University of Pretoria

# An investigation into the benefits obtained by introducing Reliability Centred Maintenance in industrial organisations

Name : Saul Machingauta
Student number : 15382878
Supervisor : Prof Jasper Coetzee

A research project submitted to the University of Pretoria, in partial fulfilment of the requirements for the degree of Master of Science in Mechanical Engineering

6 September 2019

# Acknowledgement

I would like to thank my family (my wife Felistus, sons Panashe and Tinashe, and daughter Ruvarashe) for the support they have given me throughout this research period. They have encouraged me in difficult times during my graduate and postgraduate studies. Special thanks to my daughter Rose Ruvarashe (9 years old), she has been a great inspiration for me to complete this. I have endured the sleepless nights and long days to give her an example and lead the way for her.

I would also want to appreciate Prof Jasper Coetzee, my supervisor. Not only was he my supervisor but more importantly a subject matter expert in Reliability Centred Maintenance (RCM). Without him, I would never managed to complete this research. His contribution and unconditional support will always be appreciated

Special thanks go to Dr Richard Mkhoma, a friend and colleague, for all the assistance he has given me during the time I conducted this research. I made many telephone calls to him to seek assistance and he was always willing to do so.

My sincere gratitude also goes to the management of Sierra Rutile in Sierra Leone for allowing me to carry out this research at their company. I spent many hours doing this project and the company was so considerate during this time.

# Abstract

Reliability Centred Maintenance (RCM) is a well-known maintenance process developed in the aviation industry. It has yielded great success and hence was adapted to be used in more industrial environments, such as the process developed Coetzee (2015) called Proaktiv$^{TM}$ and the process developed by Moubray (1997) called RCM2. The RCM process is considered by many to be a very effective and comprehensive maintenance process that can, if implemented correctly, improve reliability and plant availability substantially.

However, many maintenance practitioners and maintenance experts who have used RCM believe that it is an overcomplicated process that is difficult to implement. In many cases the process is abandoned and left incomplete due to the amount of resources required and the slow results it delivers initially.

This dissertation investigates the benefits of implementing RCM on a mineral sizer at Sierra Rutile in Sierra Leone. In that regard, key performance indicators (KPI) of the sizer were recorded before and after the implementation of RCM. The main KPIs taken into consideration were:

- Availability
- Overall equipment effectiveness
- Hazard rate
- Productivity
- Mean time to failure (MTTF)
- Cost of maintenance per ton

This research centres mainly on the maintenance strategy improvement plans derived from the RCM process and the improvements to the production process that resulted from that exercise.

Key words

Reliability Centred Maintenance, Reliability, Availability, Functional failures, Failure modes

Abbreviations

| | |
|---|---|
| RCM | Reliability Centred Maintenance |
| SWOT | Strengths, weaknesses, opportunities and threats |
| FMECA | Failure mode effect and criticality analysis |
| FSI | Functionally significant item |
| SAE | International Society of Automotive Engineers |
| FMEA | Failure mode and effect analysis |
| PM | Preventative Maintenance |
| FAA | Federal Aviation Agency |
| OEE | Overall Equipment Effectiveness |
| MSI | Maintenance significant items |
| MTTF | Mean Time to Failure |
| OEM | Original Equipment Manufacture |

# Contents

# Table of Figures

# Chapter One: Introduction

## 1.1 Introduction

This chapter introduces the evolution of equipment maintenance and the various maintenance strategies in application in modern industries. The chapter also gives a brief introduction to Reliability Centred Maintenance (RCM) which will be described in greater detail in the literature review chapter.

## 1.2 Background

The cost of mining operations largely depends on the performance of the equipment utilized on the operations. Modern mining equipment is becoming progressively capital intensive, complex and sophisticated, increasing the challenges in maintaining it and leading to high operational and maintenance costs. To add to this, operating conditions on mining sites are exceptionally harsh and unforgiving, which results in frequent equipment failures that are often difficult to predict and prevent. Summed up, this leads to unplanned production stoppages, which in turn cause substantial revenue losses (Faitakis, Mackenzie, & Powley, 2004), (Paraszczak, Komljenovic, & Kecojevic, 2010). Faitakis et al. (2004) claim that 5% of mining production is lost every year due to unscheduled downtime. One third of the downtime is attributable to equipment failures, some of which may also involve substantial hazards, both in terms of safety and environmental impact (Faitakis et al., 2004).

To sum it up, Paraszczak, Komljenovic and Kocejevic (2010) say that productivity on operational equipment and associated cost figures are largely dependent on the performance of the equipment employed. Modern equipment has become increasingly complex and sophisticated such that standby units' costs are prohibitive and organizations often don't have the luxury of having them on site. This leaves operating equipment with little to no redundancy. To this end, organizations have to ensure that equipment is optimally maintained to achieve better return on investment

Furthermore, maintenance costs in mining are high. According to Campbell (1995), Knights (1999), Lewis (2000), and Knights and Oyaneder (2005), direct maintenance costs in mining operations account for over 30% of the total production cost. This is because a substantial part of maintenance actions are still reactive in many mines - sometimes well over 50% (Campbell, 1995), (Lewis, 2000), (Knights, 1999), (Campbell, 1995), (Efthymiou, Papakostas, Mourtzis, & Chryssolouris, 2012), and (Krajewski & Sheu, 2015). According to Mitchell (2002), maintenance costs should be between 15% and 20% of total production costs (Mitchell, 2002)

In view of the above, maintenance schedules and tasks recommended by Original Equipment Manufacturers (OEM) cannot be considered optimal. Manufacturers' generic maintenance programs do not consider the substantial differences between various mine sites' requirements and operating and service conditions. Due to that, recommended maintenance tasks are often too cumbersome, unnecessarily time consuming and costly, up to the point where their scope, content, frequency or even pertinence may be questioned. There is also a potential conflict of interest for equipment manufacturers between developing a maintenance program that is optimal for a customer and the one that is the most profitable for them (Faitakis et al., 2004) and (Paraszczak et al., 2010)

The maintenance function in industries has become increasingly important due to its role in maintaining and improving the availability, product quality, safety requirements and operating cost levels of the process plants. Accordingly, maintenance strategy selection has become one of the most important decision making activities in industry (Vishnu & Regikumar, 2016).

## 1.3 Preventative Maintenance

Preventative maintenance includes all maintenance activities that are done with the objective of preventing equipment failure. As such, these activities are carried out on a regular basis at predetermined intervals. Over the years, preventative maintenance has been recognized as extremely important in the reduction of maintenance costs and improvement of equipment reliability (Coetzee, 1997), (Bakri, Abdul Rahim, & Mohd Yusof, 2014)

## 1.4 Reliability Centred Maintenance

Wilmeth and Usrey (2015) define RCM as a method used for the refinement of maintenance strategies (Wilmeth & Usrey, 2015) while Nabhan (2010) prefers to refer it as a logical way of identifying tasks that need to be performed during preventative maintenance activities. Nabhan (2010) goes on to explain that RCM mitigates the risk of running equipment to failure by providing means and ways to carry out tasks before failure occurs. Bae et al (2009) add to the arguments and present RCM as an approach that systematically establishes maintenance strategies that are cost effective, taking into consideration the reliability of various system components (Bae et al., 2009)

Moubray (1997) offers a twofold definition of RCM, saying that RCM is a process whose output is a determination of maintenance requirements of equipment in its operating context. He also defines it as a process of determining the maintenance requirements of equipment to ensure that functionality is not lost (Moubray, 1997).

Love (2011) argues that RCM ensures that equipment achieves its reliability targets by administering minimum prevention tasks that are necessary, at minimum cost. He goes on to explain that an RCM program is designed according to anticipated failures of equipment and the consequences of such failures. According to Love (2011) it can be concluded that a RCM program is a product of the analysis of failure modes, modes' effects, and criticality analysis (FMECA), (Love, 2011).

Adding to the definitions of RCM, Tarar (2014) argues that it provides an outline by which the functions of equipment are preserved, rather than being the preservation of physical assets (Tarar, 2014). This means that RCM is not concerned with the actual condition of equipment, it concerns itself with the ability of the equipment to continuously and reliably provide the function for which it was purchased by its owner (Love, 2011) and (Tarar, 2014). Tarar (2014) adds that maintenance programs are structured properly with critical focus on the reliability of the functions the equipment has to perform (Tarar, 2014) and (Pierpoint, 2001).

RCM is a resource optimization method that is used to develop and refine maintenance programs. The process of RCM allows a maintenance manager to focus maintenance resources on supporting only the critical functions of a piece of equipment that are necessary to ensure reliable operation. Rather than solely relying on the manufacturer's specifications and past experience to generate schedules, an RCM process enables the generation of maintenance schedules from an analysis of equipment failures and their failure modes. According to Schwan (1999), "the goal of RCM is to create routine maintenance strategies that preserve important system/equipment functions in the most cost effective manner" (Wilmeth & Usrey, 2000), (Vishnu & Regikumar, 2016), and (Schwan, 1999).

In reality, RCM does not bring new ways of performing maintenance, but it utilizes the best of the several maintenance strategies available(Sandtorv & Rausand, 1991).

There are numerous example of successful implementation of RCM in literature: The USA Navy and Aviation (NAVAIR, 2005), oil industry (OREDA Consortium, 1997), railways, maintenance of ships and submarines (Romera, Carretero, Maria, & Menor, 2006), and in other different industries(Deshpande & Modak, 2002) and (Bal & Satoglu, 2014). There are also organisations that have attempted to implement RCM but could not succeed, such as the Norwegian railway which failed because it became too ambitious during the process (Carlo & Arleo, 2013).

This research aims to investigate the benefits of implementing a RCM system on a mineral sizer on a mining site in Sierra Leone. The operation uses the traditional preventative maintenance system where the recommendations from the Original Equipment Manufacturer (OEM) is the ultimate strategy. As such this presented a great opportunity to implement RCM.

## 1.5 Conclusion

This chapter introduced the concepts of preventative maintenance and RCM, which will be explored further in the literature review chapter. The next chapter presents the statement of the problem, the purpose of this research, and the research questions. Delimitations will be presented at the end of that chapter.

This space is left empty intentionally.
Please go to the next page

# 2. Chapter Two: Problem Definition

## 2.1 Introduction

The preceding chapter introduced the concepts of preventative maintenance and reliability cantered maintenance. This chapter presents the background of the problem, statement of the problem, purpose of this research, and the research questions. Delimitations will be presented at the end of the chapter.

## 2.2 Background of the problem

In January 2018, Sierra Rutile invested in mobile mining units to replace the old dredging unit that was to be retired. This investment was meant to make the dry mining operations safer and adopt newer technologies in mining. To add to the benefits above, this new method of mining was going to drastically reduce the cost of mining, reduce headcount, and increase output.

Sitting at the heart of this mobile mining unit is a mineral sizer which reduces the heavy mineral concentrate into smaller particles, which can then easily be pumped to the scrubber and the processing plants. The sizer is the subject of this research project.

However, after commissioning in June of 2018, the results from the plant were dismal. Instead of the planned outcomes being achieved, the first nine months showed disappointing results as outlined in the table below:

**KPI's Before Implementation of RCM**

| | Total Time Available | Total Uptime | Total Downtime | Frequency Of Failure | Tonnes Produced | MTTF | Hazard Rate | Availability | Cost Of Maintenance $/ton | Number of PM Schedules |
|---|---|---|---|---|---|---|---|---|---|---|
| Apr-18 | 720 | 340.15 | 379.85 | 189 | 5041 | 3.8 | 26% | 47% | 1.88 | 4 |
| May-18 | 744 | 413.22 | 330.78 | 165 | 6007 | 4.5 | 22% | 56% | 1.90 | 6 |
| Jun-18 | 720 | 444.32 | 275.68 | 143 | 6650 | 5.0 | 20% | 62% | 1.77 | 8 |
| Jul-18 | 744 | 524.19 | 219.81 | 146 | 7509 | 5.1 | 20% | 70% | 1.62 | 8 |
| Aug-18 | 744 | 491.23 | 252.77 | 175 | 7079 | 4.3 | 24% | 66% | 1.04 | 8 |
| Sep-18 | 720 | 556.32 | 163.68 | 135 | 7722 | 5.3 | 19% | 77% | 1.13 | 8 |
| Oct-18 | 744 | 518.12 | 225.88 | 174 | 7509 | 4.3 | 23% | 70% | 1.09 | 6 |
| Nov-18 | 720 | 511.48 | 208.52 | 135 | 7616 | 5.3 | 19% | 71% | 1.13 | 6 |
| Dec-18 | 744 | 589.13 | 154.87 | 145 | 8474 | 5.1 | 19% | 79% | 0.98 | 5 |
| Average | 733 | 488 | 246 | 156 | 7067 | 4.8 | 0.21 | 66% | 1.39 | 7 |

*Figure 1: Sizer Key performance indicators Before RCM implementation*

This research project was chosen to assess and understand the mediocre performance of the plant, caused mainly by issues surrounding the sizer unit.

Although preventative maintenance schedules were being performed according to the original equipment manufacturer's (OEM) requirements, the equipment kept on breaking down. The organization realized that there was a need for new ways and new approaches to maintaining the equipment. An RCM-based program for the mobile mining unit mineral sizer was proposed after studying the success stories that such a program had brought to other organizations in a similar position.

This research therefore seeks to investigate the possibility of availability improvements, downtime reduction and cost reduction that an RCM program can bring to the mineral sizer of the mobile mining unit at Sierra Rutile in Sierra Leone.

## 2.3 Problem Statement

The problem was that the efficiency of operating the mineral sizer was too low, the availability was below prescribed standards, and costs were unexpectedly high. Although different maintenance models and strategies were tried and implemented, unit operations remained below optimal levels and it was proposed that RCM methodology be implemented.

## 2.4 Purpose of the research

The purpose of this research is to investigate and establish the benefits of implementing an RCM program on the mineral sizer at Sierra Rutile in Sierra Leone. As such, this research will investigate improvements in the availability of the mineral sizer, productivity, overall equipment effectiveness (OEE), reduction in maintenance costs, and downtime reduction.

## 2.5 Research Objectives

The objectives of the research are:

- To establish availability improvements obtained as a result of implementing an RCM program on the mineral sizer
- To determine OEE improvements on the mineral sizer after RCM implementation
- To determine the level of downtime reduction brought about by implementing an RCM program on the mineral sizer
- To establish if there is a relationship between implementing an RCM program and maintenance cost reduction
- To recommend improvement programs to optimize mineral sizer operations

## 2.6 Delimitations

Limitations in this research have been recognized, including:

- The time period in which the research was done is too short. Results obtained might not represent the same reality as it would if the research was carried out over a longer period.
- A cross-sectional research design gives snapshot results, and data collected over time may give different results.
- The equipment chosen for this research might have been going through teething problems and it's possible that the results are distorted.
- The researcher is an employee of the organization under study and views and analysis might be biased.
- Because of the short time frame in which the research was undertaken and the fact that the research was carried out on a single piece of equipment, results cannot be generalized to other equipment types
- The RCM process was introduced and implemented on this equipment but the personnel working closely with this equipment had little to no knowledge at all about RCM. As such, it took a long time do complete because the researcher had to, in many cases, explain each step of the RCM process to personnel.
- Shortage of labour and skill to implement the process successfully. The organization was not prepared to hire more knowledgeable people for the purpose of this implementation. Firstly, because they were sceptical about the results and secondly because they didn't appreciate the RCM process

## 2.7 Conclusion

This chapter presented the background of the problem, statement of the problem, purpose of this research, and the research questions. Delimitations were presented at the end of the chapter. The next chapter will present the review of literature relevant to the subject of RCM.

# 3. Chapter Three: Theoretical Background and Literature Review

## 3.1 Chapter Overview

The previous chapter presented the background to the problem, statement of the problem, purpose of this research, and the research questions. Delimitations were presented at the end of the chapter. This chapter presents a review of literature relevant to the study of Reliability Centred Maintenance (RCM). The review starts by defining relevant terms and then discusses the evolution of RCM from traditional maintenance systems. This chapter also discusses RCM implementation in other industries, comparing and contrasting the benefits obtained from the implementations, and associated shortcomings. This research seeks to explore the benefits obtained from implementing an RCM program on a mineral sizer, and relevant literature has thus been explored that relates to the evolution of RCM and maintenance in general.

## 3.2 Introduction

With increasing levels of competition faced by manufacturing and production companies, the battle to survive has grown tremendously.

Preventative maintenance has become an accepted practice in many different industries as a cost-effective means of preserving the value and function of various types of equipment, increasing reliability, and preventing equipment failure. Preventative maintenance programs are developed based on a variety of different inputs and factors. The notion of reliability is embedded in the concept of preventative maintenance, since a primary goal of preventative maintenance is to improve or increase the reliability of a component or a system.

RCM has largely replaced the historical notion of one reliability curve that fits everything, the most widely accepted graphical representation of this being the famous bathtub curve (Design, Upperstage, Jacket, & Rocket, 2008). In addition, instead of focusing on preventing equipment, components, or systems from breaking, RCM focuses on enabling the equipment, components or systems to perform certain necessary functions. The acceptance and adoption of RCM has caused wholesale changes in the development of preventative maintenance programs. This research deals with the development of optimized maintenance schedules using the RCM approach, and it is therefore important to first gain an understanding of preventative maintenance, reliability theory, and the evolution of RCM.

This chapter explores the evolution of maintenance and the history of RCM.

## 3.3 Evolution of Maintenance

Over the past few decades, maintenance has evolved from being the *"necessary evil"* to being a *"profit contributor"* and a part of the *"integrated business",* becoming a point of strategic concern for mining companies. If this is true, then maintenance has evolved from being an inevitable part of production into the means by which organisations can reach their business objectives. In other words, maintenance is now considered as a partner in success (Kobbacy, A., & Murthy, 2008), (Hora, 1987), (Griffi, Roth, & Seal, 1991), (Tombari, 1983), and (Krajewski & Sheu, 2015).

Maintenance has evolved over the years, perhaps due to increased complexities in systems or simply because there has been so much research in the field of maintenance (Moubray, 1997).

According to Moubray (1997) (figure 1) and also Arunraj and Maiti (2007) (figure 2), the evolution of maintenance can be traced through three generations.

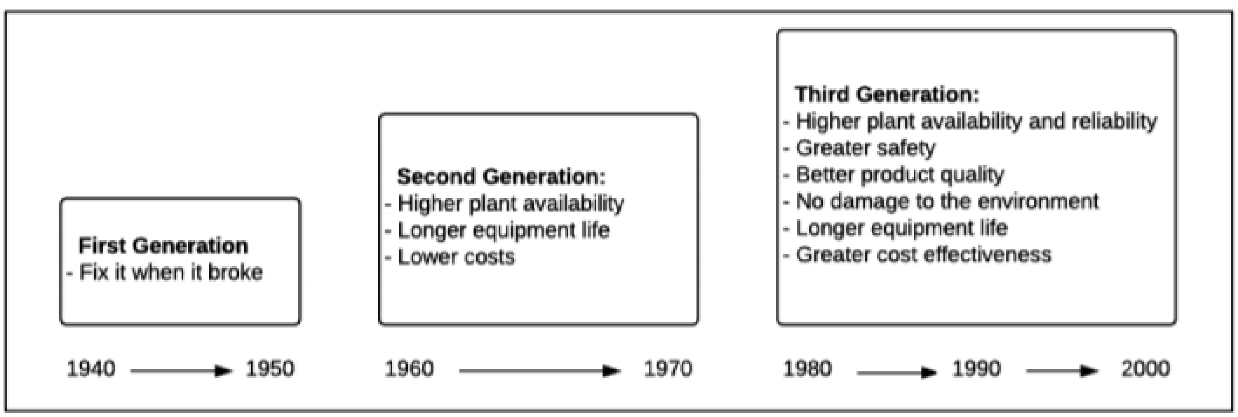



*Figure 2: The evolution of maintenance (Moubray, 1997)*

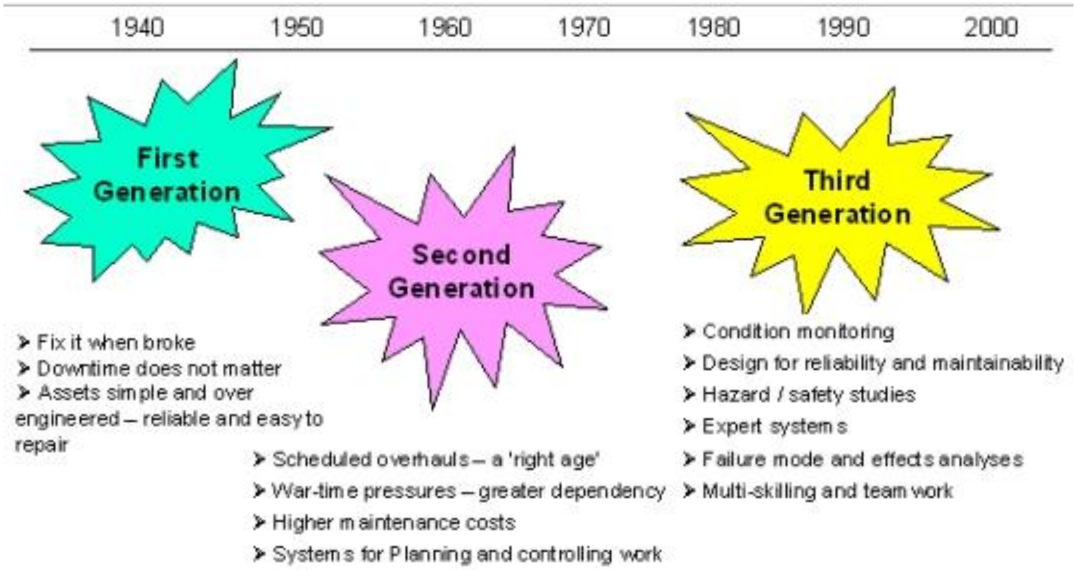



*Figure 3: Maintenance evolution*(Arunraj & Maiti, 2007)

### 3.3.1 The first generation

According to Moubray (1997), the first generation covers the period up to World War II. In those days industry was not very highly mechanized, so downtime mattered less than it does now. This meant that the prevention of equipment failure was not a very high priority in the minds of most managers. At the same time, most equipment was simple and much of it was over-designed. This made it reliable and easy to repair. As a result, there was no need for systematic maintenance of any sort beyond simple cleaning, servicing and lubrication routines. The need for specialized skills was also less than it is today. When failure occurred, the failed components could easily be replaced, and would not have adverse effects on equipment effectiveness. Therefore the maintenance strategy was not seriously considered, it was more about just fixing the equipment when it broken (Moubray, 1997) and(Morello, Karray, & Zerhouni, 2019).

### 3.3.2 The second generation

During World War II things changed drastically. Demand for goods increased during the war. Because of this demand for increased in production of goods, mechanization also increased proportionally. By the 1950s, machines became more complex. Industry was beginning to depend on them. As this dependence grew, machine breakdown came into focus. This led to the idea that equipment failures could and should be prevented, which gave birth to the concept of preventative maintenance (Moubray, 1997). In the 1960s, this consisted mainly of equipment overhauls done at fixed intervals, without considering the cost and the condition of equipment. The cost of maintenance also started to rise sharply relative to other operating costs. This led to the growth of maintenance planning and control systems, which helped to bring maintenance under control and greatly reduced costs. Because of the costs involved in maintaining machines, people began to seek ways in which they could maximize the life of assets and increase production flow passing through these assets (Morello et al., 2019).

### 3.3.3 The third generation

In this generation, the changes in industries gathered even greater momentum, summarised in new expectations, new research and new techniques (Moubray, 1997). In the 1960s and 1970s, the concept of just in time (JIT) manufacturing became the focus, highlighting that any stop in production could interfere with the operation of an entire facility. In other words, downtime (planned or unplanned) had many effects on increasing operating costs, reducing output and affecting customer service. Therefore, in this generation, downtime was an issue that needed detailed analysis (Morello et al., 2019) and (Moubray, 1997).

