart piece on paper and identify what its functions. Functions should be written according to the requirement of the organization. By other words, it is important to define what the equipment or the system is required to do rather what it is designed to do.

There is an RCM function, which describes the required performance of an asset and design function which describes the manufacturing design function. In the context of RCM, writing functions is essential for two reasons;

1- Functions allow the company to document exactly what is required of an asset. That helps the working group to determine if the asset is capable to perform what it is required to do.
2- Functions acts as the foundation of an RCM analysis process.

Therefore, it is crucial to define the functions of an asset. In the context of RCM, there are two types of functions;

1- Primary Function, main function.
2- Secondary Functions, other functions.

In the RCM worksheet, Appendix four, the primary function is always written first, and the secondary functions follow. However, functions are classified as:

1- Evident Function, is a function upon failure become evident to the operating crew under normal condition.
2- Hidden Functions, are functions upon failure does not become evident to the operating crew under normal conditions. These types of functions are always protective devices.

In the context of RCM, there is a multiple failure which is when the protective device is failed, and another function is also failed. In this scenario, the failure is called multiple failure.

Functions can be written in different methods. However, the functions must be written at a basic level in order to be easy to read them. Therefore, the author (Regan, 2012) has a good role for writing the evident function, table 1.

To + Verb + Object + Performance Standard + Operating Context (item description)
Table 1 Writing Evident function, term description, (Regan, 2012)

<table>
<thead>
<tr>
<th>To</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>verb</td>
<td>Indicates the type of action</td>
</tr>
<tr>
<td>Object</td>
<td>The thing to which the action is directed</td>
</tr>
<tr>
<td>Performance standard</td>
<td>How well it is required to perform the function</td>
</tr>
<tr>
<td>Operating Context</td>
<td>When the function is required.</td>
</tr>
</tbody>
</table>

Similar to the evident functions, there are different methods used to formulate a hidden function. As it mentioned before, hidden functions (protective devices) are used to protect. Therefore, writing hidden functions starts with (to be capable of). The method that is used to write hidden functions is:

**To be capable of [...] in the event that [...] (system or item description)**

There are also functions called a containment functions or absolute containment functions. If it is a containment function, the performance standard should be recorded, but if the function is absolute containment function (i.e. no leakage at all), the performance standard is not needed.

As mentioned in section 3.6 (system influencing factors) different issues negatively affect the equipment. In the context of RCM, it is crucial to identify them and include them. If it is possible, writing functions for these issues is essential. Because as mentioned, RCM analysis process formulates other solution than developing the preventive maintenance.

As mentioned before, an RCM analysis process is a function based process, but not all functions are written in RCM worksheet. Only the essential functions are written in RCM worksheet. Figure 3-12, illustrates the methodology to determining if the functions are written or not.

![Figure 3-12 Including RCM functions (Adapted from Regan, 2012)](image-url)
3.10.2.2 Functional Failure
The second step in an RCM process analysis is to write the functional failure for each failure. Functional failure is “unsatisfactory condition”. That means the item or the system is not able to provide its intended function. By another word, functional failure is “the inability to fulfill a function”. There are two types of functional failure:

1- Total Functional Failure
2- Partial Functional Failure

The total functional failure describes that the system is totally unable to provide its intended function. The partial functional failure describes that the system still provides its intended function but at an unsatisfactory level.

The primary function may have more than one functional failure and the same for the secondary functions. Functional failure of each function is recorded in RCM worksheet (Appendix four) under title functional failure.

3.10.2.3 Failure Mode
The third step in an RCM process analysis is, identifying the Failure Modes for each Functional Failure. This step is not less important than the previous steps, and it should be carefully determined. Failure Mode is defined as “what specifically causes a Functional Failure”. There are different failure mechanisms such as;

1- Normal wear
2- Corrosion
3- Erosion
4- Fatigue
5- Lubrication deterioration

As mentioned previously, an RCM analysis process is not just about equipment maintenance. The other elements that affect the health and performance of an equipment must also be mentioned. These elements include different issues such as;

1- Deficiencies in technical manuals.
2- Incomplete operating procedures.
3- Proper tools not available.
4- Inaccurate checklists.

Failure Mode can be written in different ways but in the context of RCM, the failure mode can be written in a specific way. The author has some method used to write the failure modes;

Noun + Verb + [as necessary: operating context]
Operating context is an important factor when writing the Failure Mode. Adding the operating context to clarify the failure mode, is really important to select the optimal maintenance strategies. However, Failure Mode is an important step in an RCM process analysis and the context of RCM; there are specific guidelines for determining which failure mode should be included in the analysis. The following figure (3-13) can be used to determine which failure mode should be included in RCM worksheet.

![Diagram](3-13)

Figure 3-13 Include failure mode in RCM analysis (Adapted from Regan, 2012)

Some consideration should be taken when writing the Failure Mode. Failure Mode is what causes the Functional failure, not an effect of the Functional Failure (step 4). To be sure that is a Failure Mode, a simple question can be asked, which is “What specifically causes X to Y?”. Another important consideration is to write the failure mode in enough details in order to assign different solutions.

3.10.2.4 Failure Effect

Failure Effects is the fourth step in an RCM process analysis. Failure Effects can be defined as “A story of what happen if nothing were done to predict or prevent the Failure Mode”. It must be written in enough details in order to the consequences can be appropriately assessed. In the context of RCM, the Failure Effects must be written with the assumption that there is nothing being done to prevent or predict the failure Mode.

Failure Effect is written for each Failure Mode, and it is recorded on the RCM information Worksheet (Appendix four). Failure Effects together with the previous steps accomplish the FMEA (Failure Mode and Effect Analysis), which has been defined and explained in details in section 3.8.
3.10.2.5 Failure Consequence

Failure consequence is the fifth step in the RCM process analysis. Failure consequences identifies how each Failure Mode matters. However, in the context of RCM there are four consequences which should be assessed in the following order;

1. Safety consequences
2. Environmental consequences
3. Operational Consequences
4. Non-operational Consequences

In the context of the RCM, a Failure Mode can either be evident or hidden, see Appendix 6 & 7. However, to determine if the Failure Mode is classified as an evident- or a hidden, the following question in figure (3-14) must be answered.

![Figure 3-14 Determining if a Failure Mode is Evident or Hidden (Adapted from Regan, 2012)](image)

If the answer to the question above is YES, then the Failure Mode is evident, and the left-side of RCM Decision Diagram will be used, see Appendix 6. Contrary to that, if the answer to the question is NO, then the Failure Mode is hidden, and the right-side of RCM Decision Diagram will be used, see Appendix 7.

Some important factor which should be in consideration is, it should be assumed that there no proactive maintenance is being performed. Therefore, if there any inspection which is expected as a “normal condition” compared to “formal condition,” should be written in the RCM operating context.