The mechanization and automation of facilities had also become issues in this generation. Therefore, reliability and availability became issues in industries as diverse as health care, data processing, and telecommunications (Moubray, 1997). Another issue was that quality standards were rising rapidly. Some failures have serious safety and environment consequences, and these types of failure had to be prevented or mitigated.

All these issues increased the dependence on the integrity of the physical asset. In this generation, it became evident to the research and maintenance engineers that there were different failure patterns (figure 5). These different failure patterns will be explained later in this chapter (Moubray, 1997) and (Morello et al., 2019).

### 3.3.4 The fourth generation

The fourth generation since 2000 has been mainly concerned about the risk and reliability during the life cycle of assets in the business. Increased awareness of risks related to equipment, personnel, environment, operation process, as well as the cost, became more and more pronounced. The most important improvement of maintenance management brought about by the fourth generation is that it integrated maintenance and safety (Muller, Marquez, & Iung, 2008). That led to the development of risk-based inspection (RBI) and risk-based maintenance (RBM) in addition to Reliability Centred Maintenance (RCM) and condition-based maintenance (CBM). Together, these increase the profitability of the operation and optimize the total life cycle cost without compromising safety or environment issues (Arunraj & Maiti, 2007), using risk and reliability analysis approaches to plan and decide on inspection and maintenance actions (Muller et al., 2008) and (Pintelon, Parodi-Herz, Kobbacy, Khairy, & Murthy, 2008).

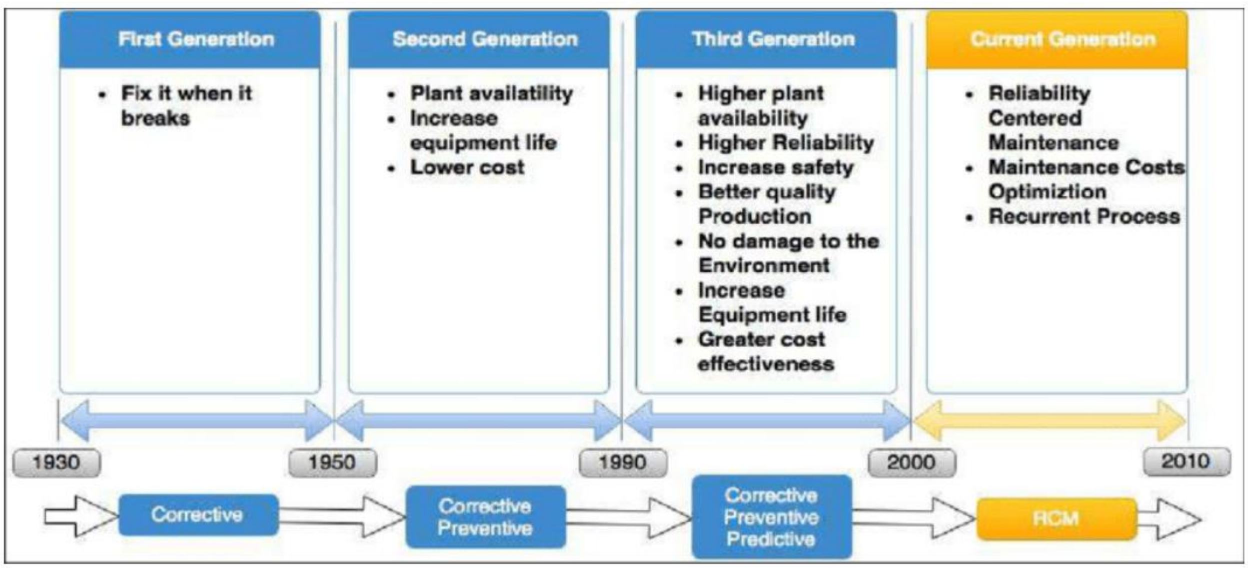



*Figure 4: Evolution of maintenance approaches (Braadbaart, n.d.)*

Preventative maintenance programs are designed to mitigate the effects of anticipated failures by carrying out routine maintenance tasks. This is normally designed around recommendations from original equipment manufacturers and from historical data that organizations have about their equipment. However, RCM identifies specific tasks to be done to reduce the probability of failure and bring it to acceptable levels. The tasks identified for RCM are a product of the failure mode effect and criticality analysis (FMECA) process (Love, 2011)

#### *3.3.4.1 Maintenance 4.0*

Over the past four decades, humans have ensured that assets within organisations deliver value to their owners and this have been accomplished through manual and tedious processes. Following the trends of industry 4.0, maintenance has adopted a technological approach digitalising processes bringing in the internet of things (IoT), wireless sensors, cloud computing, artificial intelligence (AI) and machine learning. Traditionally specialised technicians would go into the filed to manually collect data from machines using hand held devices whereas Maintenance 4.0 has introduced online sensors connected to cloud servers to collect and analysed data that is used by organisations for decision making(ReliabilityWeb.com, 2019)(Chesworth & Miet, 2018)

## 3.4 Maintenance Strategies

Every time failure occurs on equipment or a system, negative effects are experienced by the organization. The negative effects could include any or all of these:

- Production loss
- Poor quality products
- Time
- Higher costs of repair
- Threats to worker safety
- Environmental threats

Failures manifest in different forms. Some failures are evident immediately, and some failures are hidden and could cause catastrophes if not detected early enough (Coetzee, 1997). Each organization needs to make its own decisions about its approach to maintenance. A strategy has to be designed to respond to each important failure mode. If the strategy is to run to failure, money will have to be spent on repairing breakdowns. There are trade-offs that exist between the cost of prevention and the cost of failure. These trade-offs depend on the severity of each failure and the effect it has on production loss, costs, worker safety, and the effect of the failure on the environment. All these factors influence the decision whether to prevent failure, or to handle it when it occurs (Coetzee, 2015).

The end result of this logical decision framework is a combination of different maintenance strategies grouped into work packets for maintenance teams to execute. In order to select the best strategy for every situation, it is important to understand the background of each maintenance strategy. The diagram below shows strategy structure as depicted by Coetzee in his book Maintenance (Coetzee, 1997)

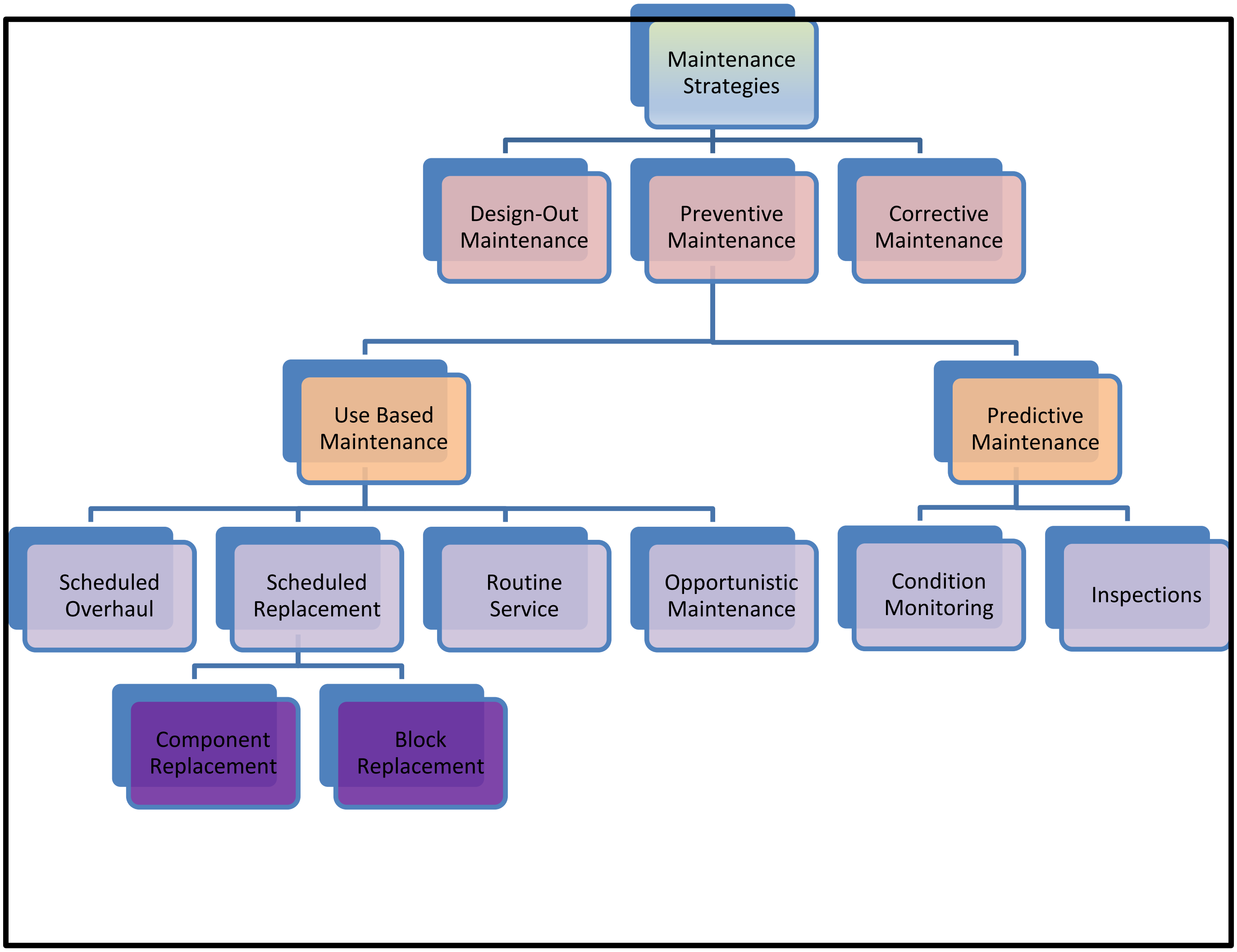



*Figure 5: Maintenance strategies (Coetzee, 1997)*

### 3.4.1 Design-Out Maintenance

This is not purely a maintenance strategy but is used extensively by maintenance engineers (Coetzee, 1997). It is aimed at rectifying design defects that originated from improper installation or poor material choice etc. Design-Out Maintenance requires a strong maintenance design interface so that the maintenance engineer works in close cooperation with the design engineer. It is more suitable for items or equipment of high maintenance cost. The choice to be made is between the cost of redesign and cost of recurring maintenance. If the maintenance cost or downtime cost of equipment is high, then the Design-Out Maintenance strategy can often be effective. This strategy differs from all the others in that it is a one-off activity, rather than a repetitive activity designed to prevent failure. Design-Out Maintenance aims to redesign those parts of the equipment which require high levels of maintenance effort or spares costs, or which have unacceptably high failure rates. The high maintenance costs may have been caused by a number of factors, including:

- Poor maintenance.
- Operation of equipment outside of its original design specification.
- A poor initial design.

The Design-Out Maintenance strategy can only be implemented effectively if high maintenance cost items can be identified and the reasons for the high cost understood. It is often the best strategy to take when breakdowns are too frequent or repair is too costly. The focus of Design-Out Maintenance is to improve the design to make maintenance easier, or even to eliminate it. (Jain, 2013).

### 3.4.2 Preventative Maintenance

Preventative maintenance includes all maintenance activities that are done with the objective of preventing failure. As such, these activities are carried out on equipment on a regular basis at predetermined intervals. Over the years, preventative maintenance has been recognized as extremely important in the reduction of maintenance costs and improvement of equipment reliability (Coetzee, 1997) and (Bakri et al., 2014).

According to Ahuja and Khamba (2008) and Shaomin and Ming (2011), this concept was introduced in 1951, as a physical check of the equipment to prevent equipment breakdown and prolong equipment service life. Preventative maintenance includes maintenance activities that are undertaken after a specified period of time or amount of machine use. During this phase, the maintenance function is established. This type of maintenance relies on the estimated probability that the equipment will break down or experience deterioration in performance in the specified interval. The preventative work undertaken may include equipment lubrication, cleaning, parts replacement, tightening, and adjustment. The production equipment may also be inspected for signs of deterioration during preventative maintenance work (Ahuja & Khamba, 2008) and (Shaomin & Ming, 2011).

According to Coetzee (1997), there are multiple misconceptions about preventative maintenance, including that it is unduly costly. This logic dictates that it would cost more for regularly scheduled downtime and maintenance than it would normally cost to operate equipment until repair is absolutely necessary. This may be true for some components; however, the costs and the long-term benefits and savings associated with preventative maintenance should be considered. Without preventative maintenance, for example, costs for lost production time from unscheduled equipment breakdown will be incurred (Coetzee, 1997).

### 3.4.3 Use Based Maintenance

Use based maintenance can be divided into two types:

- *Age based maintenance* – maintenance regular carried out on equipment based on the age of the equipment. Maintenance is often done based on the number of hours the machine has run, tonnage handled, production throughput and/or kilometres travelled (Coetzee, 1997).
- *Calendar based maintenance* – Maintenance carried out based on the amount of time elapsed for example, daily, weekly, monthly or annually. This type of maintenance is conducted irrespective of the amount of production completed on the machine (Coetzee, 1997).

#### *3.4.3.1 Scheduled overhaul*

The machine or component is completely stripped and reconditioned to an almost new condition (Coetzee, 1997).

#### *3.4.3.2 Scheduled replacement*

The machine or the component is replaced by a new unit at pre-determined times (Coetzee, 1997).

##### 3.4.3.2.1 Component Replacement

The purpose of this type of maintenance is to increase system reliability through preventative replacements of critical components within the system. It is therefore critical to identify which components within the system are candidates for preventative replacements and subsequently determine the best times for such replacements. Decisions can be made to replace the components before failure at pre-determined times. However, some components might not be subject to failure, but running costs increase with age and hence the replacement of such components is necessary to reduce running costs (Jardine & Tsang, 2013) and (Coetzee, 1997).

##### 3.4.3.2.2 Block Replacement

Sometimes it is worthwhile replacing similar items in groups rather than as single items because the cost of replacement is cheaper when replaced as a group. This decision is based on the notion that similar components have similar failure frequencies. If one fails it is then necessary to replace all the items similar to the one failed, instead of only replacing the failed component (Jardine & Tsang, 2013) and (Coetzee, 1997)

#### *3.4.3.3 Routine services*

The machine is serviced at times. During this time, checks are done, the machine is lubricated, filters changed and minor adjustments are made (Coetzee, 1997).

#### *3.4.3.4 Opportunistic Maintenance*

According to Coetzee (1997) and (2015), opportunistic maintenance is only carried out on equipment when the opportunity arises. In support of Coetzee (1997) and (2015), Cui and Li (2006) prefer to define opportunistic maintenance as a strategy in which preventative maintenance tasks are carried out at opportunities either by choice or based on the condition of the equipment. Work is identified and scheduled to be carried out if the plant is down for various reasons, including a breakdown. Opportunistic maintenance is undertaken when continuous operation of the plant is critical and the costs or effects of downtime are severe (Coetzee, 1997).

### 3.4.4 Predictive or Condition-based Maintenance

Efthymiou et al., (2012) say that unplanned maintenance can cause costly downtimes if the problem cannot be rectified in a timely manner. Predictive or condition-based maintenance (CBM) is a strategy that recommends maintenance tasks based on equipment status (Alsalaet, 2016). As such, predictive maintenance utilizes prognostics methods and is considered being more proactive if compared with the planned maintenance regarding cost (Jardine, Lin, & Banjevic, 2006). According to Efthymiou et al,.(2012), a condition-based program consists of three key steps:

1) Information collecting to obtain data relevant to system health,
2) Information handling to handle and analyse the data
3) Decision-making to recommend efficient maintenance activities

According to Coetzee (1997), predictive maintenance is applicable to any failure mode where it is found to be technically feasible and worth doing. He continues to say this strategy has a special place in cases where the risk of failure (hazard rate) does not increase with age as Use Based Preventive Maintenance cannot be used in those cases. He adds that it is a philosophy or an attitude that uses the actual operating condition of the plant and systems to optimize total plant operation. Predictive maintenance is a condition driven preventative maintenance program (Coetzee, 1997) and (Coetzee, 2015). To support Efthymiou et al,. (2012), Coetzee (1997) and

(2015) concur that this maintenance strategy uses direct monitoring of the mechanical condition to determine the actual mean time to failure or loss of efficiency for each machine in the plant. Contrary to preventative maintenance, predictive maintenance uses factual data about the condition of the machines. This data provides the maintenance manager with the actual data for scheduling maintenance activities (Mobley, 1943).

#### *3.4.4.1 Condition Monitoring*

A parameter is selected and monitored to detect imminent failure in equipment. The most commonly used condition monitoring tools are:

- Vibration: the basis of vibration analysis is an understanding that every rotating machine produces vibrations which are part of machine dynamics such as alignment and balance of rotating parts. Measuring the amplitude of vibration at certain frequencies can provide valuable information about the accuracy of shaft alignment and balance, the condition of bearings or gears, and the effect on the machine due to resonance from the housings, piping and other structures (Alsalaet, 2016).
- Oil analysis: This method is employed to gain  insight into the physical and chemical state of the lubricating oil, as well as the condition of the machine elements that come in contact with oil during routine operation (Karanović, Jocanović, Wakiru, & Orošnjak, 2018).
- Thermography: This method uses machine real time temperature distribution to indicate machine operating condition (Mobley, 1943) and (Thobiani, Tran, & Tinga, 2017).

#### *3.4.4.2 Inspections*

This is where the five senses of the artisan are used to determine the condition of the plant. Reports from plant inspections are then used to determine appropriate maintenance activities to be undertaken.

### 3.4.5 Corrective Maintenance

Repairs will always be needed on machinery and equipment. Despite all preventative and predictive maintenance, equipment will always fail at some point. Sometimes equipment failure is used as a strategy and is planned for, and other times it happens unexpectedly. This maintenance strategy is often referred to as *"Do Nothing"* and *"Wait for failure".* No effort is wasted in trying to determine when the component will fail through predictive maintenance or trying to prevent failure through preventative maintenance programs. At first impression, this method seems the most cost effective because the manpower and associated costs are minimal. But closer examination shows that when the machinery fails, considerable expense is required to allocate manpower on an emergency basis, quickly source repair/replacement parts, and lost revenues due to nonproduction can mount rapidly, depending upon the production and repair processes. Clearly, this method has the highest associated cost and maintenance is unpredictable at best. In addition, an unexpected failure can be dangerous to personnel and the facility. The major downside of reactive maintenance is unexpected and unscheduled equipment downtime. If a piece of equipment fails and repair parts are not available, delays ensue while the parts are ordered and delivered(Chalifoux, A. and Baird, 1999). If these parts are urgently required, a premium for expedited delivery must be paid. If the failed part is no longer manufactured or stocked, more drastic and expensive actions are required to restore equipment function. Cannibalization of similar or duplicate equipment or rapid prototyping technology may satisfy a temporary need but at substantial cost. Also, there is no ability to influence when failures occur because no (or minimal) action is taken to control or prevent them.

When this is the sole type of maintenance practiced, both labour and materials are used inefficiently. Labour resources are thrown at whatever breakdown is most pressing. In the event that several breakdowns occur simultaneously, it is necessary to practice a kind of maintenance triage in an attempt to bring all the breakdowns under control. Maintenance labour is used to “stabilize” (but not necessarily fix) the most urgent repair situation, then it is moved on to the next most urgent situation, etc. Replacement parts must be constantly stocked at high levels, since their use cannot be anticipated. This incurs high carrying charges and is not an efficient way to run a storeroom.

## 3.5 Reliability Centred Maintenance

With the high levels of competition among industries and businesses, the battle for survival has become more pronounced than ever. Producers the world over are striving to reduce costs of production and deliver products to customers at competitive prices. Not only are customers concerned about price implications of products, but the safety and reliability of products has become of paramount importance too (Paprocka, 2018), (Okwuobi et al., 2018) and (Swanson, 1997). This quest extends to the workplace where stakeholders and employees are entitled to a safe work environment (Zambon et al., 2018). In the past, preventative maintenance only focused on carrying out scheduled maintenance in an effort to prevent recurrence of failure, but now the focus has shifted to  anticipation of the factors that lead to failure, and ensuring that such factors are prevented from recurring (Vishnu & Regikumar, 2016). Studying reliability in production and processing plants plays a critical role in ensuring smooth running processes, leading to sustainability of businesses (Adoghe, Awosope, & Daramola, 2012).

In the past few decades, the maintenance regime has seen many changes. These changes can largely be attributed to the huge increase in the complexity of physical assets which needs to be maintained worldwide. With increasing complexities in equipment and systems, maintenance also needs to adapt to such changes and hence techniques and views on maintenance also need a paradigm shift. Maintenance people are having to adopt completely new ways of thinking and acting (Moubray, 1997).

The concept of RCM was developed over a period three decades. Historically, the commercial aviation industry played an important role in the development of the Reliability Centred Maintenance methodology in the 1960s. When the Boeing 747 was developed, the commercial aviation industries led by United Airlines realized that maintenance of the new jumbo aircraft was going to be expensive and unsustainable and re-valuation of maintenance principles had to be undertaken. This concept was developed after rigorous examination of questions that before were deemed unnecessary by many in the maintenance world (Nowlan & Heap, 1978). Some of the questions interrogated in the process were:

- How does a failure occur?
- What are the consequences of such failure occurring?
- Can such a failure be prevented from occurring?

In developing RCM, Nowlan and Heap's (1978) primary objective was preservation of system function, and not preservation of the equipment, as was common with traditional maintenance strategies (Nowlan & Heap, 1978) and (Smith, 1993)

### 3.5.1 Definitions of RCM

Wilmeth and Usrey (2015) define Reliability Centred Maintenance as a method used for the refinement of maintenance strategies (Wilmeth & Usrey, 2015) while (Nabhan, 2010) prefers to refer it as a logical way of identifying tasks that needs to be performed during preventative maintenance activities. Nabhan goes on to explain that RCM mitigates the risk of running equipment to failure by providing means and ways to carry out tasks before failure occurs (Nabhan, 2010). Bae et al., add to the argument and present RCM as an approach that systematically establishes maintenance strategies that are cost effective, taking into consideration the reliability of various system components (Bae et al., 2009).

Moubray (1997) brings about a twofold definition to Reliability Centred Maintenance. He says that Reliability Centred Maintenance is a process whose output is a determination of maintenance requirements of equipment in its operating context. He also defines it as the process of determining maintenance requirements to ensure that functionality is not lost (Moubray, 1997).

Love (2011) argues that Reliability Centred Maintenance ensures that equipment achieves its reliability targets by administering necessary minimum preventative tasks at minimum cost. He goes on to explain that a Reliability Centred Maintenance program is designed according to anticipated failures of equipment and the consequences of such failures. According to Love (2011), it can be concluded that a Reliability Centred Maintenance program is a product of the analysis of failure modes, modes effects and criticality analysis (FMECA) and (Love, 2011).

Adding to the definitions of Reliability Centred Maintenance, Tarar argues that Reliability Centred Maintenance provides an outline by which functions of equipment are preserved rather than just the preservation of physical assets (Tarar, 2014). What this means is that Reliability Centred Maintenance is not concerned with the physical being of the equipment, it rather concerns itself with the ability of the equipment to continuously and reliably provides the function for which it was purchased by its owner (Love, 2011) and (Tarar, 2014). Tarar adds that maintenance programs are structured properly with critical focus on the reliability of the functions the equipment has to perform (Tarar, 2014) and (Pierpoint, 2001).

Reliability Centred Maintenance is a resource optimization method that is used to develop and refine maintenance programs. The process of Reliability Centred Maintenance allows a maintenance manager to focus maintenance resources to support only the critical functions of a piece of equipment necessary to ensure reliable operation. Rather that solely relying on manufacturers' specifications and past experience to generate schedules, a Reliability Centred Maintenance process enables the generation of maintenance schedules from analysis of equipment failures and their failure modes. According to Schwan (1999), "the goal of Reliability Centred Maintenance is to create routine maintenance strategies that preserve important system/equipment functions in the most cost effective manner" (Wilmeth & Usrey, 2000), (Vishnu & Regikumar, 2016) and (Schwan, 1999).

In reality, Reliability Centred Maintenance does not bring new ways of performing maintenance, but utilizes the best of the several maintenance strategies available (Sandtorv & Rausand, 1991).

### 3.5.2 Evolution of Reliability Centred Maintenance

The term Reliability Centred Maintenance (RCM) was first used in 1979, when two leading American Engineers of United Airlines, Nowlan and Heap, named their report RCM intended for the American army (Nowlan & Heap, 1979). The report was a thorough presentation of the methodology of improvement of the maintenance process in civil aviation. Nowlan and Heap aimed to emphasize, by the title itself, that United Airlines was increasing the reliability of its airplanes. In 1960, research was carried out by the Federal Aviation Agency (FAA) to try and establish the effectiveness of aircraft maintenance in fixed time. Two important discoveries were made:

- The planned repair had small effects on the total reliability of complex components, except if the component had a dominant failure due to wear
- There are a lot of components for which there are no effective and efficient manners of preventive maintenance

These two discoveries changed the approach to reliability

Moubray (1997) as one of the leading theorists of RCM, defines RCM as a process which is basically the same as FMECA (Failure Modes, Effects and Criticality Analysis). The only difference is that FMECA is used by the manufacturers applying their knowledge of their product to determine potential failures while RCM sums up experience gained by operators and maintenance personnel over a long period of time.

The advancement in technology and increased size of airplanes forced the aviation industry to relook at its maintenance strategies three decades ago. Operators realized that they couldn’t continue using old methods to maintain airplanes if they were to run their businesses profitably (Wilmeth & Usrey, 2015) and (Niu, Yang, & Pecht, 2010a). According to Matteson (1995), the engineers at United Airlines pioneered the revaluation of maintenance strategies into the basic principles of what is today called Reliability Centred Maintenance (Matteson, 1995). As Matteson (1995) explains, the initial design of the Reliability Centred Maintenance process was largely based on studying of the historical records that had been accumulated within the aviation industry over many years.

According to Moubray (1997), Reliability Centred Maintenance was developed in the 1970s by the US Federal Aviation Administration (FAA), the Aerospace Industries Association (AIA) and the Air Transport Association (ATA). The introduction of the Boeing 747 introduced complex and advanced technologies to the aerospace industry.  As a result, traditional maintenance systems were not optimal to operate an airline profitably. A new way of maintaining airplanes became mandatory and engineers had the responsibility to innovate new and sustainable systems of maintenance and the concept of Reliability Centred Maintenance was born (Smith, 1993), (Nowlan & Heap, 1978) and (Moubray, 1997).

This study revealed details that shocked the aviation industry as well as the maintenance industry. The widely used tool in the maintenance field, the classic “bathtub” shaped curve of failures plotting time against the number of failures was not accurate for airplane failures (Wilmeth & Usrey, 2015). Because of the shortfall of the then used maintenance systems, United Airlines developed maintenance frameworks that holistically defined maintenance regimes (Niu et al., 2010a).

Another discovery made by Nowlan and Heap (1978) was that many types of failures could not be prevented, no matter how intensive the maintenance activities. Additionally, it was discovered that for many items the probability of failure did not increase with age. Consequently, a maintenance program based on age would have little, if any, effect on the failure rate (Nowlan & Heap, 1978)

Armed with the understanding of the benefits and importance of RCM, the International Society of Automotive Engineers (SAE) established the Technical Committee which in 1999 developed the JA1011 standard: Evaluation Criteria for Reliability Centred Maintenance (RCM) Process. This quickly become a standard which all aspirants of RCM implementation could use, since it defines guidelines and clarifies a lot of details and activities that are used during the implementation(Car, 2014)

Preventative maintenance programs are designed to mitigate the effects of anticipated failures by carrying out routine maintenance tasks. This is normally designed around recommendations from original equipment manufacturers and from the historical data organizations have on their equipment. However, Reliability Centred Maintenance identifies specific tasks to be done to reduce probability of failure and bring it to acceptable levels. The tasks identified for Reliability Centred Maintenance are a product of the FMECA process (Love, 2011).

Since then, Reliability Centred Maintenance has been used very successfully and extensively around the world.

### 3.5.3 Benefits of Reliability Centred Maintenance

Reliability Centred Maintenance methodology has highlighted that not all maintenance is necessarily good maintenance(Zio, 2009). This methodology has been used successfully in several industries, beginning with the aerospace industry in the 1970s, later to be implemented in the defence and nuclear industries before spreading to other industries, and many benefits have been realized (Sandtorv & Rausand, 1991). According to Smith (1993), Reliability Centred Maintenance has a positive impact on safety, operations and other facets of the business (Smith, 1993)

- Moubray (1997) claims that the correct implementation of Reliability Centred Maintenance can reduce the amount of routine maintenance tasks by between 40-70%. The financial benefit can be dramatic and reduction of headcount is evident (Smith, 1993) and (Moubray, 1997).
- Greater safety and environmental integrity, personal / process safety, and community / societal consequences (i.e. land / water / air pollution) are considered before the effects on economic operations (i.e. profit or revenue)(Usrey, 2000).
- Reliability Centred Maintenance helps improve machine performance because of higher machine uptimes and reliabilities achieved. The consideration of predictive/condition based maintenance implies that the life of the equipment is considerably increased (Smith, 1993) and (Moubray, 1997).
- According to Levitt (2008), Reliability Centred Maintenance leads to reduced cycle time and non-value-added activity. He goes on to say that the best way to do lean maintenance is to do Reliability Centred Maintenance. This is because maintenance activities are focused on the right places and non-value adding maintenance activities are eliminated (Levitt, 2008).
- A decreased total cost of maintenance, measured by tracking all the costs associated with the maintenance program, is possible. The focus of Reliability Centred Maintenance is to ensure the maintenance budget is spent in the place/area where it will achieve the most benefit and have the greatest impact (Zio, 2009), (Fore & Msipha, 2010)and (Bowler, Primrose, & Leonard, 1996)
- According to Hora (1987), supported by Vishnu and Regikumar (2016), Reliability Centred Maintenance changes organizational culture from *“Break fix”* to a more proactive approach. The result of this is increased machine uptime that increases production (Hora, 1987) and (Vishnu & Regikumar, 2016)
- Pintelon, Puyvelde and Nagarur (1996) argue that the Reliability Centred Maintenance methodology captures the knowledge of the aging workforce by capturing all events that happen to assets during their life cycle (Pintelon, Puyvelde, & Nagarur Van, 1996). In

addition to this, the trio claims that when employees get involved with the day to day health of their equipment, they become more motivated and interested in caring for it.

Apart from the few examples of benefits of Reliability Centred Maintenance, other benefits are presented in the table below compiled from (Pintelon et al., 1996), (Sandtorv & Rausand, 1991), (Fore & Msipha, 2010), (Anderson & Neri, 1990), (Riis, Luxhøj, James, Thorsteinsson, & Uffe, 1997), (Sandtorv & Rausand, 1991), (Hora, 1987) and (Tarar, 2014)

| Benefits of using Reliability Centred Maintenance | |
|---|---|
| • Traceability of decisions<br>• Less corrective maintenance<br>• More condition monitoring<br>• Reduced usage of spares<br>• More documentation of asset history<br>• Maintenance optimization<br>• Motivation of staff<br>• System feedback is enhanced<br>• Teamwork is encouraged | • Technical insights are enhanced<br>• Improvement in plant reliability<br>• Improvement in plant availability<br>• Improved safety awareness<br>• Multiskilling of staff is encouraged<br>• Improved communication between operations and maintenance<br>• Improved equipment performance<br>• Reduction of Maintenance costs<br>• Better trained maintenance staff |

*Figure 6: Benefits of using RCM*

However, according to Nowlan and Heap (1978) complemented by Yamashina (2000), the benefits of Reliability Centred Maintenance can only be realized when accurate data is available for the assets under review. Organizations that desire to embark on a Reliability Centred Maintenance journey must brace themselves for intensive data collection and data analysis (Yamashina, 2000), (Nowlan & Heap, 1978) and (Sandtorv & Rausand, 1991).

In conclusion, because of the intensive documentation required in an RCM environment, it's easy to refer backwards for any maintenance decision that might have been taken earlier. This has not been the case with traditional maintenance systems where it is extremely difficult, if not impossible, to refer to maintenance decisions that have been made because of a lack of data (Sandtorv & Rausand, 1991) and (Saad & Siha, 2000).

### 3.5.4 Challenges of Implementing RCM

As much as there is a record of companies that have successfully implemented Reliability Centred Maintenance (Moubray, 1997) and (Rausand, 1998). Many companies have experienced challenges in the process, including some that have failed to implement the methodology while others have abandoned it completely (Smith, 1993) and (Moubray, 1997). Some of the challenges that companies have faced include:

- *Resources*: Implementation of Reliability Centred Maintenance requires resources in the form of people, time and energy if it is to be successful (Moubray, 1997) and (Hansson, Backlund, & Lycke, 2003). According to Smith (1993), resources are not always available and that presents real challenges for RCM Implementation.
- *Costs:* Implementing Reliability Centred Maintenance is not cheap and the initial capital required might be prohibitive (Worledge, 1993) and (Kullawong & Butdee, 2015).
- *Time:* A lot of time needs to be invested in the implementation of Reliability Centred Maintenance (Backlund & Akersten, 2003) and the detractors of Reliability Centred Maintenance often accuse the process of being time consuming. In many cases operational people are pulled from production processes to help with implementation which is viewed by many as a waste of time (Moubray, 1997).
- *Commitment:* A lot of support is needed for the implementation of Reliability Centred Maintenance to be successful. All the people in the organization would need a high level of commitment to make the process a success (Moubray, 1997).
- *Collection of Accurate data:* The importance of collecting accurate data in the Reliability Centred Maintenance implementation phase can never be overemphasized. If accurate information is not collected, the chances that the Reliability Centred Maintenance implementation process will successful are quite remote (Hansson et al., 2003), (Backlund & Akersten, 2003) and (Niu, Yang, & Pecht, 2010b).

### 3.5.5 Step by step implementation of Reliability Centred Maintenance

Many scholars have exhaustively presented the Reliability Centred Maintenance methodology and several books have been written in that respect. Examples of books detailing the Reliability Centred Maintenance methodology include those by Coetzee (1997) and (2015), Smith (1993), Nowlan and Heap (1978) and Moubray (1997), (Coetzee, 2015), and (Gits, 1992). A Reliability Centred Maintenance standard has been developed and is documented in (IEC 60300-3-11, 2010) and also (Chalifoux, A. and Baird, 1999)

Moubray (1997) described the Reliability Centred Maintenance method as a process by which seven questions have to be asked about the asset under review. The seven questions are as detailed on the figure below (Moubray, 1997).

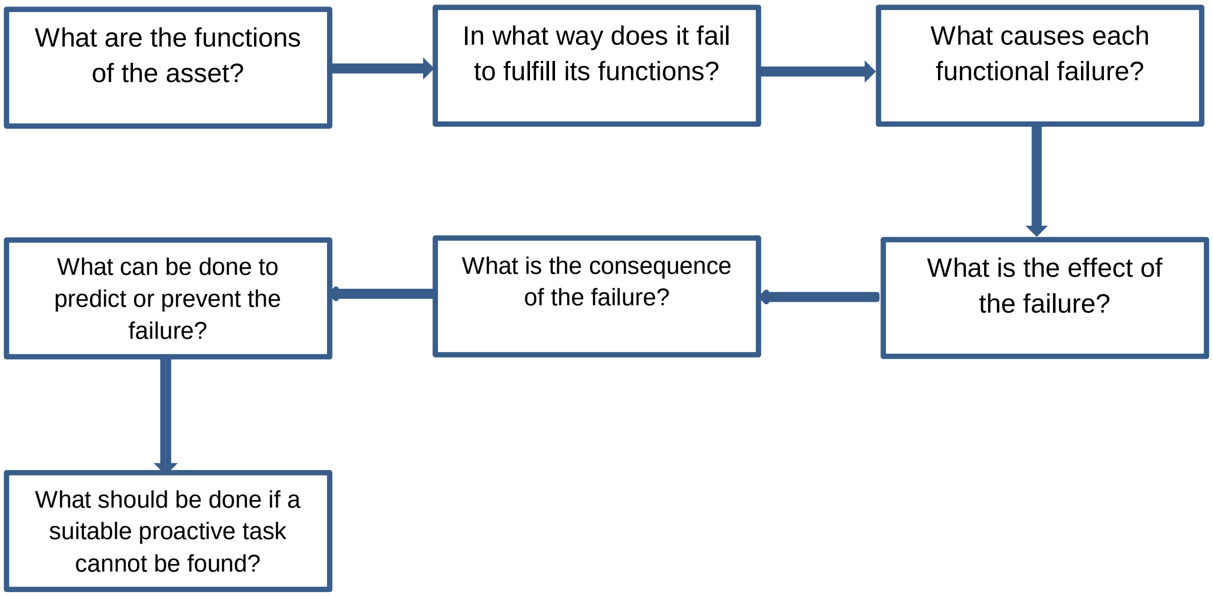



*Figure 7: RCM process steps according to Moubray(1997)*

According to Moubray (1997), answering these questions is done by going through rigorous steps of a structured process. The process to be followed is:

- Define system functions, performance standards and system boundary definitions
- Determine the ways in which the system function may fail
- Determine the significant failure modes
- Assess the effects and consequences of the failures
- Identify maintenance tasks by means of a decision-logic scheme
- Identify of maintenance task intervals
- Auditing, implementation and feedback.

The (IEC 60300-3-11, 2010) details the RCM process as a 12 stage process as shown by the figure below (IEC 60300-3-11, 2010)

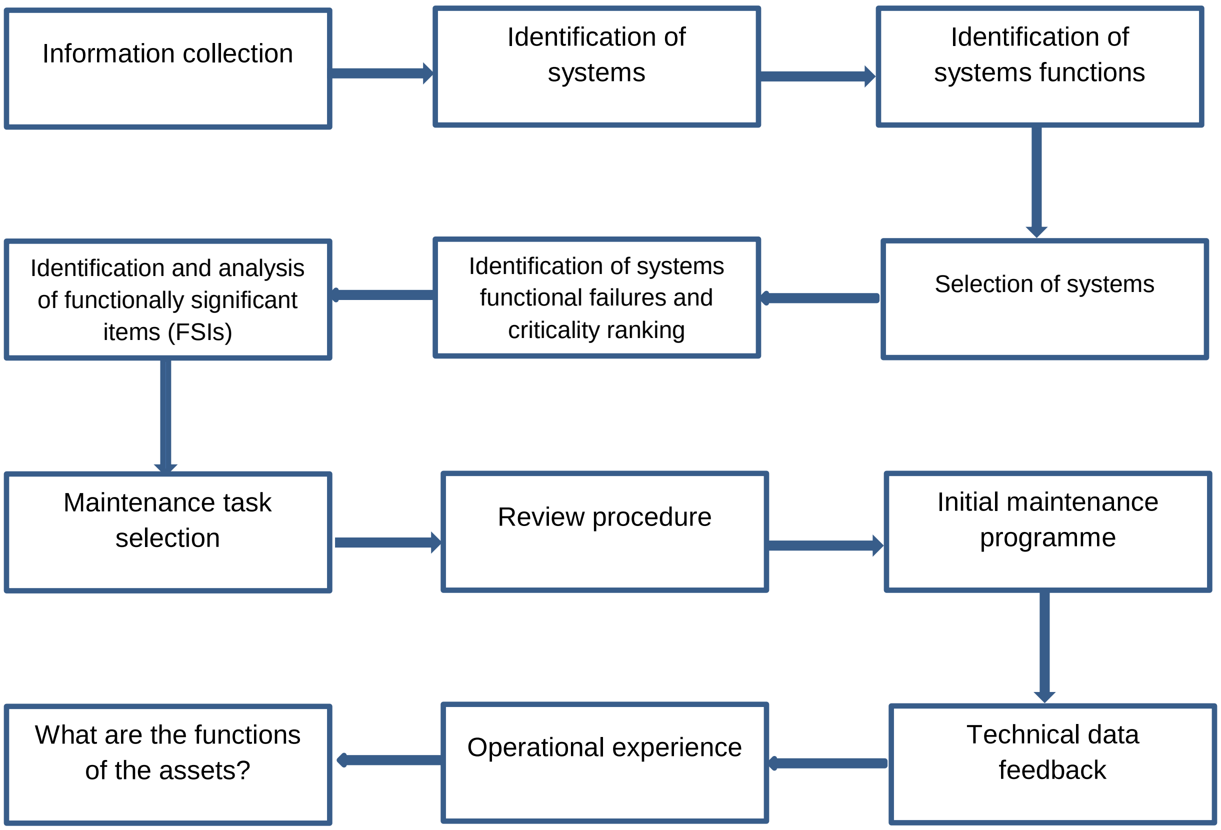



*Figure 8: Reliability Centred Maintenance process steps according to International Electrochemical Commission (1999) reviewed in (2010) (IEC 60300-3-11, 2010).*

Backlund and Akersten (2003) apply the same principle (Backlund & Akersten, 2003) detailed in the International Electrochemical Commission Standard (1999)

The approach that has been adopted in this research is the approach detailed by Coetzee (1997) and (2015). The steps as presented by Coetzee (1997) and (2015) are shown in the figure below and detailed explanations of each step is presented thereafter.

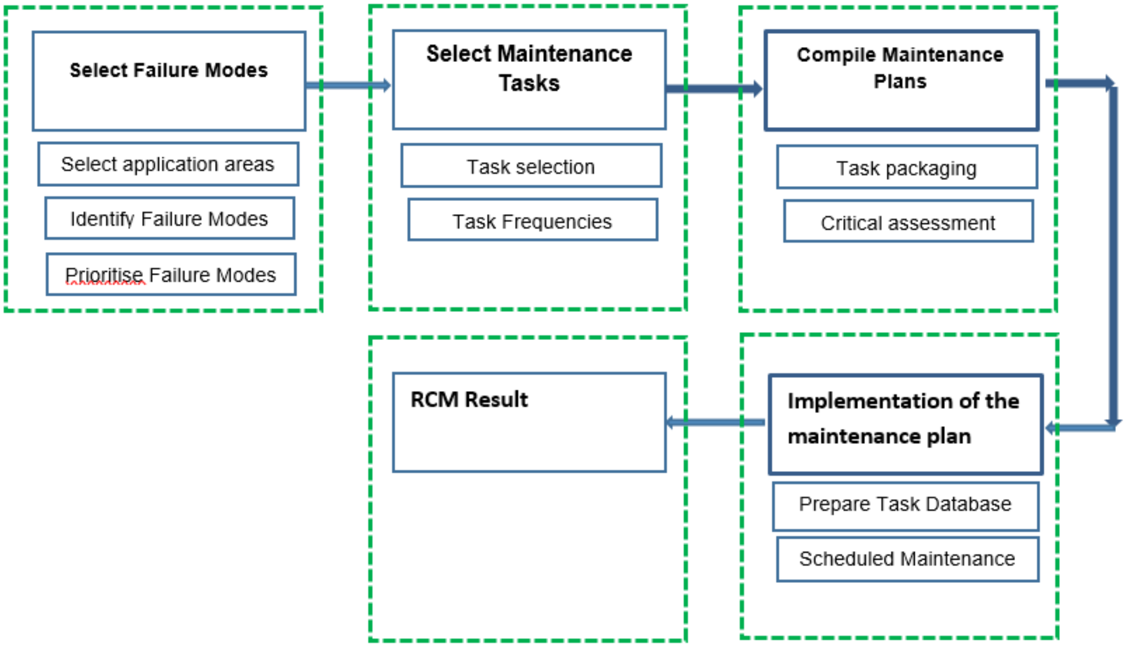



*Figure 9: Reliability Centred Maintenance process steps according to (Coetzee, 2015) (used by permission)*

#### *3.5.5.1 Defining systems functions, performance standards of the asset in its present operating context*

Functions of assets can be described as either Primary Functions or Secondary Functions. Primary Functions are those functions for which the assets were bought to perform. These functions can be easily identified because they are reflected in the name of the assets, for example a milling machine's primary function is to mill, and a forging press's primary function is to forge. In addition to performing primary functions, assets are expected to perform other functions. These other functions are what is commonly referred to as Secondary Functions. For instance, a milling machine's primary function is to mill, but it must be able to also perform a lubrication function for the tools. Milling becomes the primary function and lubrication the secondary function. Both the primary and secondary functions needs to be preserved(Chalifoux, A. and Baird, 1999), (Moubray, 1997), (Coetzee, 2015) and (Coetzee, 1997).

As alluded before, when assets are maintained, the state which they must be preserved is the state in which the assets continue to do whatever users want them to do. It must also be remembered that what the user wants the asset to do is not necessarily the same as the built-in capability of the asset (Moubray, 1997). It is of critical importance to define what the functions of assets are because it is through the loss of these functions that maintenance is required (Coetzee, 2015).

Users will not only expect an asset to perform a function. The asset is expected to perform the function at a certain level of performance standard.

It must always be remembered that, when dealing with a function and performance standards definition, it must be done in the present operating condition of the asset. The operating context influences the requirements for functions and operating performance of the asset. It also affects the nature of the failure modes and their effects. Moubray (1997) says that "Not only does the context drastically affect functions and performance expectation, but it also affects the nature of the failure modes which would occur, their effects and consequences, how often they happen and what must be done to manage them."

When defining the operating context, the following aspects must be considered:

- Type of process the asset is performing
- Is there redundancy built in the system or not?
- Quality standards
- Safety and environmental standards
- The total operating hours of the asset
- Spares and repair time of assets
- Raw materials

#### *3.5.5.2 Determining Systems functional failures*

The next step is to define ways in which the functions defined above fail. Moubray (1997) defines failure as the "inability of any asset to do what its users want it to do", and Coetzee (1997) defines failure "as an unsatisfactory condition".

Failures can be classified into two types: functional failures and potential failures.

- Functional failure - a condition in which an asset fails to meet a specified standard of performance. The standard of operating performance is not the in-built performance but is defined by the user. This loss of function includes a system failure where total loss of function is experienced and also cases where partial loss of function occurs. Partial loss of function is experienced where an asset still performs but performs outside expected level (Moubray, 1997). Functional failure definitions should be derived from the operating context of the asset. One might have two identical assets operating in two different contexts. Functional failures for these two should not be generalized as much as their functions and performance standards should not be generalized.

- Potential Failure – An identified physical condition which indicates that a functional failure is imminent (Coetzee, 1997). When a car engine seizes, it loses its function and completely stops, whereas a knocking sound in the engine is an indication that the engine is on its way to failure. The latter is an example of a potential failure.

#### *3.5.5.3 Determining causes of each functional failure (Failure Modes)*

After the functional failures have been determined, the next step is to identify the causes of these failures. In other words, one needs to identify the "root causes" of each functional failure (Coetzee, 2015). According to Moubray, *"a* failure mode is any event which causes a functional failure". All the failure modes of each failure must be identified because this then forms the basis for all proactive maintenance activities. These failure modes should be identified before they occur at all, or if not possible before they occur again (Moubray, 1997).