When the Failure Mode is classified as evident or hidden, the consequences should also be classified. The consequences can be safety consequences and/or environmental consequences, operational consequences or non-operational consequences. To determine if the consequences are related to the safety, the following questions in figure (3-15) should be answered.

“Does the Failure mode cause a loss of function or secondary damage that could have a direct adverse effect on operating safety?”

(Evident Failure Mode) Safety consequence
“Does the multiple Failure cause a loss of function or secondary damage that could have a direct adverse effect on operating safety?”

(Hidden Failure Mode) Safety consequence

If the answer to the question is YES, then the Failure Mode has a safety consequence. If not, the analysis moves to the next types of consequences.

The next step is to check if the Failure Mode has an environmental consequence. To determine that should the following questions should be answered, figure (3-16).

“Does the Failure mode cause a loss of function or secondary damage that could constitute a breach of environmental law, standard, or regulation?”

(Evident Failure Mode) Environmental consequence

“Does the multiple Failure cause a loss of function or secondary damage that could constitute a breach of environmental law, standard, or regulation?”

(Hidden Failure Mode) Environmental consequence

Figure 3-15 Safety consequences (Adapted from Regan, 2012)

Figure 3-16 Environmental consequences. (Adapted from Regan, 2012)
If the answer to the question is YES, then the Failure Mode has an environmental consequence. If not, the analysis moves to the next types of consequences.

Next step is to determine if the Failure Mode has some operational consequences. To check that, the following questions, figure (3-17) must be answered.

“Does the Failure mode cause a loss of function or secondary damage that could constitute a breach of environmental law, standard, or regulation?”

(Evident Failure Mode) Operational consequence

“Does the multiple Failure cause a loss of function or secondary damage that could constitute a breach of environmental law, standard, or regulation?”

(Hidden Failure Mode) Operational consequence

![Figure 3-17 Operational consequences (Adapted from Regan, 2012)](image)

If the answer to the question is YES, then the Failure Mode has an operational consequence. If not, the analysis moves to the next types of consequences.

The next step is to determine if the Failure Mode has some non-operational consequence. If the Single Failure Mode has not any adverse effect on the safety, environment or operation, then it can be considered has some non-operational consequence. Non-operational consequence means that the consequences of a Single Failure Mode might be related to the cost of repair.

The consequences of failure mode can also be classified in different ways than what it has been described above. Depending on the organisation, the consequences can be categorised in other levels. For instance, the consequence of failed hydraulic system pressure safety valve in LHD machine operates on the surface, has a lower impact than if the LHD machine operates underground.
3.10.2.6 Proactive Maintenance and Intervals
Proactive maintenance tasks and intervals are the sixth step in an RCM analysis process. In this step, if possible an appropriate maintenance task is assigned. Proactive maintenance task can be divided into two groups, Preventive Maintenance, and On-Condition Maintenance, figure (3-18).

In asset management community, the preventive maintenance is described as a proactive maintenance approach and it is defined as “a maintenance action carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item” (EN 13306, 2001). By the other words, the intention of doing any type of preventive maintenance task, is to reduce the probability of failure and/or in order to control the damage, as depicted in figure (3-19). The figure bellow shows that implementing of preventive maintenance tasks will reduce the magnitude of the potential losses to from hazard area (read) to some acceptable area (green or yellow).
In the context of RCM, a preventive maintenance includes only scheduled restoration and scheduled replacement. These two types of preventive maintenance do not consider the condition of the asset at the time of the task, and they are performed at fixed intervals. The second type of proactive maintenance, is on-condition maintenance (predictive maintenance or condition-based maintenance), as depicted in figure (3-20). Contrary to the preventive maintenance, on-condition maintenance consider is based on the asset’s condition.

As mentioned before and illustrated in the figure above (3-20), preventive maintenance tasks in the context of an RCM analysis process consists of scheduled restoration and scheduled replacement. In this approach, these types of preventive maintenance are defined as:

“A scheduled restoration task reworks or restore an item’s failure resistance to an acceptable level without considering the item’s condition at the time of the task”.

“A scheduled replacement task replaces an item without considering the item’s condition at the time of the task”.

As it well-known that most of failure modes give some warning that some failure is going to occur. Some typical failure warning is, vibration, noise and heat. These types of evidence are called potential failure condition. In this approach, potential failure condition is defined as “evidence that a failure is in the process of occurring”. On-conditions maintenance task is performed to detect these types of evidences.

Therefore, in this approach, on-condition maintenance task is defined as “a task performed at defined intervals to detect a potential failure condition so that maintenance task can be performed before the failure occurs”.

An RCM analysis process provides for some failure modes (evident or hidden), more than one maintenance task. Therefore, in RCM decision diagram, there is combination of task in case that more than one task is needed.
- Criteria for assigning a proactive maintenance task

In order to assign a proactive maintenance task, two important criteria must be satisfied before the decision of tasks, takes place. In this approach, these two criteria are defined as technically appropriate and worth doing figure (3-21). However, these two criteria embody different questions for each type of failure consequences.

![Figure 3-21 Criteria for assigning proactive maintenance tasks](image)

If these two criteria are satisfied, one or more of the proactive maintenance tasks can be selected. However, for each type of proactive tasks there are two different questions that must be answered, see Appendix 6 & 7.

- Assigning scheduled restoration and scheduled replacement tasks

These types of proactive maintenance tasks can be assigned for failure mode that could have safety and environment consequences, operational consequences, and non-operational consequences. However, scheduled restoration and scheduled replacement can be applicable for failure modes that behave according to the traditional view of failure, figure (3-22). The traditional view of failure means there is a useful life (not MTBF) for the asset. In this approach, useful life is defined as “the age at which a significant increase in the conditional probability of failure occurs”.

![Figure 3-22 Assigning preventive maintenance / Useful life](image)

However, to assign preventive maintenance tasks, there are different questions that must be answered. The questions are asked in order to ensure that the preventive maintenance task is technically appropriate and worth doing. As mentioned before, the questions are different depending of which failure consequence. Figure (3-23) illustrates the different questions for each failure consequences.
Assigning On-Condition Maintenance Tasks

On-Condition Maintenance is represented on the RCM Decision Diagram in the first row, see Appendix (6 & 7). This type of proactive maintenance task is performed at defined intervals. As mentioned before, this kind of proactive task is performed in order to detect the potential failure condition. Therefore, such kind of task is performed only on evidence of need. To detect potential failure condition, different types of method used to detect such kind of evidence;

1- Using simple techniques such as monitoring or human sense.
2- Using more technically such as thermography or frequency analysis
3- Using devices installed on the equipment systems.