There are various ways of identifying failure causes. Failure Mode and Effect Analysis (FMEA) is one way in which failure causes are identified before occurrence, whereas Root Cause Analysis (RCA) **is** normally carried out after the failure has occurred (Smith, 1993).

#### *3.5.5.4 Assessing the effects and consequences of the failures*

According to Moubray (1997) supported by Coetzee (2015), the fourth step in the Reliability Centred Maintenance process is assessing the effects of each failure mode, known as failure effects**.** Failure effects describe what happens when a failure mode occurs (Moubray, 1997). In describing the failures, Moubray (1997) claims that the following five questions need to be answered:

1. What is the evidence that failure has occurred?
2. What ways does it pose a threat to safety and the environment?
3. In what ways does it affect production?
4. What are the physical damages caused by the failure?
5. What must be done to repair the failure?

Failure effects describe what happens when failure occurs, and failure consequences describe how much the failure impacts manufacturing. If failure matters so much, every effort should be made to reduce its consequence, especially if it poses a risk to safety and the environment or if it interferes with production activities.

According to Nowlan and Heap (1978) and also Moubray (1997), failure consequences are grouped into four categories (Moubray, 1997), (Nowlan & Heap, 1978) and (Coetzee, 2015).

- Hidden failures: These failures have no direct impact but the organization can be exposed to multiple failures with serious consequences.
- Safety and environmental consequence: If someone is going to be killed or hurt because of a failure, it is categorized as a safety consequence. If it will result in environmental violations, it becomes an environmental consequence.
- Operational consequence: if production is affected as a result of the failure, it becomes an operational consequence.
- Non-operational consequence: these are neither classified as safety consequences or operational consequence because they affect neither of the two. In reality the only cost incurred is the cost of repair.

#### *3.5.5.5 Identification of suitable maintenance tasks*

All the effort done so far in the Reliability Centred Maintenance process was directed towards this one important aspect: to select the best optimized maintenance tasks for each failure mode that will be most profitable for the organization.

This step of the Reliability Centred Maintenance methodology is the heart of the whole process (Coetzee, 2015). This is where the whole maintenance plan is formulated to deal with failures. Failures can be dealt with in two ways:

- Proactive tasks – these are tasks carried out before a failure occurs. In the traditional maintenance world this commonly known as “Predictive” and “Preventative Maintenance”. However in the Reliability Centred Maintenance world, terms such as Scheduled Restoration, Scheduled Discard and On-condition Maintenance are used (Moubray, 1997).
- Default tasks – These deal with maintenance of assets in their failed state. This only happens when failure has occurred. Such tasks include breakdown tasks and run to failure tasks.

### 3.5.5.5.1 Task Types

The following types are used in the Reliability Centred Maintenance Process to design the maintenance plans:

#### 3.5.5.5.1.1 Condition Based tasks

The name ‘on condition task; was coined by Nowlan and Heap (1978). It is also often called condition-based tasks or predictive tasks. This involves directing efforts to attempt to predict when failure might occur, and implement proactive measures to prevent such failures from happening. This is popularly describe using the PF Curve as shown below

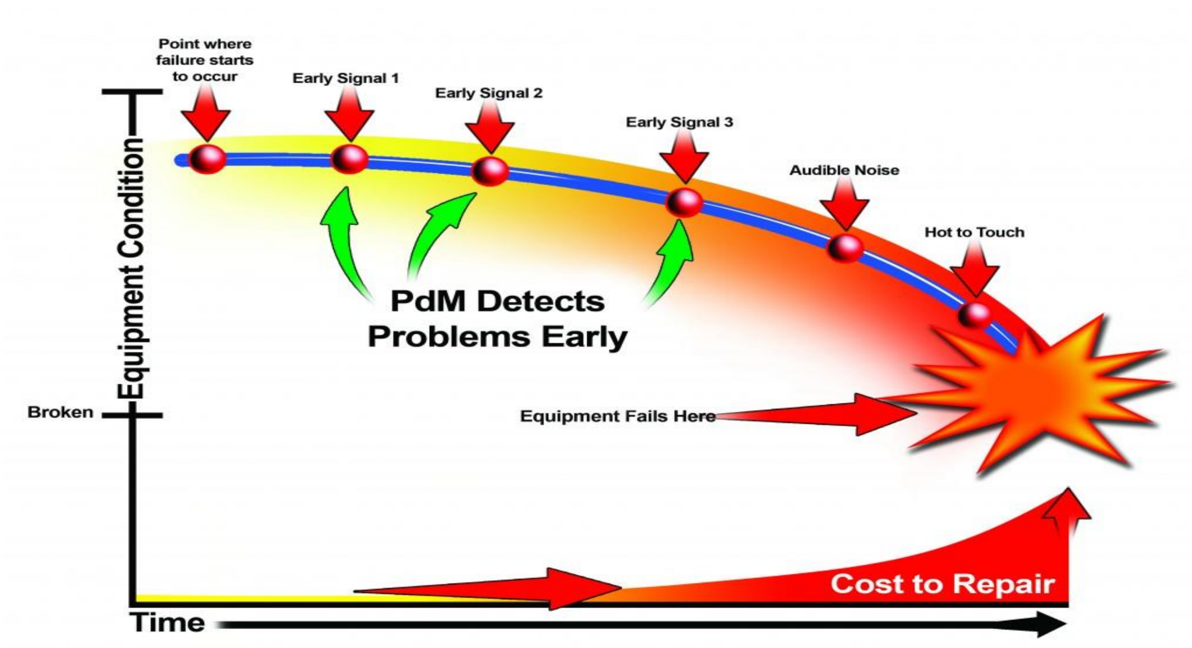



*Figure 10 : The PF Curve (Moving Back On the P-F Curve to Maximize Maintenance Effectiveness _ RCM Blitz Blog, n.d.)*

The x-axis of the curve represents Time (T) or Operating Age, and the y-axis represents resistance to failure. Starting at the top left part of the curve and moving right, point P is encountered, known as Potential Failure. This is the point in time that, when using some form of Predictive Technologies, one can first detect resistance to failure. As we continue to move right along this curve, resistance to failure continues to fall until we encounter point F, known as Functional Failure. This is the point in time when the component’s resistance to failure has deteriorated to a point where it can no longer perform its intended function. The time elapsed between point P and point F is known as the P-F interval. The value of knowing the P-F interval of a component for a specific failure mode is that the interval of the condition based (PdM) inspection can be set. In setting the interval, there should be a high level of confidence of being able to detect the failure of this component, plan a replacement or restoration task, and repair the component before the failure occurs. In doing so, a reactive task has been replaced with a PdM task. (*Moving Back On the P-F Curve to Maximize Maintenance Effectiveness _ RCM Blitz Blog*, n.d.)

###### 3.5.5.5.1.2 Scheduled Restoration Tasks

The condition of assets deteriorates with age. If this is so, it is then possible to remove the component or system from service before failure occurs, if this can be predicted. Moubray (1997) describes a Scheduled Restoration task as "A task that entails restoring the initial capability of an existing item or component at or before a specified age limit regardless of its apparent condition at the time" (Moubray, 1997).

###### 3.5.5.5.1.3 Scheduled Replacement Tasks

Nowlan and Heap (1978) refer to scheduled replacement tasks as discard tasks. In the case of scheduled restoration, it is possible to restore the condition of components or systems to their initial condition (Nowlan & Heap, 1978). However, in some cases of age-related failures, it is impossible to restore the component or system back to its original condition. In such a case, the need arises to replace the whole component with a new one at predetermined fixed intervals. By definition, a scheduled discard task "is a task that involves replacing/discarding an item or component at or before a specified age limit regardless of its condition at the time", according to (Moubray, 1997) and (Nowlan & Heap, 1978).

###### 3.5.5.5.1.4 Failure Finding Tasks

A routine maintenance task, normally an inspection task, is designed to determine whether an item or component has failed. It should not be confused with an on-condition task which is intended to determine whether an item is about to fail. These inspections can be visual, physical or by the use of instruments (Coetzee, 2015).

###### 3.5.5.5.1.5 Servicing/Lubrication tasks

These are routine tasks that are carried out at intervals. In the TPM context these are tasks that normally would be performed by operations personnel as a first level of defence. If done properly. these tasks go a long way in the prevention of failures.

###### 3.5.5.5.1.6 Design out tasks

When there is no proactive task which can be done for prevention of failure, design out tasks are preferred. This involves a completely new design of the component in order to eliminate the failure mode. This normally includes changing specifications of a component, adding new items, replacing the entire machine with a different one of a different type, or relocating the machine (Moubray, 1997).

#### 3.5.5.5.1.7 Corrective Maintenance Tasks

Corrective maintenance tasks, according to Coetzee (2015), are the "Do nothing" and "Wait for Failure" types of tasks. These tasks are also known as breakdown maintenance tasks**.** These tasks are normally applicable if the failure does not affect safety or the environment, or if it is hidden and the multiple failures do not affect safety or the environment. Corrective maintenance tasks are only valid if:

- A suitable task cannot be found for the hidden failure of which safety and the environment are not affected.
- When a cost-effective preventative task cannot be found.

#### 3.5.5.5.2 Task Selection Process

For each of the failure modes identified, a list of candidate tasks should be determined and then the most effective tasks amongst the competing candidates should be selected (A. Smith, 1993). Each of the selected tasks must be both applicable and effective, and technically and economically feasible (Coetzee, 1997) and (Coetzee, 2015).

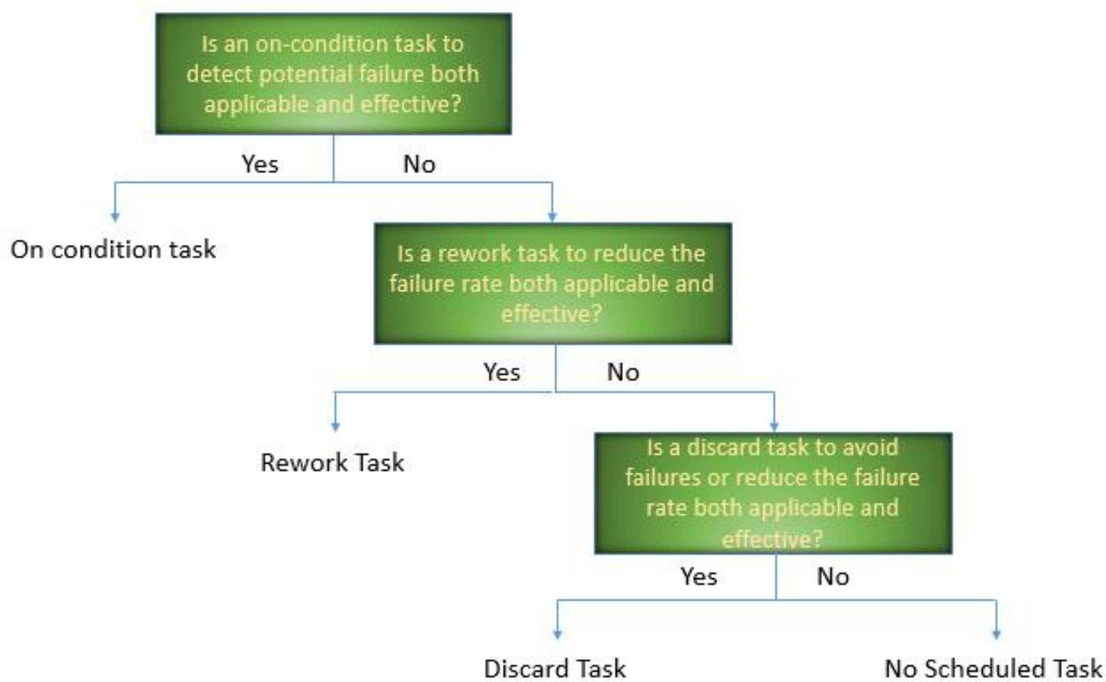



*Figure 11: Reliability Centred Maintenance Decision Diagram (Nowlan and Heap, 1978)*

The first of the Reliability Centred Maintenance decision trees was developed by Nowlan and Heap (1978) in the Reliability Centred Maintenance report for United Airlines. In their process, the first-choice task is the on-condition task. If there is no on-condition task feasible, the next choice then becomes the rework task, then the discard task, and the last would be a no schedule task (Nowlan & Heap, 1978).

Below is a similar decision tree to the Nowlan and Heap (1978) one, but it was reproduced by Coetzee (2015) in his book RCM ProAktiv. The two diagrams are similar, except that Coetzee modernized the terms used. For instance, he changed the on-condition task to be a condition based task, a rework task into a scheduled reconditioning task, etc.(Coetzee, 1997), (Coetzee, 2015) and (Nowlan & Heap, 1978).

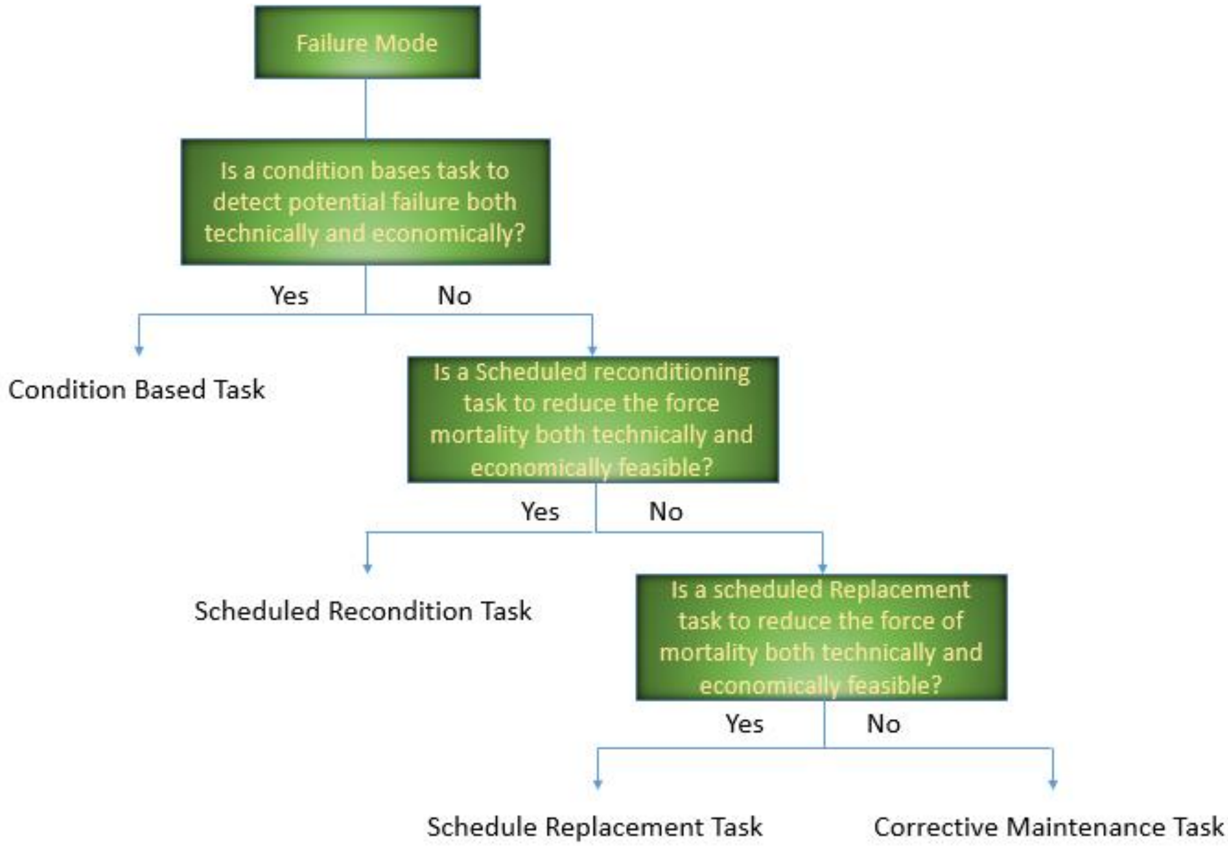



*Figure 12: RCM Decision Diagram (Coetzee, 2015)*

Nowlan and Heap (1978) use the terms 'applicable' and 'effective in the task selection process', whereas Coetzee (1997) and (2015) uses 'technically' and 'economically' feasible. According to Coetzee, the decision to select a task should be done only when technical factors and economic factors are favourable. Technically the task must be able to reduce the risk of failure to acceptable level or eliminate the risk altogether. However, though technically favourable, the task should be economically feasible. The cost of preventing the failure must be less than the cost of the operational consequences (Nowlan & Heap, 1978), (Coetzee, 2015) and (Coetzee, 1997).

#### *3.5.5.6 Implementation of the Maintenance Plan*

Coetzee (1997) stresses that only a proper reliability process will lead to proper definition of tasks for equipment and systems (Coetzee, 1997). Coetzee (2015) asserts that an RCM process will result in three task options:

- Preventative Maintenance
- Or Corrective Maintenance
- Or Design out Maintenance

The implementation plan of the RCM process therefore involves populating the database with identified tasks and scheduling maintenance in the system the organization is using (Coetzee, 2015)

#### *3.5.5.7 RCM Result*

- There is much written about Reliability Centred Maintenance, and most tends towards the same result. According to Coetzee (1997) and (2015), the Reliability Centred Maintenance process consists of five steps namely: Failure mode selection, selection of maintenance tasks, compilation of maintenance plans, implementation of the maintenance tasks and finally the maintenance results (Coetzee, 1997) and (Coetzee, 2015).

Moubray (1997) suggests that Reliability Centred Maintenance Process entails asking seven questions about the asset of system under review, as follows (Moubray, 1997)*:*

- What are the functions and associated performance standards of the asset in its present operating context?
- In what ways does it fail to fulfil its functions?
- What causes each functional failure?
- What happens when each failure occurs?

- In what way does each failure matter?
- What can be done to predict or prevent each failure?
- What should be done if a suitable proactive task cannot be found?

Smith (1993) describes the RCM Process in seven distinct steps (Smith, 1993):

- System selection and information collection
- System boundary definition
- System description and functional block diagram
- System functions and functional failures
- Failure mode and effect analysis
- Logic (decision) tree analysis
- Task selection

Nowlan and Heap (1978) defined the process of developing an initial Reliability Centred Maintenance program when the information required is lacking, as follows (Nowlan and Heap, 1978):

- Partitioning the equipment into object categories in order to identify those items that require intensive study,
- Identifying significant items that have essential safety or economic consequences and hidden functions that require scheduled maintenance.
- Evaluating the maintenance requirements for each significant item and hidden function in terms of the failure consequences and selecting only those tasks that will satisfy these requirements.
- Identifying items for which no applicable or effective task can be found, and then either recommending design changes if safety is involved, or assigning no scheduled maintenance tasks to these items until further information becomes available.
- Selecting conservative initial intervals for each of the included tasks grouping the tasks in maintenance packages for application.
- Establishing an age-exploration program to provide the factual information necessary to revise initial decisions.

## 3.6 Measuring Asset effectiveness in a Reliability Model

Over the years, manufacturing companies have developed a number of management techniques to measure performance. Common issues faced by many manufacturing companies are waste in the form of time, energy, money and overworked staff. The techniques presented below are some of the techniques developed and used in this research (Singh, Shah, Gohil, & Shah, 2013) and (Siregar et al., 2018).

Performance measurement is a subject that is often discussed. According to Ron and Rooda (2006) performance is defined as the degree to which an organization realizes its business objectives (De Ron & Rooda, 2006). Performance measurements provide important information concerning the status of the process and facilitates decisions to be made, activating the adjustment of settings and/or remedial actions to be taken to improve performance (De Ron & Rooda, 2006).

Kaydos defines five major reasons for companies to measure performance (Kaydos, 1999)

- Because feedback is received from the process, control of the process is improved.
- Responsibilities and objectives are clarified because a performance measurement model allocates responsibilities and accountabilities for results and/or problems.
- Company objectives are communicated throughout the organization through performance measurements, which leads to a solid strategic alignment of objectives.
- Measuring process data empowers the stakeholders to understand the processes better.
- Determining process capability, because understanding a process also means knowing its capacity.

The five performance measurements used to determine the improvements of the mobile unit sizer in this study, after implementation of a reliability program, are detailed below:

### 3.6.1 Overall Equipment Effectiveness (OEE)

Overall equipment effectiveness (OEE) is an indicator of equipment utilization according to Singh et al,. (Singh et al., 2013). Nakajima (1988) says that OEE measures equipment effectiveness and the effects of equipment surrounding the equipment of interest (Nakajima, 1988). OEE reveals whether the equipment is being under-utilized or over-utilized (Ireland & Dale, 2001). According to Nakajima (1988), OEE is a product of availability, productivity and quality (Nakajima, 1988). When Sharma, Kurma and Kuma applied the OEE performance measures to analyse plant performance in 2006, they concluded that OEE assists in identifying process wastages and prepares a plant for challenges (Sharma, Kurma, & Kurma, 2006)

The OEE calculation therefore is:

$$OEE = Availability\ Rate\ x\ Productivity\ Rate\ x\ Quality\ Rate$$

#### 3.6.1.1 Availability Rate

According to Ramlan et al., availability is the amount of time a piece of equipment is available for production. As such, availability defines the extent of downtime losses. In their study, they add that in comparing the planned operating time to the actual operating time, the availability component of OEE determines the production loss due to downtime (Ramlan, Ngadiman, Omar, & Yassin, 2015). The downtime includes planned downtime (planned maintenance activities) and unplanned downtime such as equipment breakdowns(Fam, Yanto, Semarang, & Prastyo, 2018)and (Samat, Kamaruddin, & Azid, 2012).

$$Availability\ Rate = \frac{\text{Planned time} - \text{downtime}}{\text{Planned Time}}$$

$$Availability\ Rate = \frac{\text{MTBF}}{(\text{MTBF} + \text{MTTR})}$$

#### 3.6.1.2 Productivity Rate

Productivity rate measures the transformation of products from input to output. In reality it is the comparison of actual production output to theoretical calculated outputs (Ramlan et al., 2015). Productivity measurement takes into account loss of production due to speed loses where machines operate at slower speeds than they are planned to run (Nakajima, 1988), (Fam et al., 2018) and (Samat et al., 2012).

$$Productivity\ Rate = \frac{\text{Cycle Time x Quantity produced}}{\text{Operating Time}}$$

#### 3.6.1.3 Quality Rate

The quality component on the OEE Model accounts for the number of products rejected because of quality defects. Rejected products include products that do not meet quality standards and also products that need to be reworked, often referred to in lean manufacturing as waste (Ramlan et al., 2015), (Neely, 1999) and (Kennerly & Neely 2003).

$$Quality\ \ Rate = \frac{\text{Processed Amount} - \text{Defective product produced}}{\text{Processed amount}}$$

OEE calculations and the matrices used differ from industry to industry and from company to company but their importance can never be over emphasized.

### 3.6.2 Mean Time to Failure (MTTF)

Mean time to failure (MTTF) is a measure of how long a machine can keep running before breakdown. MTBF is a measure of reliability - it determines how reliable a machine is in a production process(Chauhan & Pancholi, 2013). Every organization wants to lower costs and increase profitability, and MTTF plays a big role in achieving this. MTTF can be best described as the expected time between consecutive failures (Abdul Samat et al., 2012).

$$MTTF = \frac{Total\ Time}{\text{Total number of Failures}}$$

### 3.6.3 Maintenance Costs

Many researchers claim that the implementation of Reliability Centred Maintenance will drastically increase maintenance costs. From their claims, costs will be reduced through these factors, described by (Zio, 2009), (Fore & Msipha, 2010) and (Bowler et al., 1996).