In order to determine if an on-condition maintenance task could be applicable for some failure, the potential failure condition must be detected and evaluated figure (3-24).
In this approach, the P-F interval is defined as “the time from when the potential failure condition is detectable to the point that failure occurs”. Some important consideration that must be discussed is an on-condition maintenance interval is not based on the MTBF. Instead, on-condition maintenance intervals are based on the P-F interval. Generally, on condition maintenance intervals are assigned at the half of P-F interval (this is only a rule of thumb).

However, in order to assign on-condition maintenance interval, the minimum remaining time before the failure should be enough to handle the consequences of the failure. Therefore, to be sure, the net P-F interval has to be estimated. In this approach, net P-F interval is defined as “the minimum time remaining to take action in order to manage the consequences of failure”.

After deciding the P-F interval and net P-F interval (figure 3-25), some important questions must be answered in order to assign the on-condition maintenance task. If the answer to the all questions is YES, then on-condition maintenance interval is technically appropriate and worth doing. However, the questions that must be answered differ from if the failure consequence is safety and/or environmental, operational or non-operational as depicted in figure (3-26).
- Assigning Combination Tasks

In RCM decision diagram, in the fourth row, the combination of tasks is presented figure (3-27), and depicted in the appendix (6 & 7). Combination tasks are assigned for the failure modes that need more than one task. However, this type of tasks is rarely used, and they can be a combination of on-condition maintenance tasks, restoration, or replacement. However, combination must also meet the requirement for assigning proactive maintenance namely technically appropriate and worth doing.

The last step of assigning task intervals is synchronising the initial intervals, as depicted in the appendix (5). Synchronizing initial intervals are really important and it is one of the reasons that a qualified facilitator is required.
3.10.2.7 Default Strategies

Default strategies are the last step in the RCM analysis process. Default strategies can be divided into two groups depending on the type of the Failure Mode. However, the main two groups are:

1- Procedural Check
2- Failure Finding Tasks

- Procedural Check

This type of task is considered only for an Evident Failure Mode, and it can be found on the left side of the RCM Decision Diagram, as depicted in Appendix 6. This type of task is not a proactive maintenance and is considered as default strategy, only for evident failure mode. This task checks for a failure that may already have occurred. However, this type of task should also meet the criteria for assigning the proactive maintenance tasks and intervals (technically appropriate and worth doing). In order to assign procedural check, the questions in the following figure (3-28) must be answered.

![Figure 3-28 Procedural Check for Evident Failure Mode (Adapted from Regan, 2012)](image)

- Failure Finding Tasks

Failure Finding Task is considered only for the Hidden Failure Mode and can be found on the right side of an RCM Decision Diagram, as depicted in Appendix 7. In this approach, Failure Finding Task can be defined as “A task that checks if a protective device is in a failed state”. As it is mentioned before, protective devices are devices intended to protect people, the machine, and the organization when another failure occurs. However, the purpose of a Failure Finding Task is to reduce the risk of multiple failure to an acceptable level.

In order to assign Failure Finding Task, the questions in the following figure (3-29) must be answered.
- **No Scheduled Maintenance**

In both sides of an RCM Decision Diagram, No Scheduled Maintenance can be found. However, No Scheduled Maintenance means that maintenance, in general, is not needed or it is not the answer to manage the Failure Mode. This type of default strategy is not applicable for Failure Modes that have safety or environmental consequences. That is because for Failure Mode with safety of environmental consequences, have to be prevented or managed. However, this type of default strategy is applicable for Failure Mode that has operational or non-operational consequences.

- **Other Default strategies**

As it is mentioned before, the RCM analysis process can provide more than a proactive maintenance but rather solutions. Some of the other solutions that an RCM analysis process can provide could be:

1. Equipment redesign.
2. Modification of the operating procedures.
3. Update to the technical publications.

Even an RCM analysis process find some kind of proactive maintenance tasks; a default strategy is still possible to be assigned. As mentioned before, an RCM analysis process is not only to define a proactive maintenance; there are many solutions that RCM could provide.

After completing of an RCM analysis process, a team that acts as quality assurance, need to validate the result, determine what recommendation will be implemented, and set the implementation process motion.
3.11 RCM Outsourcing and Benchmarking

Outsourcing and benchmarking are two things that have directly or indirectly effects on an RCM analysis process. However, outsourcing can be defined as “a managed process of transferring activities performed in-house to some external agent” (Dohi et al. 2013). As depicted in figure (3-30), outsourcing focuses on different things. Around 36% of the analysis that are carried out by outsourcing focuses on the core which can be increasing of the reliability of a system or an equipment. Moreover, outsourcing focuses on the costs and reduce it be 36 % as depicted in figure (3-30).

![Figure 3-30 Reasons for outsourcing (the 2001 outsourcing world summit)](image)

As mentioned before, an RCM analysis process must be carried out by a trained facilitator. A trained facilitator has an enormous impact on the analysis. That is because the facilitator is responsible by others to:

1- Plan the RCM analysis
2- Facilitate the analysis
3- Produce an RCM validation package
4- Produce the final report

However, if the company or the organisation has not the ability to conduct an RCM analysis process, it might be possible to use consulting firm. When an organisation uses a consulting firm, the facilitator must be certified, if not, the result can be counterproductive and in some case, it might be dangerous. The figure (3-31) below shows the percentage of using a consulting firm for RCM analysis.

It is clearly shown in figure (3-31) that only 24.18 % of the responses, answered that the facilitator was certified. Around 9.84 % of the responses answered that the facilitator was not certified and the rest was either not sure, did not conduct RCM, or they did not use a consulting firm (the organisation or the company did the analysis by themselves).
Some organisations or companies have conducted an RCM analysis process but they stopped using RCM. According to (benchmarking report, 2015), companies or organisations stopped using RCM due to different reasons, as depicted in figure (3-32) shown below.
4 RESULT

This chapter summarises the results that are achieved by the research done in this thesis. This chapter describes case studies which in turn illustrate how an RCM analysis process can be carried out. By other words, the intention of analysing the case-studies is to see how the RCM has been implemented, not appoint the weakness or judge the result. The case-studies can be found in the database Scopus or even in the google Scholar.

Moreover, an implementation approach is suggested and it could be used in mining companies or in any facility if there is a desire to implement an RCM analysis process.

4.1 Analysing and selecting procedure of the case studies

As mentioned previously in section 2.4 (Phase 4: selection criteria for case-studies), some criteria are used for selecting the case-studies. The first priority is given to the case-studies that are published in an international journal which has a high impact factor (IPP) (minimum IPP is 0.5). The second priority is given to case-studies which have many citations, and the last priority is given to the case-studies which have an author that has high h-index (minimum h-index 1). In this thesis, the criteria for selection case-studies has been followed exactly step by step.

After an enormous research, it is found that there are a few number of published case-studies which handle the implementation of an RCM analysis process. There are many case-studies published in international journals with high IPP, but they do not handle the implementation of the RCM. However, in this thesis the case studies are selected according to the criteria. The analysis of the case-studies is done only by considering the following three questions as depicted in figure (4-1):

1- How the RCM analysis process (implementation) has been carried out?
2- Which type of RCM implementation approaches has been used?
3- Has the case-study any modifications or adaptations to the original RCM approach?

Figure 4-1 Analysing questions
4.1.1 Analysed case-study 1

This case-study is selected among different case studies where an RCM analysis process has been implemented. The case-study is titled “Reliability Centered Maintenance of cone crusher: a case study” and published in the International Journal of Systems Assurance Engineering and Management, on 25 February 2014, and it is written by R. S. Sinha and A. K. Mukhopadhyay.

This case-study meets the criteria for selecting the case-studies in this thesis by having an acceptable IPP (IPP is 0.576). The case-study is done by the Society for Reliability Engineering, Quality and Operations Management (SREQOM), India and the Division of Operation and Maintenance, LTU, Sweden 2014. The following text is the abstract of the case-study which is only an excerpt of the case-study.

“A cone crusher is used for crushing rock. The vast majority of these installations are found in mineral processing plants. The reliability of crusher influences the productivity of the plant. The purpose of this paper is to focus on the application of reliability centered maintenance with an aim to improve the reliability of the cone-crusher. Reliability tools failure modes and effects analysis and total time to test plot are explored in support of the study. Crusher component failure details for one year have been considered for the analysis” (Sinha & Mukhopadhyay, 2015).

Q1: How the RCM analysis process (implementation) has been carried out?

Systematically, this case-study can be considered as systematic case-study. It has very clear failure data (Table 1). The failure mode and effect analysis (Table 2) is well-done. Moreover, the criteria for failure modes evaluation (Table 3) is also well-done.

However, this case-study includes only the Failure Mode and Effect Analysis (FMEA) which is only a part of an RCM analysis process. Therefore, it cannot be considered as a complete RCM analysis process because any proactive maintenance and intervals or default strategies are not assigned.

Q2: Which type of RCM implementation approaches has been used?

This case-study follows the steps that a true RCM analysis process includes (however only the four steps; function, functional failure, failure mode, and failure effects). It seems that in this case-study, equipment-based approach than system-based approach is used because there is no description of system and dividing it into subsystems and component. Therefore, it is not clear which approach has been used in this case-study, but the steps are done exactly according to Nowlan and Heap (described approach according to Regan).

Q3: Has the case-study any modifications or adaptations to the original RCM approach?

NO. There is no any modification or adaptation to the RCM steps. However, it is not a complete RCM analysis process.
4.1.2 Analysed case-study 2

This case-study is selected among different case studies where an RCM analysis process has been implemented. The case-study is titled “Reliability centered maintenance: a case study” and it is found in the database Scopus (reference database for scientific articles in all subjects), and published the *Proceedings of the IEEE International Conference on Transmission and Distribution Construction and Live Line Maintenance, ESMO* (conference) in 2000. It is written by Rajotte Claude and Jolicoeur Alain.

This case-study meets the criteria for selecting the case-studies in this thesis by have high h-index for the author (h-index is 3). The case-study is done by the IEEE 9th International Conference on Transmission and Distribution Construction, Operation and Live-Line Maintenance Proceedings (ESMO 2000); Montreal, Quebec, Canada 2000. The following text is the abstract of the case-study which is only an excerpt of the case-study.

“Electric utilities should optimize their maintenance efforts to maximize equipment reliability and availability at lowest cost. This makes utilities want to know as much as possible the real condition of equipment by using an optimal systematic preventive maintenance (SPM) program. This program usually defines “what to do?” and “when to do?” SPM actions. Since SPM programs are too expensive or has poor apparatus reliability, the reliability centered maintenance (RCM) method is used to select “what to do?” in an SPM program. An RCM method is implemented in Hydro-Québec transmission system” (Rajotte and Jolicoeur, 2000).

**Q1: How the RCM analysis process (implementation) has been carried out?**

Unsystematically in comparison to how an RCM analysis should be carried out. In this case-study, functions and functional failure are not determined. Moreover, failure modes criticality is done by using another method than i.e. RPN. It is even not clear how the criticality of failure modes is done.

**Q2: Which type of RCM implementation approaches has been used?**

- Equipment selection for study
- Failure Mode definition for studied equipment
- Failure Mode & Failure Cause identification and criticality determination
- Maintenance employees’ consultation
- SPM program proposal including pertinent documentation
- Final validation by a working group
- Program implementation.

**Q3: Has the case-study any modifications or adaptations to the original RCM approach?**

YES. There is one adaptation to the RCM, which can lead to a significant inappropriate decision. The first adaptation is switching from system-based approach to equipment-based approach. In this case-study, it says that steps in classical RCM approach are onerous; therefore, functions and functional failures are not defined.
4.2 RCM implementation Criteria

Many RCM processes on the market contain different implementation approaches, some of them differ significantly from the original one. However, if the RCM analysis process is done correctly and by right people the result could give some benefits to the organisation.

An RCM analysis process examines the equipment as a series of functional systems, each of which has inputs and outputs. It is the reliability of the system, rather than the functionality that is considered. According to (SAE JA 1011, 2009), there are minimum criteria before any maintenance strategy can be called as RCM. The following seven steps are suggested to complete an RCM analysis process (RCM implementation) for each asset in mining or any industry plant:

1. What are the functions and desired performance standards of each asset? **Functions**
   - Primary function or Secondary function.

2. How can each asset fail to fulfil its functions? **Functional Failure**
   - Total functional failure.
   - Partial functional failure.

3. What are the failure modes for each functional failure? **Failure Mode**
   - Evident Failure Mode.
   - Hidden Failure Mode.

4. What causes each of the failure modes? **Failure Effect**
   - Failure effect should be written in enough details because it helps to understand the failure mode and failure mechanism.

5. What are the consequences of each failure? **Failure consequences**
   - Safety or Environment consequences
   - Operational consequences
   - Non-operational consequences

6. What can and/or should be done to predict or prevent each failure? **Proactive maintenance**
   - Preventive maintenance.
     - Scheduled restoration.
     - Scheduled replacement.
   - Condition Based Maintenance.

7. What should be done if a suitable proactive task cannot be determined? **Default strategies**
   - Failure Finding Task for hidden failure modes
   - Procedural check for evident failure mode.