- Reduction in spare usage
- Reduction of labour
- Reduction of maintenance schedules

$$Maintainance\ Costs = \frac{Total\ Time\ x\ Volume\ Produced}{\text{Maintenance Costs incurred}}$$

## 3.7 Conclusion

This chapter presented a review of literature relevant to the study of Reliability Centred Maintenance. The review started by defining relevant terms and then discussed the evolution of Reliability Centred Maintenance from traditional maintenance systems. This chapter also discussed Reliability Centred Maintenance implementation in other industries, comparing and contrasting the benefits obtained from the implementations and the associated short comings. The next chapter presents the methodology used in this research.

This space is left empty intentionally.
Please go to the next page

# 4. Chapter 4: Methodology

## 4.1 Introduction

The previous chapter presented a review of literature relevant to the study of Reliability Centred Maintenance (RCM). The review started by defining relevant terms and then discussed the evolution of Reliability Centred Maintenance from traditional maintenance systems.

The previous chapter also discussed RCM implementation in other industries, comparing and contrasting the benefits obtained from the implementations and the associated shortcomings.

This chapter discusses the methodology that was used for this study. This research is quantitative. The research method, data analysis and sampling methods reinforced the chosen approach.

This research was done in quantitative format. According to Soiferman (2010), any research is considered as quantitative if statistical analysis of data will be used to analyse information collected (Soiferman, 2010).  A quantitative method of research was used to emphasize the objective measurement through the analysis of the new data. This helped determine understanding about the specified sample (Saunders & Lewis, 2012). Soiferman explains that it is possible to get visual representations for the data using graphs, plots, charts, and tables with quantitative analysis. Conclusions are drawn from logic, evidence, and argument (Soiferman, 2010). Gibson and Brown (2011) argue that quantitative research involves numerical methods of analysing observations. He continues that in quantitative research, all verbal data is reduced to numerical data for analysis (Gibson & Brown, 2011) and (Rahman, 2016).

An experimental design was employed in this research. According to de Winter and Dodou (2017), experimental design involves subjecting the sample under considerations to a set of interventions. Data is recorded and analysed before and after the intervention and comparisons are made to derive conclusions (de Winter & Dodou, 2017).

*Figure 13 : Generic Experimental Design*

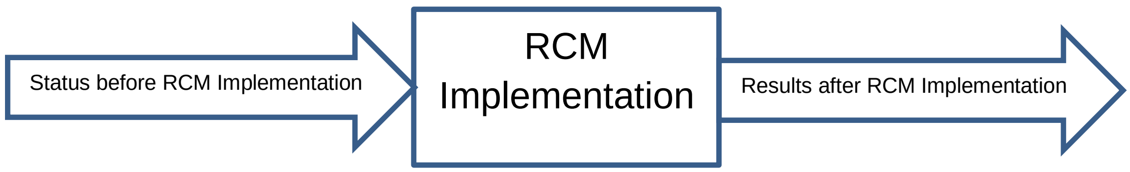



*Figure 14 : Research Experimental Design*

A deductive methodology approach was implemented. The deductive approach involves examining the theoretical proposition and defending the causal relations between the identified variables (Saunders & Lewis, 2012) and (Soiferman, 2010). In the case of this research, the relationship between implementation of RCM on the mineral sizer performance will be tested. This testing was based on the hypotheses previously described in Chapter 2.

The data was analysed and evaluated according to the research procedures. A cross-sectional time horizon was used for this study. This time horizon collects data at a specific point in time "snapshot" (Saunders & Lewis, 2012). Primary data was collected to examine the abovementioned hypotheses. The relationships between the variables will be determined by descriptive, correlation and regression analysis. Graphs and tables will be used to show the results of the statistical analysis. An explanation of these results will be provided.

## 4.2 Analysis Tools

This space is left empty intentionally.
Please go to the next page

The analysis tool that was used for reliability analysis in this research is the Failure Mode, Effect and Criticality Analysis (FMECA) defined below

### 4.2.1 Failure Mode, Effect and Criticality Analysis (FMECA)

Reliability cantered maintenance (RCM) is a methodology used to determine what needs to be done to ensure that a system continues to do whatever its users want it to do in its present operating context (Moubray, 1997). The result of an RCM process is an identification of maintenance strategies to preserve system functions (Smith & Hinchcliffe, 2003)

RCM utilizes the failure mode, effect and criticality analysis (FMECA) in order to establish system functions, functional failures, failure modes and their criticality (McDermott, Mikulak, & Beauregard, 2008). In order to be effective, FMECA must be applied under normal conditions, abnormal conditions and emergency conditions (McDermott et al., 2008). The identification of the potential failures leads to the development of action plans to prevent these failures (Pascu & Paraschiv, 2016).

According to Zajicek(2018), FMECA is the most popular and widely used approach for system reliability analysis. FMECA is a semi-quantitative approach for risk evaluation. To be able to do the risk evaluation, the FMECA approach used the RPN risk number with the main aim of analysing failure modes (Zajicek, 2018). In this research, the RPN will be denoted as Failure Mode Criticality Classification ($C_r$) as per Coetzee (2015).

According to Coetzee (2015) FMECA is an expansion of Failure Mode and Effect Analysis (FMEA). As such it is not an additional analysis method. The only difference is FMECA allocates a critically number to the failure modes from the FMEA process (Coetzee, 2015).

Coetzee (2015) continues saying the purpose of the FMECA process is to allocate a ranking to failure modes identified by the FMEA process. This is done by getting the product of the failure mode consequence and the probability of occurrence. The equation to get the criticality classification is given by Coetzee (2015):

$$Failure\ Mode\ Criticality\ Classification\ (Cr) = Consequence\ (C) x\ Probability\ of\ occurence\ (Po)$$

### 4.2.2 Failure Mode Consequence (C)

According to Coetzee (2015), under normal circumstances the risk is presented in financial terms but in this research a qualitative approach for the consequence had been adopted. The consequence, according to Zajicek (2018) and the Reliability Analysis Centre (1993), is the resultant effect in the event that a failure mode does occur (Reliability Analysis Center, 1993) (Zajicek, 2018) (Coetzee, 2015). The consequence classifications used in this research are shown in the table below:

| Consequence Level | Description | Ranking |
|---|---|---|
| Catastrophic | A failure mode that can cause death or system loss | 7 |
| Critical | A failure that may cause severe injury, major property damage, minor system damage, which result in mission loss | 5 |
| Marginal | A failure that may cause minor injury, minor property damage, minor systems damage, which may result in delay or mission degradation | 3 |
| Minor | A failure that will not cause injury, property damage, system damage, but will result in unscheduled maintenance or repair | 1 |

*Figure 15: Failure Mode Classification*

### 4.2.3 Failure Mode probability of Occurrence ($P_O$)

According to Zajicek(2018) and also Coetzee (2015) this is the probability that a specific failure mode will happen in a certain period of time. According to the Reliability Analysis Centre (1993) the failure mode probability of occurrence is listed qualitatively (Reliability Analysis Center, 1993). In this research the following classifications were used as indicate in the table below:

| Level of Occurrence | % of Failures | $P_O$ |
|---|---|---|
| Frequent | % Fail > 20% | 9 |
| Reasonably Probable | 10% < % Fail ≤ 20% | 7 |
| Occasional | 1% < % Fail ≤ 10% | 5 |
| Remote | 0.1% < % Fail ≤ 1% | 3 |
| Extremely unlikely | % Fail ≤ 0.1% | 1 |

*Figure 16: Failure Mode Probability of Occurrence*

### 4.2.4 Failure Mode Criticality Classification (Cr)

To get to the Failure Mode Criticality Classification, the risk consequence is multiplied by the probability that that risk will occur during the period under investigation (Coetzee, 2015) (Reliability Analysis Center, 1993),(Zajicek, 2018). The classifications used are as presented in the table below:

| Criticality number range (C x $P_o$) | $C_r$ |
|---|---|
| 52 - 63 | A |
| 39 - 51 | B |
| 26 - 38 | C |
| 13 - 25 | D |
| 0 - 12 | E |

*Figure 17: Failure mode Criticality Classification*

Therefore, the FMECA is a proven method used in the identification and classification of failure modes. As such, all the failure modes that were identified in the failure modes identification phase of the research were then classified and ranked using the FMECA process.

## 4.3 Analysis process

The failure mode and effect analysis was conducted iteratively over several rounds. The initial FMEA to identify failures and failure modes was conducted by the researcher. The results of that initial process were presented to the participants for review. The review process included but was not limited to adding failure modes that could have been omitted and removing the ones they deemed not applicable.

After every iteration, the researcher would take the information from each participant and consolidate the findings and repeat the process again until consensus was reached from information coming from the participants.

The summary of the final FMEA results was collated by the researcher, ahead of the next FMECA process. Once again, the initial FMECA process of allocating probabilities of occurrence ($P_O$) and the consequence of failure modes (C) was done by the researcher. This initial draft was again sent to the participants to review and the same process as the FMEA process was followed. The process was iteratively repeated several times until convergence of responses was reached and the researcher consolidated the final draft from the FMECA process (Holey, Feeley, Dixon, & Whittaker, 2007).

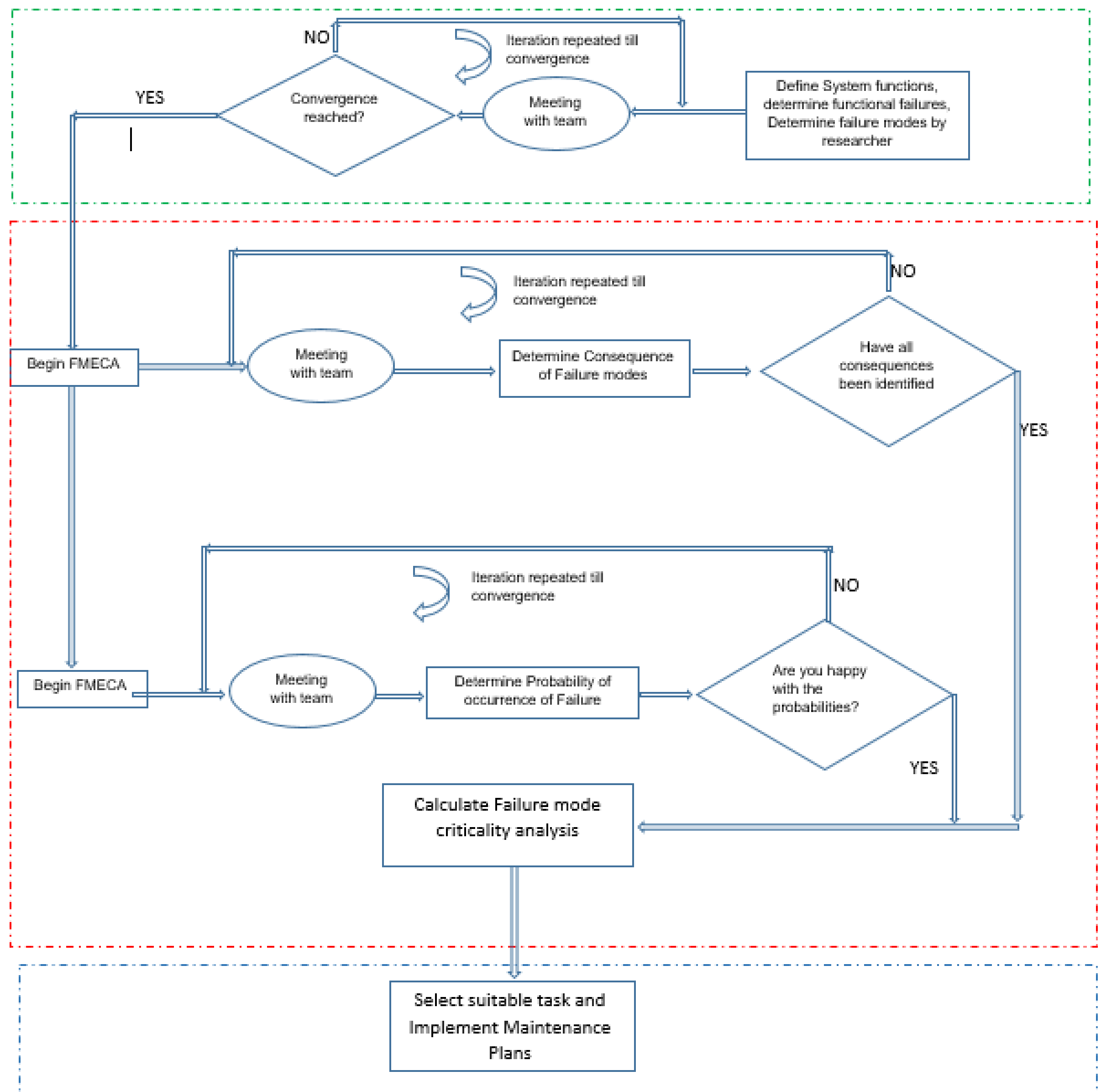



*Figure 18: Flow Chart used for FMECA Analysis*

The results of the FMECA process where then used by the researcher to determine suitable tasks for execution. Failure modes with safety and environmental impacts were prioritized, followed by those with higher criticality ranking.

## 4.4 Scope of the Research

The study was conducted on the mineral sizer of the mobile mining unit at Sierra Rutile in Sierra Leone. The study was aimed at establishing the benefits if implementing a Reliability Centred Maintenance system, initially for the mineral sizer, and then to cascade it to the rest of the mine equipment if successful.

## 4.5 Limitations of qualitative research

Limitations in this research have been recognized. The following limitations have been identified:

- It is difficult to duplicate the experiment and the conditions in which the experiment was carried out (Almeida, 2017).
- Silverman (2010) and also Rahman (2016) argues that because of the small sample sizes, qualitative research cannot be generalised to wider populations. (Rahman, 2016) (Masue, Swai, & Anasel, 2013)(Silverman, 2010).

As such this research cannot be generalised to generality of equipment in different organisations

## 4.6 Ethical considerations

The following ethical considerations were applicable to the study:

- Written permission to conduct the study was obtained from the management of the Sierra Rutile Limited (See attached scanned copy).
- The researcher was going to disclose the results of the research to the company management.
- Participation in the research was totally voluntary. The participants were not forced in any way to participate in the research.
- The right to anonymity and confidentiality had to be considered. Information about the participants was not mentioned in this study.
- The right to not be harmed in any manner (physically, psychologically or emotionally). If the participants felt that they were threatened in any way and their safety and security was at risk, they could stop their participation at any stage of the research. In addition, participants could only respond or participate in areas where they felt comfortable to do so.

The researcher confirms and agrees that the above considerations were adhered to during the research.

## 4.7 Conclusion

The detailed methodology has been described in this chapter. This quantitative research methodology was used to examine the suggested hypothesis – whether a relationship exists between the introduction of RCM, and the performance of the mineral sizer after application of RCM. Statistical analysis was used to determine validity and reliability. Multiple regression was used to determine whether a significant relationship exists between the variables. The next chapter gives the results of the research.

This space is left empty intentionally.
Please go to the next page

# 5. Chapter 5: Application Process of RCM to the Mobile Mining Unit Sizer

## 5.1 Chapter Overview

The previous chapter detailed the methodology that was employed in this research. This next chapter presents the process that was followed in implementing the RCM process on the mineral sizer. To this end a step by step process will be detailed in this chapter.

## 5.2 Step by Step Implementation Process

### 5.2.1 Selection of Asset for analysis

The mobile mining unit sizer is costly equipment and it is a heavy rotating machinery prone to high wear and tear. Vibration problems are prevalent with such units and major problems are experienced on the bearings, gearboxes and shafts. Compounding these challenges is the harsh environment in which this piece of equipment operates, with high impact loading exposing it to premature failure due to impact loads. This piece of equipment forms the heart of the Mobile Mining unit and there is no operation without it.

This equipment was purchased to aid in the mining process at the recommendation of the parent company in Australia because it has used these units successfully for similar operations. However, as the company would later discover, there are massive differences between the heavy minerals mined in Australia and those mined in the Sierra Leone operations: the Australian mineral is sandy, while the Sierra Leone mineral  is rocky and not easily sized with such a unit.

The sizer is a critical piece of equipment, expensive to maintain, and has a serious impact on the operation. As such, the sizer was selected for analysis to try and improve the efficiency of its performance, and so increase availability, reduce downtime, improve mean time to failure and reduce costs of maintenance.

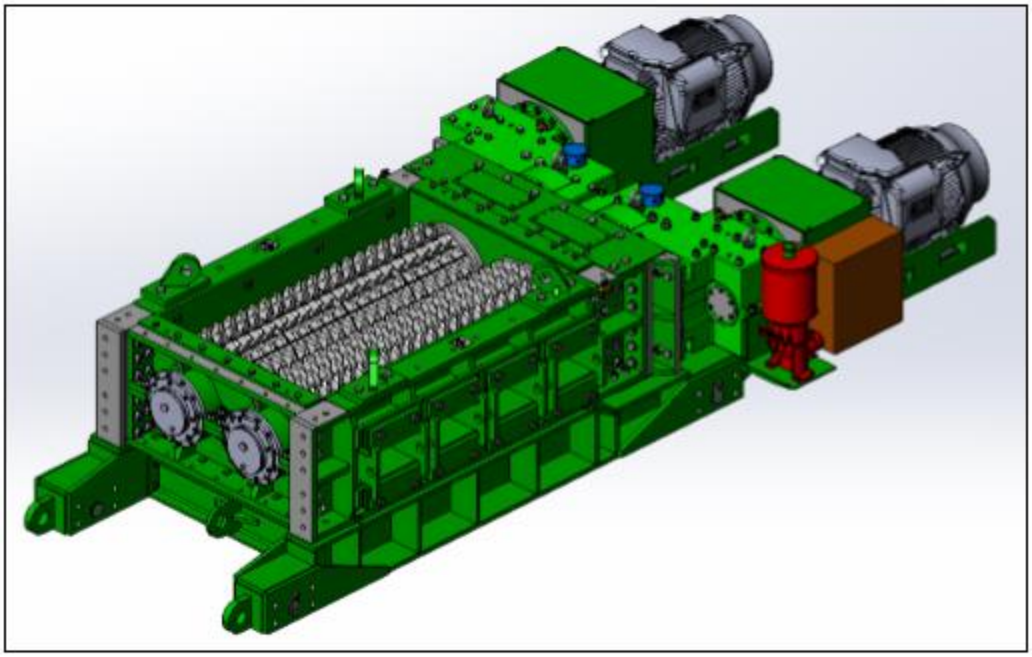


*Figure 19 : Sizer Unit*

The main function of the mineral sizer is to act as a crusher, reducing the size of mined material to particles that can be conveyed easily, either by conveyors or pumping systems. In the case of this research, the unit sizes material that will be conveyed through pumping systems.

It's is important to emphasise that there are a lot of undesirable failure consequences associated with the sizer. The sizer is at the beginning of the process, which means that failure causes the whole process comes to a halt. Such stoppages have huge cost implications to the business. For this reason, a decision was made to start RCM implementation, to quickly realise its benefits for the business.

It is also important to note that the maintenance costs of this mining unit form the largest share of the total costs in this specific operation, so any operational and maintenance improvements that would assist in improving productivity and reducing costs would be welcome.

### 5.2.2 Defining systems functions, performance standards of the asset in its present operating context

The main function of the sizer is to reduce the size of mined minerals to particles that can easily be conveyed through a pumping system. The sizer achieves this particle reduction using the crushing principle used in traditional crushers.

In its operating context the sizer was designed to produce:

- 600 tons/hr of ore at
- 90% availability

However, as the statistics in Figure 1 show, the plant has not been able to produce ore at 600 tons an hour and availability at an average of 66%. There was therefore high expectation that the implementation of RCM on this equipment would help increase throughput and improve availability to expected levels.

*Figure 20 : Operations principle of the mineral sizer*

This space is left empty intentionally.
Please go to the next page

### 5.2.3 Determining systems functional failures, failure modes and failure effects

The mineral sizer was divided into sub-systems and the sub-systems were also divided into components to make the analysis of the sizer easier. As such, the mineral sizer was divided into four distinct subsystems, as shown in the diagram below:

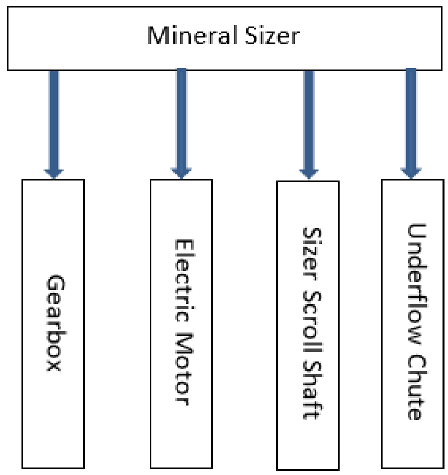



*Figure 21 : Four sub-systems of the sizer*

The sub-systems were then divided into components. For each component the following were determined:

- Functions of each component
- Functional failures of each component
- Failure modes associated with each component
- Failure effects of each failure mode

See Figures 23, 25, 27 and 29 on the following pages for the FMEA analyses of the four sub-systems.