If the seven steps above curried out by qualified facilitator, the implementation of RCM analysis process will increase equipment/system availability, achieve equipment inherent reliability, and reduce maintenance and resource costs. According to (Jardine and Tsang, 2006), implementation of an RCM analysis process has many results. In mining industry sector, implementation of RCM analysis process reduces annual oil filter replacement costs in haul truck fleet by 150,000 $/year.
4.3 Rigorous implementation approach

As mentioned in section (3.4.1), a formal Rigorous RCM analysis of each system, subsystem, and the component is normally performed on new, high-cost systems. However, this suggests approach figure (4-2) should be limited to the following situations (NASA, 2008);

1- The consequences of failure result in catastrophic risk regarding the environment, health, safety, or complete economic failure of the business unit.
2- The resultant reliability and associated maintenance cost are still unacceptable after performing and implementing a streamlined type FMEA (intuitive RCM approach).
3- The system or equipment is new to the organization and insufficient corporate maintenance, and operational knowledge exists on its function and functional failures.

![RCM implementation process (Rigorous)](image)

*Figure 4-2 Rigorous implementation process*

**Step 1. Select equipment**
Under this step the key physical assets are selected. These key physical assets are then prioritized according to the criticality to in case of downtime, cost to repair and so on.

**Step 2: Define Functions**
Functions for each system are selected

**Step 3: Define Functional Failures**
Identify the ways where a system can fail

**Step 4: Identify Failure Modes**
For each failure, it might be different failure modes. Identify each one

**Step 5: Identify Failure Effects and Failure consequences**
The effect of each failure must be written in enough details. Failure consequences can be safety & environmental consequences, operational consequences, or non-operational consequences

**Step 6: Select tactics using RCM logic (section 3.9.6)**
**Step 7: Implement and refine the maintenance plan**
4.4 Suggested Implementation approach

This RCM pilot project figure (4-3) is suggested to be used if an RCM analysis process is going to be applied. Each step of this pilot project has been defined in details in chapter three. However, it is only a streamlined RCM and more details can be found as mentioned in chapter three.
5 DISCUSSION

In this chapter, the focus is going to be on the misconceptions and issues and challenges of implementation of an RCM analysis process. This chapter is aimed to illustrate the challenges of applying an RCM analysis process. Moreover, difference between FMEA and RCM, myths of RCM implementation and more are discussed in this chapter.

5.1 Issues and challenges of RCM implementation

Companies around the world have criticised the RCM. It says that an RCM analysis process takes so much time, or it is so expensive. Contrary to the criticism, an RCM analysis process gives the organisations the opportunities to transform into a safer and cost effective operation. Moreover, an RCM analysis process can be carried out swiftly and efficiently when executed properly (Regan, 2012). RCM principles can be widely applied either to an entire asset or more narrowly applied to a selected pieces of an equipment.

There are many reasons for why companies are afraid of applying an RCM analysis process. Companies that are afraid of applying an RCM analysis process have different reasons that make them afraid or unable to implement the RCM analysis process, such as:

1- It is so difficult
2- RCM takes too long to complete
3- RCM goes into too much details
4- RCM requires too many resources
5- Very few companies ever completed their first RCM
6- Requires a lot of data
7- Requires a lot of support

These misconceptions can be resolved if the companies which need an efficient RCM effort and have a desire to develop their preventive maintenance, take the time to research and gather information about the RCM. The companies that suffer from inappropriate maintenance plan or need to increase the reliability of their equipment should answer the following questions:

1- Why is it so difficult to implement the RCM analysis process?
2- Why does it take too long to complete an RCM analysis process?
3- Which type of resources an RCM analysis process requires?
4- Why doesn’t the management support the effort?

In the aircraft industries around the world, the RCM is one of the most used tool and it applies on all component of the airplane. In other industries such as mining industry, an RCM process is seldom used. RCM is not a favourable tool or seldom used in mining industries because there are misunderstanding between the financial section and maintenance section or production section.
To explain that, the following example, could be helpful to understand what is meant by misunderstanding between business strategy and maintenance strategy. In some mining companies, the business objectives could be to produce 33 Mton ore/year in 2020. In order to increase the current production from 30 to 33 Mton/year, the maintenance managers need to reduce the corrective maintenance by 10% and increase the preventive & predictive maintenance by 50% and 40%, respectively (according to the result of an RCM analysis process, to reduce the number of failures). They need probably to use new techniques or perhaps they need to increase the manpower in order to achieve the business objectives.

Reducing corrective maintenance and increasing preventive and predictive maintenance leads to increase of the maintenance cost which is not acceptable for the business strategy due to in business strategy they need to reduce maintenance cost by 20%. In this case, result of an RCM analysis process maybe be not favourable because it requires new investment which are not acceptable for business managers. This in turn forces maintenance managers to not use RCM and continue with the used method of applied maintenance type.

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<table>
<thead>
<tr>
<th>Business objectives</th>
<th>To produce 33 Mton/year in 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Business strategy</td>
<td>To reduce maintenance cost by 20% and increase existing production by 10%</td>
</tr>
<tr>
<td>Maintenance strategy</td>
<td>To support production of 33 Mton/year by availability 90%</td>
</tr>
<tr>
<td>Maintenance objectives</td>
<td>Corrective 10%; Preventive 50% and Predictive 40%</td>
</tr>
</tbody>
</table>

*Figure 5-1 The Relationship between business- and Maintenance objectives*

Therefore, it is essential for planner of the maintenance strategy and maintenance plan, to get the needed amount of capital in order to they can plan the right maintenance strategy for long term, and maintenance plan for short term by using RCM technique.

Another reason is that mining companies may have become accustomed to use a secure maintenance method for long time. They are afraid to invest in new techniques which requires high investment in term of

1. Changing the equipment,
2. Increasing the downtime for maintenance (for old and unreliable equipment),
3. Changing the production procedures,
4. Changing the operation and maintenance procedures.
5. Increasing the manpower
5.2 Misconceptions of RCM
One of the important factors that make companies to not be interested of using and RCM analysis process, is believing that an RCM analysis process is quite easy and simple to be implemented for any asset. Moreover, companies think, there is no need to gather all information for the RCM operating context and they start the RCM analysis process directly by identifying functions for the system. However, having the belief that the implementation process is so simple, leads to destroy the nature of the RCM and probably, make the RCM some useless tool or sometime as a dangerous tool. Therefore, it is essential that an RCM analysis process must be done correctly and by right people in order to say that an RCM analysis process is simple, easy and useful.

According to (Reliability-web, 2016), the survey of more than 250 organisations around the world, over 85% of the RCM analysis process completed are never implemented or used. If an RCM suggested tasks are not implemented, the organisation cannot see any results from the time and money invested in performing the analysis. It is only wasting time if the result is not used.