This space is left empty intentionally.
Please go to the next page

### *5.2.3.1 Gearbox (Voith Gearbox)*

*Figure 22 : Voith Mineral Sizer Gearbox*

| FMEA FOR SIZER GEARBOX | | | | | | |
|---|---|---|---|---|---|---|
| System | **Gearbox** | Analyst | **Saul Machingauta** | Approved | Saul Machingauta | |
| | | Date | 10-Jan-19 | | | |
| System Function | Transmit power from elecric motor shaft to Scroll shaft | | | | | |
| **MSI** | **Component** | **Function** | **Functional Failure** | **Faiure Mode** | **Comments** | **Fref** |
| Gearbox | Bearing | Support shaft, Faciltates rotation and reduce friction | Failure to enable shaft rotation | Seizure,wear | Happens when there is lack of lubrication in the gerabox and heat is generated | 001 |
| | | | | Bearing Cracks | Can be caused dues to tight fits | 002 |
| | | | | Bearing Pitting | High Temperature can cause pitting | 003 |
| | | | | Bearing Fretting | Same reason as rust and corrosion | 004 |
| | | | | Bearing Corrosion | Can be caused by water ingress into the bearing | 005 |
| | Gears | Transmit rotary motion and also transfer power fromone shaft to another | Bending fatigue | Bending fatigue | Heavy loads on gears when rorating a major cause | 006 |
| | | | Fretting corrosion | Fretting corrosion | Water ingress into the gearbox | 007 |
| | | | Scuffing | Scuffing of gears | Caused by inadequate lubrication | 008 |
| | | | Pitting | Pitting of gears | Caused by high temperatures | 009 |
| | Lubrication Oil | Provide surface wear protection | Reduction of Lubrication properties | Lubrication Foaming | | 010 |
| | | Rust Protection | Gears and bearings rusting | Water Ingress | | 011 |
| | | Cooling | Gearbox overheats | Lubricant Overheating | | 012 |
| | Shaft | Transfer Power to gears | Fails to transfer Power | Snapped Shaft | | 013 |
| | | | | Journal Wear | Wear on bearing journals | 014 |
| | Mechanical Seal | Protect the gearbox from external envirnment | Dust, water and dirty enters gearbox | Leaking seals | | 015 |
| | Mounting Frame | Hold gearbox in position | Fails to keep gearbox in position causing vibration and misalignment | Loose bolts | | 016 |
| | | | | Crack in frame | | 017 |
| **Failure Effects** | | | | | | |
| **Fref** | 001 - 002 | 003 - 004 | 005 | 006 | 007 - 009 | 010 - 011 |
| **Failure Effect** | Bearing will not Run | Bearing will overheat | Uneven load distribution | Gearbox noise, vibration | Accelerated wear of gear teeth | Oil Contamination |
| **Fref** | 012 | 013 | 014 | 015 | 016 -17 | |
| **Failure Effect** | Gearbox Overheats | Gearbox stops | Noise, Vibration | Environmental pollution | Gearbox Vibration | |

*Figure 23 : FMEA for Gearbox*

### *5.2.3.2 Electric Motor*

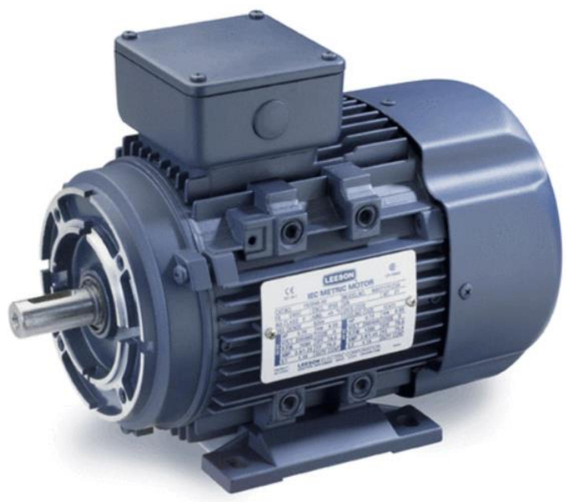


*Figure 24 : Gearbox Motor*

| FMEA FOR ELECTRIC MOTOR | | | | | | |
|---|---|---|---|---|---|---|
| System | **Electric Motor** | Analyst | **Saul Machingauta** | Approved | Saul Machingauta | |
| | | Date | 18-Jan-19 | | | |
| System Function | Converts Mechanical Energy to Mechanical Energy | | | | | |
| **MSI** | **Component** | **Function** | **Functional Failure** | **Faiure Mode** | **Comments** | **Fref** |
| Electric Motor | Motor Bearings | Support shaft, Faciltates rotation and reduce friction | Failure to enable shaft rotation | Seizure,wear | Happens when there is lack of lubrication in the gerabox and heat is generated | 001 |
| | | | | Bearing Cracks | Can be caused dues to tight fits | 002 |
| | | | | Bearing Pitting | High Temperature can cause pitting | 003 |
| | | | | Bearing Fretting | Same reason as rust and corrosion | 004 |
| | | | | Bearing Corrosion | Can be caused by water ingress into the bearing | 005 |
| | Motor Stator | Provides mechanical support and protection for the motor | Motor inefficiency | No eccentricity on stator | Failure consequecy is the same for both failure modes | 006 |
| | | | | Short Lamination on stator | | 007 |
| | Motor Rotor | Facilitates electromechachanical energy conversion | No energy conversion | Rotor Wear | Falure consequence the same for all failure modes | 008 |
| | | | | Rotor Burnt | | 009 |
| | | | | Rotors bars Broken | | 010 |
| | Motor Shaft | Transfer Power to gears | Fails to transfer Power | Snapped Shaft | | 011 |
| | | | | Shaft Wear | Wear on bearing journals | 012 |
| | Windings and Insulation | Creates the magnetic field that make the shaft to turn | No Magnetic field | Wiindings Overheating | All failure modes will lead to electric motor failure | 013 |
| | | | | Windings Insulation Breakdown | | 014 |
| | | | | Windings Vibration | | 015 |
| | | | | Windings Voltage surges | | 016 |
| | | | | Windings failure/Shortage | | 017 |
| | Mechanical Seal | Protect the gearbox from external envirnment | Dust, water and dirty enters gearbox | Leaking seals | | 018 |
| | Mounting Frame | Hold Motor in position | Fails to keep Motor in position causing vibration and misalignment | Loose bolts | | 019 |
| | | | | Crack in frame | | 020 |
| **Failure Effects** | | | | | | |
| **Fref** | 001 - 002 | 003 - 004 | 005 | 006 - 012 | 013 - 017 | 018 |
| **Failure Effects** | Bearing will not Run | Bearing will overheat | Uneven load distribution | Motor stops running | Failure modes will lead to motor failur | Oil leaks |
| **Fref** | 019 -102 | | | | | |
| **Unit** | Motor Vibration | | | | | |

*Figure 25 : FMEA for Electric Motor*

### *5.2.3.3 Sizer Scroll Shaft*

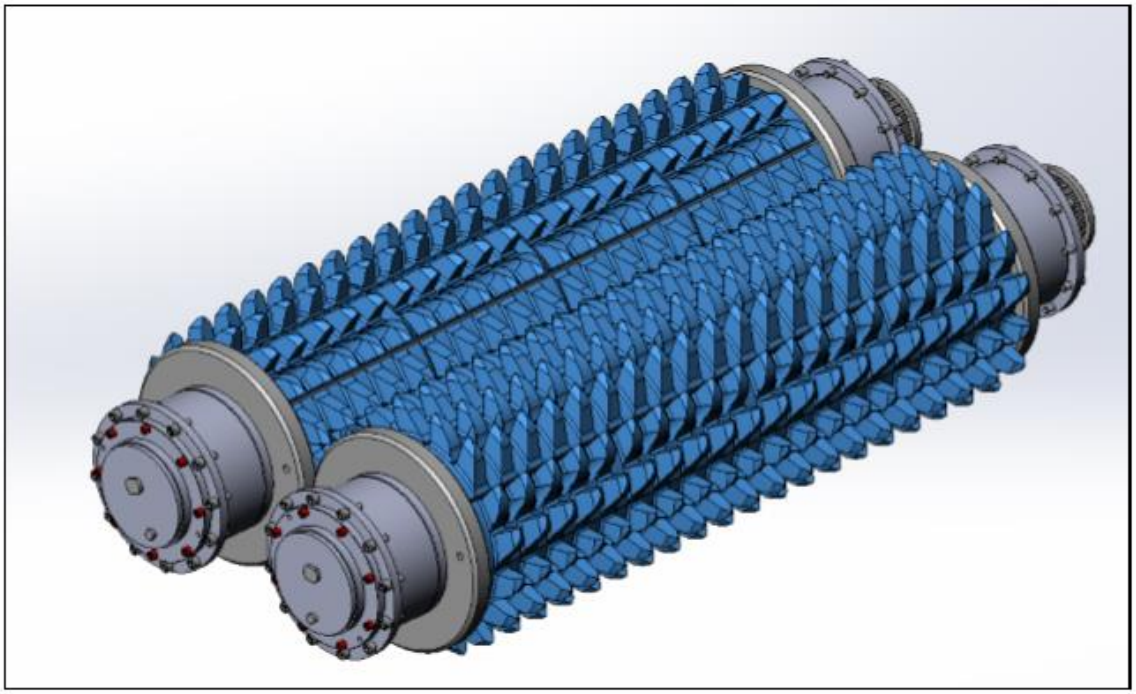


*Figure 26 : Mineral Sizer scroll shafts*

| FMEA FOR SIZER - SCROLL SHAFTS | | | | | | |
|---|---|---|---|---|---|---|
| System | **Gearbox** | Analyst | **Saul Machingauta** | Approved | Saul Machingauta | |
| | | Date | 10-Jan-19 | | | |
| System Function | Support the scroll teeth and provides the rotational effect of the teeth | | | | | |
| **MSI** | **Component** | **Function** | **Functional Failure** | **Faiure Mode** | **Comments** | **Fref** |
| Scroll Shaft | Scroll Shaft Bearings | Support shaft, Faciltates rotation and reduce friction | Failure to enable shaft rotation | Seizure,wear | Happens when there is lack of lubrication in the gerabox and heat is generated | 001 |
| | | | | Bearing Cracks | Can be caused dues to tight fits | 002 |
| | | | | Bearing Pitting | High Temperature can cause pitting | 003 |
| | | | | Bearing Fretting | Same reason as rust and corrosion | 004 |
| | | | | Bearing Corrosion | Can be caused by water ingress into the bearing | 005 |
| | Fluid Coupling | Transmit Torque between gearbox and scroll shaft | Fails to transmit Torque | Overheating | Failure consequecy is the same for both failure modes | 006 |
| | | | | Oil leaks | | 007 |
| | | | | Misalignment between gearbox and scroll shaft | | 008 |
| | Scroll Teeth | Provides the crushing and sizing on the mineral | Fails to crush and size of inefficiency in the process | Teeth Wear | Failure consequence the same for all failure modes | 009 |
| | | | | Teeth Loose | | 010 |
| | Scroll Side Combs | Assist teeth size and crush on the side of the sizer | Fails to crush and size of inefficiency in the process | Side Combs Wear | | 011 |
| | | | | Side Combs Loose | | 012 |
| | Scroll Shaft | Support the scroll teeth and provides the rotational effect of the teeth | Fails to transfer Power | Snapped Shaft | | 013 |
| | | | | Journal Wear | Wear on bearing journals | 014 |
| **Failure Effects** | | | | | | |
| **Fref** | 001 - 002 | 003 - 004 | 005 | 006 to 008 | 009 - 012 | 013 - 014 |
| **Failure Effects** | Bearing will not Run | Bearing will overheat | Uneven load distribution | Fluid coupling fuse blows | Size fail to size ore | Shaft stops turning |

*Figure 27 : FMEA for Mineral Sizer Scroll Shafts*

#### *5.2.3.4 Underflow Chute*

*Figure 28 : Underflow Chute*

| FMEA FOR UNDERFLOW CHUTE | | | | | | |
|---|---|---|---|---|---|---|
| System | **Gearbox** | Analyst | **Saul Machingauta** | Approved | Saul Machingauta | |
| | | Date | 25-Jan-19 | | | |
| System Function | Acts as temporary storage for material and as also as a transporting system to the next stage of the process | | | | | |
| **MSI** | **Component** | **Function** | **Functional Failure** | **Faiure Mode** | **Comments** | **Fref** |
| Undeflow Chute | Liners | Protect plate work from impact and wear | Failure to protect Platework | Liner wear | Same effect from the two failure modes | 001 |
| | | | | Liner Cracks | | 002 |
| | | | | Liner holes worn | | 003 |
| | Platework | To contain mineral orebefore discharge into gravel pump | Fails to contain mineral ore | Plate wear | Same as above | 004 |
| | | | | Plate Cracks | | 005 |
| | | | | Plate holes worn | | 006 |
| | Holding bolts | Hold liners and chute platework together | Faild to hold liners onto position | Bolt wear | | 007 |
| | | | | Loose bols | | 008 |
| | Welded joints | Joins together chute platework | Fail to hold platework together | Welds cracks | Impact loads on chute a major cause | 009 |
| Failure Effects | | | | | | |
| **Fref** | 001 to 002 | 003, 006 to 009 | 004 to 005 | | | |
| **Failure Effect** | Accelarated chute wear | Chute Vibrations | Material leaks from Chute | | | |

*Figure 29 : FMEA for sizer underflow chute*

The analysis through the FMECA process addressed all the failure modes of all the critical components of each subsystem. Relationships were developed between components, their functions and functional failures and subsequently the associated failure modes. These relationships would be important as the RCM analysis progresses.

### 5.2.4 Prioritizing Identified Failure Modes

After identifying the functions of the sizer, sub-assemblies and components, functional failures, failure modes and failure consequences, the failure modes were prioritized. The failure mode, effect and criticality analysis (FMECA) method was used to rank the failure modes. According to Zajicek (2018), FMECA is the most popular reliability analysis tool. He goes on to explain that failure mode criticality is a product of failure mode probability of occurrence and the resultant impact in the case of an occurrence.

The scales used for the consequence level (C), probability of occurrence ($P_o$) and FMECA criticality classification ($C_r$) according to Coetzee (2015) is shown on the tables below respectively (Coetzee, 2015) and (Zajicek, 2018)

Using the decision tree described by Coetzee (2015), the failure modes were evaluated and classification was made, the criteria of which is shown below.

| **Consequence Level** | **Description** | **Ranking** |
|---|---|---|
| Catastrophic | A failure mode that can cause death or system loss | 7 |
| Critical | A failure that may cause severe injury, major property damage, minor system damage, which result in mission loss | 5 |
| Marginal | A failure that may cause minor injury, minor property damage, minor systems damage, which may result in delay or mission degradation | 3 |
| Minor | A failure that will not cause injury, property damage, system damage, but will result in unscheduled maintenance or repair | 1 |

*Figure 30 : Failure mode consequence ranking*

| Level of Occurrence | % of Failures | Po |
|---|---|---|
| Frequent | % Fail > 20% | 9 |
| Reasonably probable | 10% < % Fail ≤ 20% | 7 |
| Occasional | 1% < % Fail ≤ 10% | 5 |
| Remote | 0.1% < % Fail ≤ 1% | 3 |
| Extremely unlikely | % Fail ≤ 0.1% | 1 |

*Figure 31 : Failure Mode frequency of occurrence*

| Criticality number range (C x $P_o$) | $C_r$ |
|---|---|
| 52 - 63 | A |
| 39 - 51 | B |
| 26 - 38 | C |
| 13 - 25 | D |
| 0 - 12 | E |

*Figure 32 : Failure mode criticality ranking*

| Task Abbreviation | Task Description |
|---|---|
| H | Hidden Safety/ Environmental Consequence |
| HO | Hidden Operational Consequence |
| S | Safety/Environmental Consequence |
| O | Operational Consequence |
| NO | Non-Operational Consequence |

*Figure 33 : Failure Mode Consequence types*

This space is left empty intentionally.
Please go to the next page

#### 5.2.4.1 Gearbox

The failure modes as presented in Fig 23 were taken and analysed and the following critical classification for the gearbox were determined as indicated on table below

| Fref | Failure mode | Failure Mode Consequence | Failure Mode Probability of occurance | Failure Mode Criticality ranking | Critical Classification ($C_r$) | Failure Consequence Classification |
|---|---|---|---|---|---|---|
| 001 | Seizure,wear | 5 | 9 | 45 | B | O |
| 002 | Bearing Cracks | 5 | 9 | 45 | B | O |
| 005 | Bearing Corrosion | 5 | 9 | 45 | B | HO |
| 007 | Fretting corrosion | 5 | 9 | 45 | B | HO |
| 011 | Water Ingress | 5 | 9 | 45 | B | HO |
| 012 | Lubricant Overheating | 5 | 9 | 45 | B | HO |
| 015 | Leaking seals | 5 | 9 | 45 | B | S |
| 016 | Loose bolts | 5 | 9 | 45 | B | S |
| 017 | Crack in frame | 5 | 9 | 45 | B | S |
| 006 | Bending fatigue | 5 | 7 | 35 | C | O |
| 010 | Lubrication Foaming | 3 | 9 | 27 | C | HO |
| 014 | Journal Wear | 3 | 9 | 27 | C | O |
| 008 | Scuffing of gears | 3 | 7 | 21 | D | O |
| 003 | Bearing Pitting | 3 | 5 | 15 | D | O |
| 004 | Bearing Fretting | 3 | 5 | 15 | D | O |
| 009 | Pitting of gears | 3 | 5 | 15 | D | O |
| 013 | Snapped Shaft | 5 | 3 | 15 | D | O |

*Figure 34: Gearbox Failure Mode ranking and classification*

This space is left empty intentionally.
Please go to the next page

### 5.2.4.2 Electric Motor

The failure modes as presented in Fig 25 were taken and analysed and the following critical classifications for the electric motor were determined as indicated on table below:

| Fref | Failure mode | Failure Mode Consequence | Failure Mode Probability of occurance | Failure Mode Criticality ranking | Critical Classifocation ($C_r$) | Failure Consequence Classification |
|---|---|---|---|---|---|---|
| 001 | Seizure,wear | 5 | 9 | 45 | B | O |
| 002 | Bearing Cracks | 5 | 9 | 45 | B | O |
| 005 | Bearing Corrosion | 5 | 9 | 45 | B | HO |
| 007 | Short Lamination on stator | 5 | 9 | 45 | B | HO |
| 009 | Rotor Burnt | 5 | 9 | 45 | B | HO |
| 010 | Rotors bars Broken | 5 | 9 | 45 | B | HO |
| 013 | Wiindings Overheating | 5 | 9 | 45 | B | HO |
| 014 | Windings Insulation Breakdown | 5 | 9 | 45 | B | HO |
| 015 | Windings Vibration | 5 | 9 | 45 | B | O |
| 016 | Windings Voltage surges | 5 | 9 | 45 | B | S |
| 017 | Windings failure/Shortage | 5 | 9 | 45 | B | HO |
| 018 | Leaking seals | 5 | 9 | 45 | B | S |
| 019 | Loose bolts | 5 | 9 | 45 | B | S |
| 006 | No eccentricity on stator | 5 | 7 | 35 | C | HO |
| 008 | Rotor Wear | 5 | 7 | 35 | C | HO |
| 012 | Shaft Wear | 3 | 9 | 27 | C | HO |
| 020 | Crack in frame | 3 | 7 | 21 | D | S |
| 003 | Bearing Pitting | 3 | 5 | 15 | D | HO |
| 004 | Bearing Fretting | 3 | 5 | 15 | D | HO |
| 011 | Snapped Shaft | 5 | 3 | 15 | D | S |

*Figure 35 : Electric Motor Failure Mode ranking and classification*

### 5.2.4.3 Scroll Shaft

The failure modes as presented on Fig 27 were taken and analysed and the following critical classifications for the scroll shaft were determined, as indicated on table below

| Fref | Failure mode | Failure Mode Consequence | Failure Mode Probability of occurance | Failure Mode Criticality ranking | Critical Classifocation ($C_r$) | Failure Consequence Classification |
|---|---|---|---|---|---|---|
| 001 | Seizure,wear | 5 | 9 | 45 | B | O |
| 002 | Bearing Cracks | 5 | 9 | 45 | B | HO |
| 005 | Bearing Corrosion | 5 | 9 | 45 | B | HO |
| 006 | Overheating | 5 | 9 | 45 | B | HO |
| 007 | Oil leaks | 5 | 9 | 45 | B | S |
| 008 | Misalignment between gearbox and scroll shaft | 5 | 9 | 45 | B | O |
| 009 | Teeth Wear | 5 | 9 | 45 | B | O |
| 010 | Teeth Loose | 5 | 9 | 45 | B | O |
| 011 | Side Combs Wear | 5 | 9 | 45 | B | O |
| 012 | Side Combs Loose | 3 | 9 | 27 | C | O |
| 014 | Journal Wear | 3 | 9 | 27 | C | HO |
| 003 | Bearing Pitting | 3 | 5 | 15 | C | HO |
| 004 | Bearing Fretting | 3 | 5 | 15 | C | HO |
| 013 | Snapped Shaft | 5 | 3 | 15 | C | HO |

*Figure 36: Scroll Shafts Failure Mode ranking and classification*

#### *5.2.4.4 Underflow Chute*

The failure modes as presented on Fig 29 were taken and analysed and the following critical classification for the underflow chute were determined, as indicated on table below

| Fref | Failure mode | Failure Mode Consequence | Failure Mode Probability of occurance | Failure Mode Criticality ranking | Critical Classificat ion ($C_r$) | Failure Consequence Classification |
|---|---|---|---|---|---|---|
| 001 | Liner wear | 5 | 9 | 45 | B | HO |
| 002 | Liner Cracks | 5 | 9 | 45 | B | HO |
| 004 | Plate wear | 5 | 9 | 45 | B | HO |
| 005 | Plate Cracks | 5 | 9 | 45 | B | HO |
| 009 | Welds cracks | 5 | 9 | 45 | B | S |
| 007 | Bolt wear | 3 | 9 | 27 | C | G |
| 008 | Loose bolts | 3 | 7 | 21 | D | G |
| 003 | Liner holes worn | 3 | 5 | 15 | D | O |
| 006 | Plate holes worn | 3 | 5 | 15 | D | O |

*Figure 37 : Underflow Chute Failure Mode ranking and classification*

### 5.2.5 Identification of suitable maintenance tasks

According to Coetzee (2015) and Moubray (1997), the task selection process is the most critical stage of the RCM methodology. This is so because this is where identification of the actual tasks is done. If this is done correctly, then the deployment of the methodology will be a success. The opposite is also true.

As already presented in the literature review chapter, the tasks identified for RCM implementation are:

- Condition based tasks
- Scheduled reconditioning tasks
- Scheduled replacement tasks
- Failure finding tasks
- Servicing/lubrication tasks
- Design out tasks
- Corrective maintenance tasks

As Coetzee (2015) put it, the first five tasks can be considered as preventative maintenance tasks, which means that there are three classifications of tasks, namely:

- Preventative Maintenance Tasks
- Design out Tasks
- Corrective Maintenance Tasks

Using the task selection model as described in the literature review in Chapter 3, the tasks below were determined from the failure modes identified earlier.

It is important to note that in this process, tasks were prioritized based on the criticality ranking as well as the failure consequence classification as described above.