5.3 RCM vs FMEA
Reliability Centered Maintenance (RCM) and Failure Mode Effect Analysis (FMEA) are two different maintenance tools. Like FMEA, RCM can be performed in the design phase of a project. RCM is most commonly performed on new equipment to develop a complete maintenance strategy in the hope of improving and achieving high reliability of an asset.

According to Doug Plunknette, 2012 (creator of the RCM Blitz Methodology, author of the book Reliability Centered Maintenance using the RCM Blitz Method), there are many differences between RCM and FMEA.

**Functions**, RCM analysis process requires that functions are written in enough details and they should contain the performance standard of the asset. FMEA does not require in the analysis that system functions should be written in enough details and even the performance standards are not always needed. **Failure Mode**, RCM analysis process required that failure modes should be written in a detailed level, namely addressing the part, the problem, and the specific cause of failure. FMEA does not require that failure modes must be written in a detailed level. They are written at a much higher level. That is because FMEA process is designed to assets risk in the design phase.

RCM uses a structured method to assign different maintenance tasks to reduce the consequence of each failure mode. Therefore, an RCM analysis process is a complete maintenance strategy which is designed to ensure inherent reliability of an asset. Contrary to the RCM, FMEA is not designed for developing maintenance tasks. It is used to mitigate the risk of a failure mode by a recommended tasks that maybe occur in the design phase of an asset. Well-done RCM analysis process assign default strategies while FMEA does not include this type of tasks.
5.4 Myths of RCM Implementation

RCM analysis process has been discussed from different perspectives and described in somehow deep details. As mentioned before, it is a reliable method/process used for defining the required maintenance plan for different assets. However, this method has been criticised by companies which are afraid of using it or by companies that try to convince another companies to implement this method.

Therefore, it is essential in this master thesis to illustrate the myths about RCM and discuss it by naming different myths. According to Mr Carlos Mario Perez Jaramillo (Reliability-web, 2016), there are different myths about RCM.

5.4.1 Does RCM solve all reliability problems of a company?

RCM cannot solve all reliability problems of a company. RCM must be conjugated with other activities, tools and methodologies in order to solve the reliability problems. The word Failure must also be defined before starting the analysis. For some companies Failure means a Stop, for other companies Failure means when it is no longer safe or if the assets starting to be expensive to be operated and maintained.

5.4.2 There will be no more failures after applying RCM?

As, mentioned in section (3.1), the essence of RCM is to manage the consequences of the failure, not necessarily preventing them. Therefore, RCM cannot prevent all failures and it is not used to prevent them.

5.4.3 It is hard to define systems and functions in RCM

As mentioned in section (3.10.2.1), there is RCM-function and design-function. Design-functions are already defined by the manufacturing companies and RCM-functions are defined by the company which buy the equipment. Therefore, companies which clam that it is hard to define systems and functions of the equipment do not know what is exactly required from the equipment. This myth is a groundless because even an operator who maintain the equipment has no problem to define what it is used to perform and know exactly what is expected from its operation.

5.4.4 Application of RCM should start from the current maintenance plan

As mentioned in section (1.2.3), RCM is a zero-based maintenance which means that failure modes and failure effects are written assuming that nothing is being done to prevent or predict the failure mode. That leads to failure consequences to be assessed, and solutions are formulated without mentioning to what is currently being done.

RCM analysis process will provide companies different maintenance actions without biases to the current maintenance plan.
6 CONCLUSION AND FURTHER WORK

The chapter includes two important parts namely the conclusion and the further work. The purpose of the conclusion is to answer the research questions. The answers to the research questions are simplified. The purpose of the further work is to suggest if an RCM can be used in mining companies.

6.1 Conclusion
Reliability Centered Maintenance analysis process is a powerful and helpful tool. It helps the mining companies to ensure that they understand how to create value from an asset. However, it requires a lot of research and qualification.

RCM analysis process can be applied by using the described implementation approaches in this master thesis or use the suggested pilot project for applying the RCM, section (4.4). However, RCM analysis must follow the RCM criteria, section (4.2) in order to complete the process according to standard (SAE JA 1011, 2009).

RCM analysis process can be used to define the most applicable and cost effective maintenance plan for any asset such as:

1- Conveyors Belts
2- Ore Milling & Processing Equipment
3- Magnetic Separator of ore.
4- Ore Sieve Equipment
5- Other equipment which is critical due to its effect of safety, environment or operation.

RCM analysis process requires a qualified facilitator who can lead the RCM-team and the mining company should have a big desire to implement the RCM. The result or suggested maintenance tasks which are provided by the RCM analysis process must be implemented in order to get the benefits of this method.

6.2 Further work
RCM should be conjugated with TPM in order to accomplish beneficial work and it forms a powerful combination due to RCM focus on the machine and TPM focus on the operator. Therefore, supporting the RCM process with TPM method will further solidify the maintenance management foundation.
7 REFERENCES

Articles and Books


Others
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7- Maintenance resources, 2016 viewed (On 2016.09.14 at 08:40) http://www.maintenanceresources.com/referencelibrary/maintenancemanagement/keyterms.htm#M.
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APPENDIX 1  GLOSSARY

Asset: Unlike in the accounting definition, in maintenance this is commonly taken to be any item of physical plant or equipment (Maintenance Resources, 2016).

Availability: The probability that a piece of equipment/system is functioning satisfactorily at time t when used according to specified conditions, where the total time includes operating, logistical time, active repair time, and administrative time (Dhillon, 2008).

Breakdown: A specific type of failure, where an item of plant or equipment is completely unable to function (Maintenance Resources, 2016).

Classical RCM: This refers to the only truly acknowledged form of RCM as is intended by its pioneers in the commercial aviation industry (Bloom 2006, 266).

Condition Based Maintenance: An equipment maintenance strategy based on measuring the condition of equipment to assess whether it will fail during some future period, and then taking appropriate action to avoid the consequences of that failure (Maintenance Resources, 2016).

Corrective Maintenance: Any maintenance activity which is required to correct a failure that has occurred or is in the process of occurring. This activity may consist of repair, restoration or replacement of components (Maintenance Resources, 2016).

Cost: Is the amount of money paid or payable for the acquirement of materials, property, or service (Dhillon 2010, 2).

Criticality: The priority rank of a failure mode, based on some assessment criteria (Maintenance Resources 2016).

Critical Components: Critical components are those components for which the occurrence of the failure is evident, and the failure immediately results in an unwanted plant consequence (Bloom 2006, 271).

Defect: A term typically used in the maintenance of mobile equipment. A defect is typically a potential failure or other condition that will require maintenance attention at some time in the future, but which is not currently preventing the equipment from fulfilling its functions (Maintenance Resources 2016).

Downtime: Is the total time during which the item or system is not in a condition to perform its specified mission or function (Dhillon 2010, 2).

Environmental Consequences: A failure has environmental consequences if it could cause a breach of any known environmental standard or regulation (Maintenance Resources 2016).

Evident Function: A function that, upon its loss, becomes evident to the operating crew under normal condition (Regan 2012, 239).
**Failure:** The inability of an item/piece of equipment/system to operate within specified guidelines (Dhillon 2008, 3).

**Failure Consequences:** Describe how the loss of function caused by a failure mode matters; the categories of Failure consequences are safety, environmental, operational, and non-operational (Regan, 2012).

**Failure Effect:** A description of the events that occur after a failure has occurred as a result of a specific failure mode. Used in reliability centered maintenance, FMEA and FMECA analysis (Maintenance Resources, 2016).

**Failure Mode:** Is what specifically causes a functional failure (Regan 2012, 241).

**Failure Mode and Effects Analysis FMEA:** A document that records the first four steps of the RCM processes, functions, functional failure, failure mode, and failure consequences (Regan, 2012).

**Function:** The definition of what we want an item of equipment to do, and the level of performance which the users of the equipment require when it does it. Note that an item of equipment can have many functions, commonly split into primary and secondary (Maintenance Resources, 2016).

**Functional failure:** An unsatisfactory condition in which either some or all of a function cannot be performed (Regan 2012, 241).

**Hazard:** The source of energy and the behavioral and physiological factors that, when not controlled effectively, lead to harmful incidents (Dhillon 2008, 3).

**Hidden Function:** A function that, upon its loss, does not become evident to the operating crew under normal conditions (Regan 2012, 241).

**Life Cycle Cost:** Is the sum of all costs incurred during the lifespan of an item or system (i.e., the total of procurement and ownership costs) (Dhillon 2010, 2).

**Maintainability:** Is defined to be the probability that a failed component or system will be restored or repaired to a specified condition within a period when maintenance is performed by prescribed procedures (Ebeling 2010, 6).

**Maintainability Engineering:** The set of technical processes that apply maintainability theory to establish system maintainability requirements, allocate these requirements down to system elements and predict and verify system maintainability performance (Maintenance Resources 2016).

**Maintenance:** Is the combination of technical, administrative, and managerial actions carried out during the life cycle of an item and intended to retain it in, or restore it to, a state in which it can perform the required functions (SS-EN 13306).
Maintenance Policy: A statement of principle used to guide Maintenance Management decision making (Maintenance Resources 2016).

Maintenance Strategy: A long-term plan, covering all aspects of maintenance management which set the direction for maintenance management, and contains firm action plans for achieving the desired future state for the maintenance function (Maintenance Resources 2016).

Mean Time Between Failures (MTBF): A measure of equipment reliability. Equal to the number of failures in a given period, divided by the total equipment uptime in that period (Maintenance Resources 2016).

Mean Time to Failure (MTTF): The sum of operating time of given items divided by the total number of failures (Dhillon 2008, 3).

Mean Time to Repair (MTTR): A figure of merit depending on item/equipment/system maintainability equal to the mean item/equipment/system repair time; in the case of exponentially distributed times to repair, mean time to repair is the reciprocal of the repair rate (Dhillon 2008, 3).

Multiple Failure: Includes the failure of a protective device and another failure, e.g., low-pressure switch fails, and system pressure fails below normal levels (Dhillon 2008, 3).

Modification: Any activity carried out on an asset which increases the capability of that asset to perform its required functions (Maintenance Resources 2016).

Net P-F interval: The minimum time remaining to take action in order to manage the consequences of failure (Regan 2012, 139).

P-F Interval: The time from when a potential failure condition is detectable to the point that failure occurs (Regan 2012, 241).

Potential Failure: A term used in reliability centered maintenance. An identifiable condition which indicates that a functional failure is either about to occur, or in the process of occurring (Maintenance Resources 2016).

Preventive Maintenance: A scheduled restoration or scheduled replacement task that is performed at a defined interval without considering the item’s condition at the time of the task (Regan 2012, 242).

Reliability: Is the probability that an item or system will perform its function satisfactorily for the desired period when used according to specified conditions (Dhillon 2010, 2).

Reliability Centered Maintenance: A zero-based, structured process used to identify the failure management strategies required to ensure an asset meets its mission requirements in its operational environment in the safest and cost-effective manner (Regan 2012, 242).
APPENDIX 2  STEPS TO INITIATE AN RCM PROGRAM (REGAN, 2012)

Identify an RCM team leader

Commit to apply RCM correctly

Start of small

Don't go it alone

Obtain buy-in from the organization and spread the word throughout the organization

Plan the pilot project

Conduct an introductory RCM training course

Conduct the pilot project analysis

Prepare the validation package

Conduct the validation meeting

Achieve consensus and deliver the final report

Implement the results
APPENDIX 3  THE RCM PROCESS (REGAN, 2012)

- Prepare the Operating Context
- Step 1: Functions
- Step 2: Functional Failures
- Step 3: Failure Modes
- Step 4: Failure Effects
- Step 5: Failure Consequences
- Step 6: Proactive Maintenance and Intervals
- Step 7: Default Strategies
## APPENDIX 4  
RCM INFORMATION WORKSHEET I (REGAN, 2012)

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<thead>
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<th>Function</th>
<th>Functional Failure</th>
<th>Failure Mode</th>
<th>Failure Effect</th>
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<td>Primary Function</td>
<td>Total Functional failure 1</td>
<td>Failure Mode</td>
<td>Failure Effect</td>
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<td>A Partial Functional failure 2</td>
<td>Failure Mode</td>
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</tr>
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<td>A Partial Functional failure 3</td>
<td>Failure Mode</td>
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<td>Failure Mode</td>
<td>Failure Effect</td>
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<tr>
<td>Secondary Function</td>
<td>Total Functional Failure 1 A</td>
<td>Failure Mode</td>
<td>Failure Effect</td>
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</table>
## APPENDIX 5  RCM DECISION WORKSHEET II (REGAN, 2012)

<table>
<thead>
<tr>
<th>Failure Mode</th>
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<th>HO</th>
<th>HNO</th>
<th>OC</th>
<th>RST</th>
<th>RPL</th>
<th>C</th>
<th>PC</th>
<th>TASK</th>
<th>INITIAL INTERVAL</th>
<th>Default strategy</th>
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<tr>
<td>I A I Y</td>
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</tbody>
</table>