The determination of task frequencies was done as recommended by Coetzee (2015), who suggested that initial frequencies be based on:

- Experience with similar equipment and OEM recommendations
- Study and understanding of the patterns of failure on the mineral sizer
- Analysis of historical failure data

Below is a presentation of the maintenance tasks determined during the analysis of the failure modes on the four sub-assemblies, namely:

- Gearbox
- Electric motor
- Scroll shaft
- Underflow chute

The abbreviations used in the tables are defined in Figure 38 below, and the detail of each is presented in the appendices.

| **Abbreviation** | **Description** |
|---|---|
| C | Failure mode consequence |
| $P_o$ | Failure mode probability of occurrence |
| $C_r$ | Failure mode criticality classification |
| TC | Ticked if combination of tasks is used |
| F | Task frequency |
| T | Trade description |
| P | Production indicator (Whether or not a task can be performed during production run) |
| SG | Scheduling group |

*Figure 38 : Abbreviation descriptions used in task selection tables*

### *5.2.5.1 Task Selection for Gearbox*

| Fref | Failure mode | C | $P_O$ | $C_r$ | Cons Type | Task Type | Task | Task Detail | TC | F | T | P | SG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 001 | Seizure,wear | 5 | 9 | 45 | O | LSA | Lubricate | Lubricate bearings | | W | O | P | OW |
| 002 | Bearing Cracks | 5 | 9 | 45 | O | CB | Do oil analysis | Take oil samples and send for analysis | √ | M | CM | P | CM |
| | | | | | | CB | Perform Vibration Analysis | Check vibration using analyser | | M | CM | | CM |
| 005 | Bearing Corrosion | 5 | 9 | 45 | HO | CB | Do oil analysis | Take oil samples and send for analysis | | M | CM | P | CM |
| 007 | Fretting corrosion | 5 | 9 | 45 | HO | CB | Do oil analysis | Take oil samples and send for analysis | | M | CM | P | CM |
| 011 | Water Ingress | 5 | 9 | 45 | HO | CB | Do oil analysis | Take oil samples and send for analysis | | M | CM | P | CM |
| 012 | Lubricant Overheating | 5 | 9 | 45 | HO | Rep | Replace Oil | Replace oil at predetermined times | √ | HY | F | SD | TY |
| | | | | | | CB | Check Temperature | Use thermal imaging Camera | | M | CM | P | CM |
| 015 | Leaking seals | 5 | 9 | 45 | S | CB | Inspect seals | Carry out inspection os gearbox seals | | M | F | SD | TM |
| 016 | Loose bolts | 5 | 9 | 45 | S | CB | Inspect bolts | Inspect bolts | √ | M | B | P | TM |
| | | | | | | | Perform Vibration Analysis | Check vibration using analyser | | M | CM | P | CM |
| 017 | Crack in frame | 5 | 9 | 45 | S | CB | Do crack detection | Use dye Penentration to detect cracks | | Y | CM | P | CM |
| 006 | Bending fatigue | 5 | 7 | 35 | O | CB | Do oil analysis | Take oil samples and send for analysis | √ | M | CM | P | CM |
| | | | | | | | Perform Vibration Analysis | Check vibration using analyser | | M | CM | P | CM |
| 010 | Lubrication Foaming | 3 | 9 | 27 | HO | CB | Do oil analysis | Take oil samples and send for analysis | | M | CM | P | CM |
| 014 | Journal Wear | 3 | 9 | 27 | O | CB | Do oil analysis | Take oil samples and send for analysis | | M | CM | P | CM |
| 008 | Scuffing of gears | 3 | 7 | 21 | O | CB | Do oil analysis | Take oil samples and send for analysis | | M | CM | P | CM |
| 003 | Bearing Pitting | 3 | 5 | 15 | O | CB | Do oil analysis | Take oil samples and send for analysis | | M | CM | P | CM |
| 004 | Bearing Fretting | 3 | 5 | 15 | O | CB | Do oil analysis | Take oil samples and send for analysis | | M | CM | P | CM |
| 009 | Pitting of gears | 3 | 5 | 15 | O | CB | Do oil analysis | Take oil samples and send for analysis | | M | CM | P | CM |
| 013 | Snapped Shaft | 5 | 3 | 15 | O | CB | Do oil analysis | Take oil samples and send for analysis | √ | M | CM | P | CM |
| | | | | | | CB | Check Alignment | Check Alignment using alignment machine | | Q | AS | SD | SQ |

*Figure 39: Task selection for gearbox*

### *5.2.5.2 Task selection for Electric Motor*

| Fref | Failure mode | C | $P_O$ | $C_r$ | Cons Type | Task Type | Task | Task Detail | TC | F | T | P | SG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 001 | Seizure,wear | 5 | 9 | 45 | O | LSA | Lubricate | Lubricate bearings | | W | O | P | OW |
| 002 | Bearing Cracks | 5 | 9 | 45 | O | CB | Perform Vibration Analysis | Check vibration using analyser | | M | CM | P | CM |
| | | | | | | | Check Alignment | Use alignment machine to check alignment | √ | | | | |
| 005 | Bearing Corrosion | 5 | 9 | 45 | O | CB | Inspect bearing | Perfomm inspection | | M | CM | | CM |
| 007 | Short Lamination on stator | 5 | 9 | 45 | HO | CB | Temperature analysis | Use thermal imaging camera to check temperature | | M | CM | P | CM |
| 009 | Rotor Burnt | 5 | 9 | 45 | HO | CB | Temperature analysis | Use thermal imaging camera to check temperature | | M | CM | P | CM |
| 010 | Rotors bars Broken | 5 | 9 | 45 | HO | CB | Temperature analysis | Use thermal imaging camera to check temperature | | M | CM | P | CM |
| 013 | Windings Overheating | 5 | 9 | 45 | HO | Rep | Temperature analysis | Use thermal imaging camera to check temperature | √ | HY | F | SD | TY |
| 014 | Windings Insulation Breakdown | 5 | 9 | 45 | | CB | Temperature analysis | Use thermal imaging camera to check temperature | | M | CM | P | CM |
| 015 | Windings Vibration | 5 | 9 | 45 | S | CB | Check vibration | Use vibration analyser to check vibration | | M | F | SD | TM |
| 016 | Windings Voltage surges | 5 | 9 | 45 | S | CB | Temperature analysis | Perform inspection | √ | M | B | P | TM |
| 017 | Windings failure/Shortage | 5 | 9 | 45 | | CB | Temperature analysis | Perform inspection | | M | CM | P | CM |
| 018 | Leaking seals | 5 | 9 | 45 | S | CB | Inpect motor for leaks | Inspect motor | | Y | CM | P | CM |
| 019 | Loose bolts | 5 | 9 | 45 | O | CB | Inspect Motor | Inspect bolts for looseness | | M | CM | P | CM |
| | | | | | O | CB | Check vibration | Use vibration analyser to check vibration | √ | M | F | SD | TM |
| 006 | No eccentricity on stator | 5 | 7 | 35 | HO | CB | Temperature analysis | Use thermal imaging camera to check temperature | | M | CM | P | CM |
| 008 | Rotor Wear | 5 | 7 | 35 | HO | CB | Temperature analysis | Use thermal imaging camera to check temperature | | M | CM | P | CM |
| 012 | Shaft Wear | 3 | 9 | 27 | O | CB | Inspect Motor | Carry out inspection | | M | CM | P | CM |
| 020 | Crack in frame | 3 | 7 | 21 | O | CB | Inspect Motor | Carry out inspection | | M | CM | P | CM |
| 003 | Bearing Pitting | 3 | 5 | 15 | O | CB | Do oil analysis | Take oil samples and send for analysis | | M | CM | P | CM |
| 004 | Bearing Fretting | 3 | 5 | 15 | O | CB | Do oil analysis | Take oil samples and send for analysis | | M | CM | P | CM |
| 011 | Snapped Shaft | 5 | 3 | 15 | O | CB | Do oil analysis | Take oil samples and send for analysis | | M | CM | P | CM |

*Figure 40: Task Selection for Electric Motor*

### 5.2.5.3 Task selection for Scroll shafts

| Fref | Failure mode | C | $P_O$ | $C_r$ | Cons Type | Task Type | Task | Task Detail | TC | F | T | P | SG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 001 | Seizure,wear | 5 | 9 | 45 | O | LSA | Lubricate | Lubricate bearings | | W | O | P | OW |
| 002 | Bearing Cracks | 5 | 9 | 45 | HO | CB | Do oil analysis | Take oil samples and send for analysis | √ | M | CM | P | CM |
| | | | | | | | Design new feeding system | Design new feeding system to minimise impact | | | P | P | |
| 005 | Bearing Corrosion | 5 | 9 | 45 | HO | CB | Do oil analysis | Take oil samples and send for analysis | | M | CM | | CM |
| 006 | Overheating | 5 | 9 | 45 | HO | CB | Check Temperature | Use thermal imaging Camera | | M | CM | P | CM |
| 007 | Oil leaks | 5 | 9 | 45 | S | CB | Inspect fo leaks | Carry out inspection on coupling for leaks | | M | CM | P | CM |
| 008 | Misalignment between gearbox and scroll shaft | 5 | 9 | 45 | O | CB | Perform Aligment between gearbox and scroll shaft | Use alignment machines to align | √ | Y | AS | SD | SQ |
| | | | | | | CB | Perform vibration analysis | Use analyser to check vibration | | M | CM | P | SM |
| 009 | Teeth Wear | 5 | 9 | 45 | O | Rep | Inspect | Inspect and measure tooth height | √ | W | F | SD | FW |
| | | | | | | | Design new feeding system | Design new feeding system to minimise impact | | | P | P | |
| 010 | Teeth Loose | | | | | CB | Inspect | Inspect and check bolds for looseness | √ | W | F | SD | FW |
| | | 5 | 9 | 45 | O | CB | Perform Vibration Analysis | Check vibration using analyser | | M | CM | P | SM |
| 011 | Side Combs Wear | 5 | 9 | 45 | O | CB | Inspect | Inspect and measure combs height | √ | M | F | SD | TM |
| | | | | | | DO | Design new feeding system | Design new feeding system to minimise impact | | | P | P | |
| 012 | Side Combs Loose | | | | | CB | Inspect bolts | Inspect bolts | √ | M | B | P | TM |
| | | 3 | 9 | 27 | O | CB | Perform Vibration Analysis | Check vibration using analyser | | M | CM | P | SM |
| 014 | Journal Wear | 3 | 9 | 27 | HO | CB | Inspect shaft journals for wear | Inspect shaft for wear | | M | F | SD | FM |
| 003 | Bearing Pitting | 3 | 5 | 15 | HO | CB | Visually Inspect Bearing | Inspect bearing for pitting | | Y | CM | P | CM |
| 004 | Bearing Fretting | 3 | 5 | 15 | HO | CB | Visually Inspect bearing | Inspect bearing for fretting | | M | CM | P | CM |
| 013 | Snapped Shaft | 5 | 3 | 15 | HO | S | Perform Vibration Analysis | Check vibration using analyser | | M | CM | P | SQ |

*Figure 41 : Task Selection for Scroll Shafts*

### 5.2.5.4 Task selection for Underflow Chute

| Fref | Failure mode | C | $P_O$ | $C_r$ | Cons Type | Task Type | Task | Task Detail | TC | F | T | P | SG |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 001 | Liner wear | 5 | 9 | 45 | O | LSA | Lubricate | Lubricate bearings | | W | O | P | OW |
| 002 | Liner Cracks | 5 | 9 | 45 | HO | CB | Do oil analysis | Take oil samples and send for analysis | | M | CM | P | CM |
| 004 | Plate wear | | | | | CB | Do oil analysis | Take oil samples and send for analysis | √ | M | F | P | FM |
| | | 5 | 9 | 45 | HO | CB | Perfom thickness test | Use thickness test machines for thickness testing | | M | SD | P | CM |
| 005 | Plate Cracks | 5 | 9 | 45 | HO | CB | Check Temperature | Use thermal imaging Camera | | M | CM | P | CM |
| 009 | Welds cracks | | | | | CB | Inspect fo leaks | Carry out inspection on coupling for leaks | √ | M | CM | P | CM |
| | | 5 | 9 | 45 | S | CB | Perfom weld non destructive tests | Use dye pen to check welds | | Q | CM | SD | CQ |
| 007 | Bolt wear | 3 | 9 | 27 | O | CB | Perform Aligment between gearbox and scroll shaft | Use alignment machines to align | | Y | AS | SD | SQ |
| 008 | Loose bolts | 3 | 7 | 21 | | CB | Perform vibration analysis | Use analyser to check vibration | | M | CM | P | SM |
| 003 | Liner holes worn | 3 | 5 | 15 | O | Rep | Inspect | Inspect and measure tooth height | | W | F | SD | FW |
| 006 | Plate holes worn | 3 | 5 | 15 | O | CB | Inspect | Inspect and check bolds for looseness | | W | F | SD | FW |

*Figure 42: Task selection for Underflow chute*

Lessons learnt from the task selection process:

- Most generic tasks that were being carried out were set aside because most of the tasks chosen were specific to a failure mode.
- Most tasks that required plant shutdowns were abandoned and most of the tasks absorbed could be done during production runs. This greatly reduced plant stoppage time.

- Scheduled component change-out of parts was also abandoned, opting for a condition-based maintenance strategy where condition monitoring determined parts replacement. This drastically reduced the maintenance costs.
- All failure modes that had safety and environmental consequences were given priority over any other tasks, regardless of their criticality rankings.
- Failure modes with higher criticality rankings were accorded second place priority after the safety and environmental failure modes.
- Some tasks traditionally done by trade personnel were re-allocated to be done by operators.

### 5.2.6 Implementation of the maintenance strategies

#### *5.2.6.1 Design out of the sizer feeding system*

One of the discoveries made during the RCM analysis was the effect of the sizer feeding systems that was used (See fig 43). It was noted that feeding the sizer directly using an excavator had adverse effects on the operation of the unit.

- The impact of ore dropping onto the scroll shafts resulted in failures of
  - Scroll teeth
  - Bearings
  - Electric motors
  - Gearbox
  - Fluid coupling

As such a new system (See Fig 44) was designed in collaboration with the manufacturer of the sizer. This ensured that:

- Feed into the sizer was controlled
- Impact loading on the shaft was eliminated
- Component failures are reduced


*Figure 43: Feeding system before RCM*

*Figure 44: Feeding system after RCM*

## 5.3 Conclusion

This chapter presented the process that was followed in implementing the RCM process on the mineral sizer. The next chapter explores the results and findings of implementing the RCM process on the mineral sizer.

This space is left empty intentionally.
Please go to the next page

# 6. Chapter 6: Research Results and Findings

## 6.1 Introduction

The previous chapter presented the process that was followed in implementing the RCM process on the mineral sizer. A step by step process was detailed. This chapter explores the results and findings of implementing this RCM process on the mineral sizer. The benefits established from the process will be presented and analysed. The KPIs that were measured before the application of the Reliability Centred Maintenance (see Fig 45 below) are revisited and compared with the results after implementation of the process, and then analysed.

**KPI's Before Implementation of RCM**

| Month | Total Time Available | Total Uptime | Total Downtime | Frequency Of Failure | Tonnes Produced | MTTF | Hazard Rate | Availability | Cost Of Maintenance $/ton | Number of PM Schedules |
|---|---|---|---|---|---|---|---|---|---|---|
| Apr-18 | 720 | 340.15 | 379.85 | 189 | 5041 | 3.8 | 26% | 47% | 1.88 | 4 |
| May-18 | 744 | 413.22 | 330.78 | 165 | 6007 | 4.5 | 22% | 56% | 1.90 | 6 |
| Jun-18 | 720 | 444.32 | 275.68 | 143 | 6650 | 5.0 | 20% | 62% | 1.77 | 8 |
| Jul-18 | 744 | 524.19 | 219.81 | 146 | 7509 | 5.1 | 20% | 70% | 1.62 | 8 |
| Aug-18 | 744 | 491.23 | 252.77 | 175 | 7079 | 4.3 | 24% | 66% | 1.04 | 8 |
| Sep-18 | 720 | 556.32 | 163.68 | 135 | 7722 | 5.3 | 19% | 77% | 1.13 | 8 |
| Oct-18 | 744 | 518.12 | 225.88 | 174 | 7509 | 4.3 | 23% | 70% | 1.09 | 6 |
| Nov-18 | 720 | 511.48 | 208.52 | 135 | 7616 | 5.3 | 19% | 71% | 1.13 | 6 |
| Dec-18 | 744 | 589.13 | 154.87 | 145 | 8474 | 5.1 | 19% | 79% | 0.98 | 5 |
| Average | 733 | 488 | 246 | 156 | 7067 | 4.8 | 21% | 66% | 1.39 | 7 |

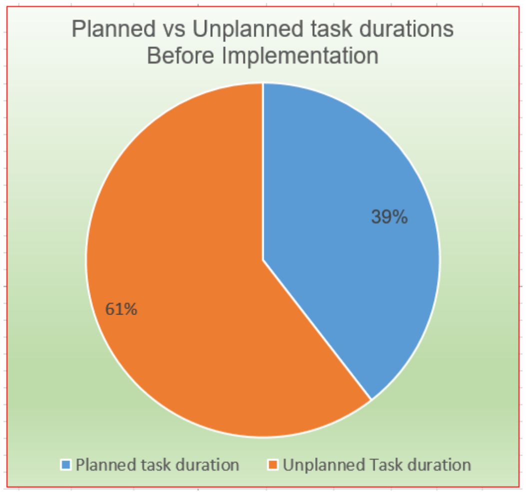
**KPI's After Implementation of RCM**

| | Total Time Available | Total Uptime | Total Downtime | Frequency Of Failure | Tonnes Produced | MTTF | Hazard Rate | Availability | Cost Of Maintenance | Number of PM Schedules |
|---|---|---|---|---|---|---|---|---|---|---|
| Jan-19 | 744 | 625.68 | 118.32 | 96 | 9632 | 7.8 | 13% | 84% | 0.88 | 2 |
| Feb-19 | 672 | 581 | 91 | 120 | 7652 | 5.6 | 18% | 86% | 0.91 | 2 |
| Mar-19 | 744 | 608.84 | 135.16 | 134 | 7798 | 5.6 | 18% | 82% | 0.69 | 2 |
| Apr-19 | 720 | 600.68 | 119.32 | 121 | 8689 | 6.0 | 17% | 83% | 0.55 | 2 |
| May-19 | 744 | 643.99 | 100.01 | 108 | 9214 | 6.9 | 15% | 87% | 0.53 | 2 |
| Jun-19 | 720 | 622.7 | 97.3 | 91 | 9122 | 7.9 | 13% | 86% | 0.58 | 2 |
| Jul-19 | 744 | 652.2 | 91.8 | 86 | 9301 | 8.7 | 12% | 88% | 0.52 | 2 |
| Average | 726.8571 | 619.3 | 107.56 | 108 | 8772.57 | 6.90 | 15% | 85% | 0.67 | 2 |

*Figure 45: Key Performance indicator results before and after RCM Implementation*

When Sierra Rutile purchased the sizing units they purchased two off. The sets of results for the two units before implementation looked very much similar and RCM was introduced on one sizer unit. After the results were collated after implementation, a huge improvement was realised on the one on which RCM was introduced than the one that didn't. The conclusion made in this regard is, even though the two pieces of equipment were new with obvious teething problems, the implementation of RCM, has proved that focused maintenance on equipment improves equipment efficiency.

### 6.1.1 Planned vs Unplanned Task durations



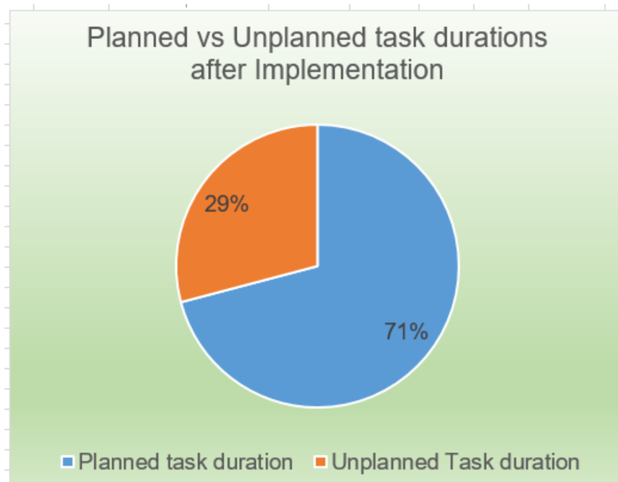




*Figure 46: Task durations before and after RCM implementation*

One of the biggest benefits that was realized from this process was an increase in planned work and the reduction of tasks caused by breakdowns. Most interesting was the discovery that many of the tasks introduced were condition monitoring tasks that needed to be done during the run, without stopping the plant's operations. If a condition that was undesirable was observed during the condition monitoring tasks, a conscious decision would then be made to stop the plant and rectify it. This supports the assertion made by Moubray (1997) when he asserted that the correct implementation of Reliability Centred Maintenance can reduce the amount of routine maintenance tasks by 40-70%. The financial benefit can be dramatic and reduction of headcount is evident (Smith, 1993) and (Moubray, 1997).

### 6.1.2 Overall Equipment Effectiveness (OEE)

From the time the mineral sizer commenced operations, the OEE rate was 25% in April 2018. This increased considerably to 82% by July 2019. This discovery complements the assertions by Moubray (1997) and Smith (1993) that Reliability Centred Maintenance helps improve machine performance because of higher machine uptimes and reliabilities (Smith, 1993) and (Moubray, 1997).

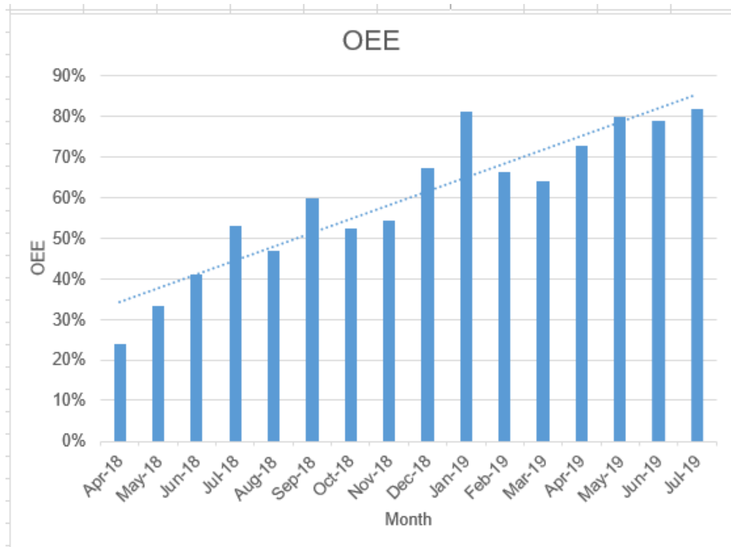



*Figure 47: Overall Equipment Effectiveness trending graph*

#### *6.1.2.1 Availability Rate*

This research sought to prove Moubray's (1997) assertion that implementation of a Reliability Centred Maintenance program improves machine uptime and availability. As is seen in the graph below, availability of the mineral sizer increased considerably from 47% in April 2018 to a high of 88% in July 2019. This research therefore agrees with Moubray's (1997) findings on availability.

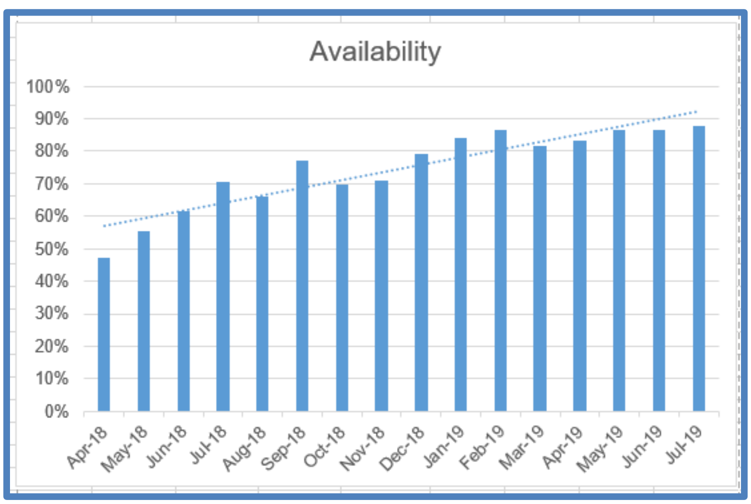



*Figure 48: Availability trending graph*

#### *6.1.2.2 Productivity Rate*

Coupled with investigating the increase in availability, this research also investigated the assertion by Moubray(1997) that machine performance increases with the implementation of Reliability Centred Maintenance. As can be seen in the graph below, production rates increased comparatively with availability. The results from this research concur with Moubray's (1997) claim about increased availability rates of equipment after the implementation of Reliability Centred Maintenance.

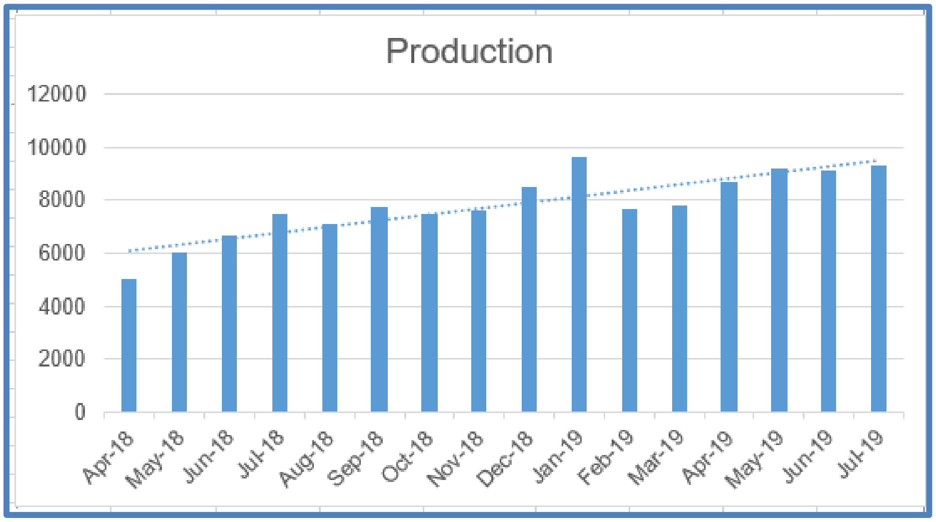



*Figure 49: Productivity trending graph*

#### *6.1.2.3 Quality Rate*

Although quality rate is considered in the calculation of OEE, in the case of this mineral sizer, quality is not determined by the machine. It is determined by the quality of the ore body being mined. As such, in all calculations, the quality rate of the machine will be taken as 100%.