E: EVIDENT FAILURE MODE  
ES: EVIDENT SAFETY  
EE: EVIDENT ENVIRONMENTAL  
EO: EVIDENT OPERATIONAL  
ENO: EVIDENT NON-OPERATIONAL  
H: HIDDEN FAILURE MODE  
HS: HIDDEN SAFETY  
HE: HIDDEN ENVIRONMENTAL  
HO: HIDDEN OPERATIONAL  
HNO: HIDDEN NON-OPERATIONAL  
OC: ON-CONDITION TASK  
RST: RESTORATION TASK  
RPL: REPLACEMENT TASK  
C: COMBINATION TASK  
PC: PROCEDURAL CHECK  
FF: FAILURE FINDING TASK  
DS: DEFAULT STRATEGY
RCM DECISION DIAGRAM, EVIDENT FAILURE MODE
(REGAN, 2012)

Evident Failure Mode

Without inspection, will the loss of function caused by this single Failure Mode become evident to the operating crew during normal conditions? (Time does not matter)

- Safety (S)
  - On-Condition
    - Is the task technically appropriate? Does the task reduce the risk of failure to an acceptable level?
      - NO: Assign On-Condition Task Default Strategy
      - YES: No Scheduled Maintenance
  - Restoration
    - Is the task technically appropriate? Does the task reduce the risk of failure to an acceptable level?
      - NO: Assign Restoration Task Default Strategy
      - YES: No Scheduled Maintenance
  - Replacement
    - Is the task technically appropriate? Does the task reduce the risk of failure to an acceptable level?
      - NO: Assign Replacement Task Default Strategy
      - YES: No Scheduled Maintenance
  - Combination of Tasks
    - Is a combination of proactive tasks technically appropriate? Does the check reduce the risk of failure to an acceptable level?
      - NO: Assign Combination of Tasks Default Strategy
      - YES: No Scheduled Maintenance
  - Procedural Check
    - Is the check technically appropriate? Does the check reduce the risk of failure to an acceptable level?
      - NO: Default Strategy Required
      - YES: Assign Default Strategy

- Environmental (E)
  - On-Condition
    - Is the task technically appropriate? Is the task cost effective?
      - NO: Assign On-Condition Task Default Strategy
      - YES: No Scheduled Maintenance
  - Restoration
    - Is the task technically appropriate? Is the task cost effective?
      - NO: Assign Restoration Task Default Strategy
      - YES: No Scheduled Maintenance
  - Replacement
    - Is the task technically appropriate? Is the task cost effective?
      - NO: Assign Replacement Task Default Strategy
      - YES: No Scheduled Maintenance
  - Combination of Tasks
    - Is a combination of proactive tasks technically appropriate? Are the tasks cost effective?
      - NO: Assign Combination of Tasks Default Strategy
      - YES: No Scheduled Maintenance
  - Procedural Check
    - Is the check technically appropriate? Is the check cost effective?
      - NO: Default Strategy Required
      - YES: Assign Default Strategy

- Operational (O)
  - On-Condition
    - Is the task technically appropriate? Is the task cost effective?
      - NO: Assign On-Condition Task Default Strategy
      - YES: No Scheduled Maintenance
  - Restoration
    - Is the task technically appropriate? Is the task cost effective?
      - NO: Assign Restoration Task Default Strategy
      - YES: No Scheduled Maintenance
  - Replacement
    - Is the task technically appropriate? Is the task cost effective?
      - NO: Assign Replacement Task Default Strategy
      - YES: No Scheduled Maintenance
  - Combination of Tasks
    - Is a combination of proactive tasks technically appropriate? Is the cost of the tasks less than repair costs?
      - NO: Assign Combination of Tasks Default Strategy
      - YES: No Scheduled Maintenance
  - Procedural Check
    - Is the check technically appropriate? Is the cost of the check less than repair costs?
      - NO: Default Strategy Required
      - YES: Assign Default Strategy

- Non-Operational (NO)
  - On-Condition
    - Is the task technically appropriate? Is the cost of the task less than repair costs?
      - NO: Assign On-Condition Task Default Strategy
      - YES: No Scheduled Maintenance
  - Restoration
    - Is the task technically appropriate? Is the cost of the task less than repair costs?
      - NO: Assign Restoration Task Default Strategy
      - YES: No Scheduled Maintenance
  - Replacement
    - Is the task technically appropriate? Is the cost of the task less than repair costs?
      - NO: Assign Replacement Task Default Strategy
      - YES: No Scheduled Maintenance
  - Combination of Tasks
    - Is a combination of proactive tasks technically appropriate? Is the cost of the tasks less than repair costs?
      - NO: Assign Combination of Tasks Default Strategy
      - YES: No Scheduled Maintenance
  - Procedural Check
    - Is the check technically appropriate? Is the cost of the check less than repair costs?
      - NO: Default Strategy Required
      - YES: Assign Default Strategy
APPENDIX 7 RCM DECISION DIAGRAM, HIDDEN FAILURE MODE (REGAN, 2012)
<table>
<thead>
<tr>
<th>#</th>
<th>Item Description</th>
<th>Function</th>
<th>Failure Mode</th>
<th>Cause of Failure</th>
<th>Symptoms of Failure</th>
<th>Effect of Failure</th>
<th>Preventive Countermeasures</th>
</tr>
</thead>
</table>

**Worksheet for Failure Mode and Effect Analysis (FMEA)**

Approved by:

Date:

Equipment:

System:

**Drawing**: [Blank]

**Comments**: [Blank]
APPENDIX 9  RCM IMPLEMENTATION APPROACH (HINCHCLIFFE & SMITH, 2004)

RCM Implementation, adapted from Hinchcliffe & Smith Approach

Step 1 System Selection and data Collection
   1.1 Selection of Critical Equipment
   1.2 Operation and Maintenance data collection

Step 2 System Boundary Definition
   2.1 Boundary Overview
   2.2 Boundary Details

Step 3 System Description and Functional Block Diagram
   3.1 System Description
   3.2 Functional Block Diagram
   3.3 Equipment History

Step 4 System Function and Functional Failure
   4.1 System Functions
   4.2 Functional Failures

Step 5: FMEA

Step 6: LTA

Step 7: PM Tasks Selection

5 Failure Mode and Effect Analysis (FMEA)
6. Logic Tree Analysis (LTA)
7. Task Selection
APPENDIX 10    TASK SELECTION (HINCHCLIFFE & SMITH, 2004)

(1) Is the age reliability relationship for this failure known?

Yes Partial No

(2) Are there any applicable time directed tasks?

Yes No

Specify time directed tasks

Can this relationship be determined with further analysis?

Specify condition directed tasks

(3) Are there any applicable condition directed tasks?

Yes No

(4) Is this category "D" failure mode?

Yes No

(5) Are there any applicable failure finding tasks

Yes No

Specify failure finding tasks

(6) Are these tasks effective?

Yes No

(7) Can a design mode eliminate the failure mode or its effects?

Yes No

Specify the selected tasks

Design modification

Design modification