### 6.1.3 Mean Time to Failure (MTTF)

MTTF is one of the main measures of reliability. This research investigated the MTTF improvements with the implementation of Reliability Centred Maintenance. Concurring with other scholars, this research discovers that a marked improvement in the MTTF, which greatly improved the reliability of the mineral sizer. The MTTF improvements are detailed in the graph (Fig 50) below:

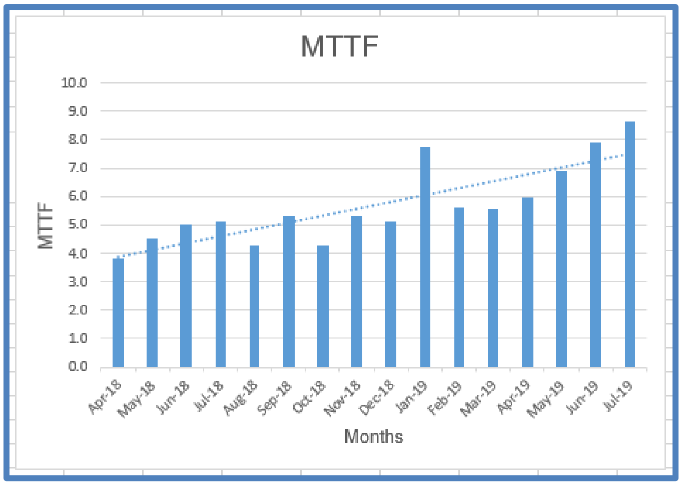



*Figure 50: MTTF trending Graph*

### 6.1.4 Maintenance costs

Many researchers claim that the implementation of Reliability Centred Maintenance will drastically decrease maintenance costs. From their claims, costs will be reduced through these factors, described by (Zio, 2009), (Fore & Msipha, 2010) and (Bowler et al., 1996).

- Reduction in spares usage
- Reduction of labour
- Reduction of maintenance schedules

This research agrees with these researchers, as was witnessed after the implementation of Reliability Centred Maintenance on the mineral sizer. The finding was that the use of spares was substantially reduced because the time-based change-out of spares was abandoned in favour of condition-based change-outs. Because of this reduction in the number of planned schedules, a marked reduction in maintenance personnel was realized and the number of tasks performed was also reduced. However, there was a marked increase in the number of condition monitoring and predictive maintenance tasks, with the advantage of being able to perform these tasks during the plant run. The change in maintenance costs is shown in the graph in Fig 51 below.


*Figure 51: Maintenance Cost trending Graph*

### 6.1.5 Reduction of Downtime

Together with the improvements in availability and reliability, reduced downtime for the mineral sizer realised great improvements. This improvement relates to both planned and unplanned downtime. Because of the massive reduction in routine tasks from a whopping eight stoppages per month to a mere two per month, a significant reduction in planned downtime was achieved. This is in line with the discovery from literature that claims that the implementation of Reliability Centred Maintenance results in reduction of downtime - see the graph in Fig 52 below.

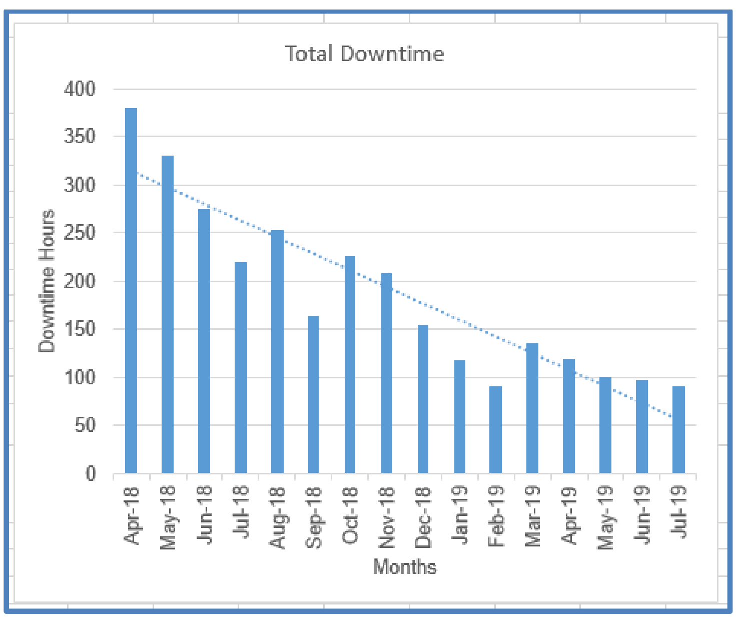



*Figure 52: Downtime Trending Graph*

### 6.1.6 Failure Frequency

Before the implementation of Reliability Centred Maintenance, the mineral sizer experienced 189 failures in April 2018. After the implementation of Reliability Centred Maintenance, massive reductions were realized, down to a record low of 86 failures in July 2019. This research therefore agrees with other scholars that Reliability Centred Maintenance helps reduce the number of failures in equipment - see the graph in Fig 53 below for reduction in Failure Frequency.

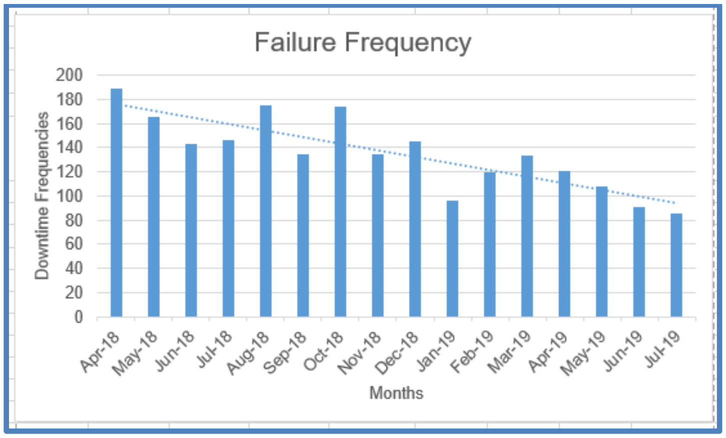



*Figure 53: Failure Frequency trending graph*

### 6.1.7 Maintenance Schedules

According to Moubray (1997), Reliability Centred Maintenance can reduce the amount of routine maintenance tasks by 40-70%. The financial benefit can be dramatic and reduction of headcount is evident (Smith, 1993) and (Moubray, 1997). This research agrees with this claim as can be seen in the graph below that shows the massive reduction in the number of schedules. This was mainly because maintenance became more focused on preventing functional failure, and all non-value adding tasks were abandoned – made possible by Reliability Centred Maintenance.

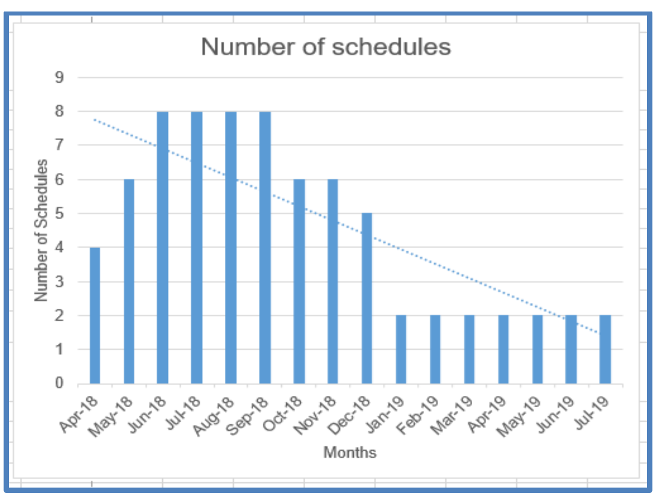


*Figure 54: Number of Schedules trending graph*

## 6.2 Conclusion

This chapter presented the results of the Reliability Centred Maintenance program implemented on the mineral sizer. The chapter details the improvements in the following measurements:

- Planned task durations vs unplanned task durations
- Overall Equipment Effectiveness (OEE)
- Availability
- Production Rate
- Quality Rate
- Mean Time to Failure
- Maintenance Costs
- Downtime
- Failure Frequency
- Maintenance Schedules

The results presented show that most of the measurements during the course of this research showed great improvement, agreeing with literature from other scholars as presented in the Chapter 3 literature review. One discovery that emerged from this research is that routine tasks were reduced but overall planned scheduled tasks increased. However, the increase did not in any way increase total planned downtime for the mineral sizer. This is because most of the tasks introduced were condition monitoring and predictive maintenance tasks, which can be carried out during the run time of the equipment. This approach improved machine uptime and increased reliability.

The next chapter presents the conclusion and recommendations.

This space is left empty intentionally.
Please go to the next page

# 7. Conclusion and Recommendations

## 7.1 Introduction

The previous chapter presented the results and findings of the research. This chapter will present the conclusions of the research as discussed in Chapter 3, the theoretical background and literature review, and will present results and the discussions of findings described in Chapter 6, of a Reliability Centred Maintenance program on a mineral sizer at Sierra Rutile Limited.

## 7.2 Summary of the results

The best strategy for maintaining physical assets has been debated for many decades. Substantial research has been done by academics trying to find optimal mix of maintenance strategies to maximize return on investment of assets. Different views have emerged over the years.

According to Hansson et al., (2003), organisations have spent considerable sums of money in trying to find the best methods for maintaining their assets. Some organisations have achieved better results, while some have struggled to get their assets run at optimal levels.

In this quest to achieve optimal use of physical assets, RCM was introduced by the Maintenance Steering Group (MSG-1) in 1968 when they developed maintenance requirements decision and analysis logic, of which Stan Nowlan and Harold Heap were part of during the construction of the Boeing 747. The FAA and industry used MSG-1 procedures to develop the initial minimum scheduled maintenance/inspection recommendations for the B-747-100 aircraft and its engines. In 1970, a task force which became known as MSG-2 updated the procedures from the learnings and experience gained from MSG-1 which became the new standard for new aircrafts and their engines. MSG-3, the document was refined and revised to be used by foreign airlines, European and US aircraft and engine manufacturers(Federal-Aviation-Administration, 2012). Since then, the concept has been reviewed, modified and refined by several RCM pioneers, including Moubray (1997) and Coetzee (2015) of South Africa.

However, several organisations have tried to replicate this concept, but according to Hansson et al (2003) many organisations have been faced by cumbersome and at times failed RCM introductions for several reasons (Hansson et al., 2003). However, there have been pockets of excellence in RCM introductions in industry and these have realised massive benefits.

This research therefore sought to explore the implementation of RCM on a different piece of equipment and in a different country to see if the same benefits would be achieved and below are the summary results achieved from the research.

- Overall Equipment Effectiveness increased by 128% from a mere 25% in April 2018 to 82% in July 2019.
- Availability of the sizer improved from 48% to 88% in the same period.
- An upward trend on production tonnage produced was seen, from 5041 tons produced in April 2018 to 9621 tons produced in July 2019.
- In April 2018 when the equipment was introduced, the MTTF on the equipment was 3.8 hours, meaning there was a failure after every 3.8 hours. After the introduction of RCM, the MTTF rose to an impressive 8.7 hours.
- When operations started, maintenance costs were a massive $1.88 per ton of ore produced, which was almost unsustainable. This number came down to $0.52 per ton of ore produced. At this cost the operation managed to surpass breakeven point.
- With improved availability, downtime reduced considerably. In April 2018, downtime totalled 379.85 hours (planned and unplanned) and was reduced to 91.8 hours in July 2019. It is important to note that, in reality, there was an increase in planned work being carried out without necessarily stopping the plant, because many planned failure identifying tasks were done when the plant was running, which reduced plant stoppages.
- This research also determined that the failure frequency of the equipment reduced drastically with the introduction of RCM. In the same period, the failure frequency reduced from 189 failures per month to 86 per month. This meant the reliability of the equipment improved.
- Finally, the number of preventive maintenance schedules carried out on the equipment reduced from eight to two in the same period. Because of this reduction, the equipment was stopped fewer times for maintenance. This came as a result of focused maintenance and taking away all non-value adding maintenance tasks.

## 7.3 Recommendations

From the experience obtained during the course of this research, the following recommendations are made:

- The study needs to be expanded to other types of equipment, because the results obtained could be just as relevant for other critical equipment that was not included in this research.
- Manufacturing and industrial companies should invest more into RCM programs, based on the positive results of this research.
- Many people are not familiar with RCM methodology, even though it has been in industry since the 1980s. As such, organisations must invest in training and developing their employees in the methodology if they are to benefit from successful implementation.
- Top management needs to buy in into the principles of RCM, and support it financially

## 7.4 Recommendations for further study

This research was done on one sizer and in a unique environment. This makes it very difficult to generalize these results to similar equipment operating in different environments, doing different operations. As such, the researcher recommends that further research be done on similar equipment working in different settings to see if similar results are obtained.

## 7.5 Conclusion

In the beginning of the research, the researcher outlined the research objectives that needed to be achieved at the end of the study. The objectives as outlined in Chapter 2 of the study were:

- To establish availability improvements obtained as a result of implementing an RCM program on the mineral sizer
- To determine OEE improvements on the mineral sizer after RCM implementation
- To determine the level of downtime reduction brought about by implementing an RCM program on the mineral sizer
- To establish if there is a relationship between implementing an RCM program and maintenance cost reduction
- To recommend improvement programs to optimize mineral sizer operations

The study has managed to fulfil the objectives as outlined below:

- After the analysis, a task package was developed that was used for maintenance on the sizer. As can be seen in the results, equipment availability improved from 48% in April

2018 to 88% at the end of July. Although the improvement didn't achieve the recommended availability target of 90%, a marked improvement was realized.

- The results of the study also show an increase in OEE from 25% in April 2018 to a high of 82% in July 2019.
- A marked decrease in downtime from 379.85 hours in April 2018 with an average of 246 hours per month before implementation, to 91.8 hours in July 2019 and an average of 107.56 hours per month after implementation
- A positive relationship between RCM implementation and costs was established. It has been established that if RCM is implemented, costs go down. It is evident in research that maintenance costs before implementation were on average $1.39/ton of ore produced and steadily reduced over the course of implementation to an all-time low of $0.67/ton of ore produced.
- From the analysis, maintenance programs were established and recommended for implementation. Most of them on the priority list have already been implemented and results have been shown in the results chapter.

This space is left empty intentionally.
Please go to the next page

# 8. Bibliography

Abdul Samat, H., Kamaruddin, S., & Abdul Azid, I. (2012). Integration of Overall Equipment Effectiveness (Oee) and Reliability Method for Measuring Machine Effectiveness. *The South African Journal of Industrial Engineering*, *23*(1). https://doi.org/10.7166/23-1-222

Adoghe, A. U., Awosope, C. O. A., & Daramola, S. A. (2012). Critical review of reliability centred maintenance ( RCM ) for asset management in electric power distribution. *International Journal of Engineering and Technology*, *2*(6), 1020–1026.

Ahuja, I. P. S., & Khamba, J. . (2008). Total productive maintenance: Literature review and directions. *International Journal of Quality and Reliability Management*, *25*(7), 709–756. https://doi.org/DOI 10.1108/02656710810890890

Almeida, F. (2017). Strenghts and Limitations Qualitative and Quantitative. *European Journal of Education Studies*, (September), 369–387. https://doi.org/10.5281/zenodo.887089

Alsalaet, J. (2016). *Vibration Analysis and Diagnostic Guide*. Retrieved from https://www.researchgate.net/publication/311420765_Vibration_Analysis_and_Diagnostic_Guide/download

Amit Kumar Jain. (2013). Influence of Modification of Design out Maintenance & Design Out Information System For Maintenance Cost Control & A Lucrative Business (With Case Study). *International Journal of Engineering Trends and Technology*, *4*(1).

Anderson, R. ., & Neri, L. (1990). *Reliability Centered Maintenance*. London-UK: Elsevier.

Arunraj, N. S., & Maiti, J. (2007). Risk-based maintenance: techniques and applications. *Journal of Hazardous Materials*, *143*, 633–661. https://doi.org/https://doi.org/10.1016/j.jhazmat.2006.06.069

Backlund, F., & Akersten, P. A. (2003). RCM introduction: Process and requirements management aspects. *Journal of Quality in Maintenance Engineering*, *9*(3), 250–264. https://doi.org/10.1108/13552510310493701

Bae, C., Koo, T., Son, Y., Park, K., Jung, J., Han, S., & Suh, M. (2009). A study on reliability centered maintenance planning of a standard electric motor unit subsystem using computational techniques. *Journal of Mechanical Science and Technology*, *23*(4), 1157–1168. https://doi.org/10.1007/s12206-009-0305-8

Bakri, H. A., Abdul Rahim, A. R., & Mohd Yusof, N. bin. (2014). Maintenance Management: Rationale of TPM as the Research Focus. *Applied Mechanics and Materials*, *670–671*(January 2017), 1575–1582. https://doi.org/10.4028/www.scientific.net/amm.670-671.1575

Bal, A., & Satoglu, S. I. (2014). *Maintenance Management of Production Systems with Sensors and RFID : A Case Maintenance Management of Production Systems with Sensors and RFID : A Case Study*. (June).

Bowler, D. ., Primrose, P. ., & Leonard, R. (1996). Economic evaluation of reliability-centred maintenance (RCM): an electricity transmission industry perspective. *IET Proceedings - Generation Transmission and Distribution*, 9–16. Retrieved from doi: 10.1049/ipgtd:19951600

Campbell, J. . (1995). *Uptime – Strategies for Excellence in Maintenance Management* (Portland, Ed.). Oregon, USA: Productivity Press.

Car, Z. (2014). *Implementation of the RCM Methodology on the Example of City Waterworks*. (June), 25–28. Retrieved from http://www.mfkv.kg.ac.rs/urbanoise/media/14_M33.07-Implementation_of_the_RCM_Methodology_on_the_Example_of_City_Waterwork.pdf

Carlo, F. De, & Arleo, M. A. (2013). *Maintenance cost optimization in condition based maintenance : a case study for critical facilities*. (May 2014).

Chalifoux, A. and Baird, J. (1999). *Reliability centered maintenance (RCM) guide: Operating a more effective maintenance program*. Retrieved from http://docshare01.docshare.tips/files/18499/184996320.pdf

Chauhan, N. D., & Pancholi, P. N. H. (2013). Guidelines to Understanding to estimate MTBF. *International Journal of Scientific Research & Development*, *1*(3), 493–495. Retrieved from https://www.researchgate.net/publication/255173402_Guidelines_to_Understanding_to_estimate_MTBF/link/0deec520073f624502000000/download

Chesworth, D., & Miet, H. (2018). *Industry 4 . 0 Techniques as a Maintenance Strategy ( A Review Paper ) Industry 4 . 0 Techniques as a Maintenance Strategy ( A Review Paper )*. (January), 0–8. https://doi.org/10.13140/RG.2.2.18116.32644

Coetzee. (2015). *RCM - ProAktiv*. Maintenance Publishers.

Coetzee, J. (1997). *Maintenance* (1st ed.). Johannesburg: Maintenance Publishers.

De Ron, A. J., & Rooda, J. E. (2006). OEE and equipment effectiveness: An evaluation. *International Journal of Production Research*, *44*(23), 4987–5003. https://doi.org/10.1080/00207540600573402

de Winter, J. C. F., & Dodou, D. (2017). *Human Subject Research for Engineers*. (April 2019). https://doi.org/10.1007/978-3-319-56964-2

Deshpande, V. ., & Modak, J. (2002). Application of RCM to a medium scale industry. *System Safety*, *77*(2), 31–43. https://doi.org/https://doi.org/10.1016/S0951-8320(02)00011-X

Design, C., Upperstage, O. F., Jacket, C., & Rocket, F. O. R. D. (2008). *Implementing Reliability - Centered Maintenance Analysis in Revised Preventive Maintenance Programme For The F-15*.

Efthymiou, K., Papakostas, N., Mourtzis, D., & Chryssolouris, G. (2012). On a predictive maintenance platform for production systems. *Procedia CIRP*, *3*(1), 221–226. https://doi.org/10.1016/j.procir.2012.07.039

F.S.Nowlan and H.F.Heap. (1978). *Reliability Centered Maintenance*. Calofonia: Dolby Access Press.

Faitakis, Y., Mackenzie, C., & Powley, G. J. (2004). Reducing maintenance cost through predictive fault detection. *CIM Bulletin*, *99*(1076), 63–66.

Fam, S., Yanto, H., Semarang, & Prastyo, D. (2018). *Lean manufacturing and overall equipment* *efficiency ( OEE ) in paper manufacturing and paper products industry*. Retrieved from https://www.researchgate.net/publication/327664585_Lean_manufacturing_and_overall_equipment_efficiency_OEE_in_paper_manufacturing_and_paper_products_industry

Federal-Aviation-Administration. (2012). *Advisory Circular*. Retrieved from https://www.faa.gov/documentlibrary/media/advisory_circular/ac 121-22c.pdf

Fore, S., & Msipha, A. (2010). Preventive Maintenance Using Reliability Centred Maintenance (Rcm): a Case Study of a Ferrochrome Manufacturing Company. *The South African Journal of Industrial Engineering*, *21*(1). Retrieved from https://www.bing.com/search?q=preventive+maintenance+using+reliability+centred+maintenance+%28rcm%29%3A+a+case+study+of+a+ferrochrome+manufacturing+company&form=EDGEAR&qs=PF&cvid=864767864e114392b1d40a78a05f03d0&cc=SL&setlang=en-US&PC=LCTS

Gibson, W., & Brown, A. (2011). Research Design. *Working with Qualitative Data*, (September), 47–64.

Gits, C. W. (1992). Design of maintenance. *International Journal of Production Economics*, *24*(1992), 217–226.

Griffi, Roth, A. ., & Seal, G. . (1991). *Competing in World-class manufacturing: America's 21st century challenge* (R. . Irwin, Ed.). Illinois: Homewood.

Hansson, J., Backlund, F., & Lycke, L. (2003). "Managing commitment: increasing the odds for successful implementation of TQM, TPM or RCM." *International Journal of Quality & Reliability Management*, *20*(9), 993–1008. Retrieved from https://doi.org/10.1108/02656710310500815

Holey, E. A., Feeley, J. L., Dixon, J., & Whittaker, V. J. (2007). *An exploration of the use of simple statistics to measure consensus and stability in Delphi studies*. *10*, 1–10. https://doi.org/10.1186/1471-2288-7-52

Hora, M. . (1987). The unglamourous game of managing Maintenance. *Business Horizon*, (May-June), 67–75.

IEC 60300-3-11. (2010). *International Standard* (Vol. 2003). Retrieved from https://www.sis.se/api/document/preview/562766/

Ireland, F., & Dale, B. . (2001). A study of total productive maintenance implementation. *Journal of Quality in Maintenance Engineering*, *7*(3), 183–191. Retrieved from http://www.emerald-library.com/ft

Jardine, A.K.S., Lin, D., & Banjevic, D. (2006). A Review on Machinery Diagnostics and Prognostics Implementing Condition-Based Maintenance. Mechanical Systems and Signal Processing. *Engineering*, *20*, 1483–1510.

Jardine, Andrew K.S., & Tsang, A. H. C. (2013). *Maintenance, Replacement and Reliability theory and Applications* (Second). Taylor & Francis Group.

Karanović, V. V., Jocanović, M. T., Wakiru, J. M., & Orošnjak, M. D. (2018). Benefits of lubricant oil analysis for maintenance decision support: A case study. *IOP Conference Series: Materials Science and Engineering*, *393*(1). https://doi.org/10.1088/1757-

899X/393/1/012013

Kaydos, W. (1999). *Operational performance measurement : increasing total productivity*. Boca Raton: (St. Lucie Press.

Kennerly. M. and Neely. A. (2003). “Measuring performance in a changing business environment.” *International Journal of Operation & Production Management*, *23*(2), 213–229.

Knights, P. . (1999, September). Analysing Breakdowns. *Mining Magazine*, 165–171.

Kobbacy, H., A., K., & Murthy, D. N. P. (2008). *Complex system maintenance Handbook*. London-UK: Springer London.

Krajewski, L. J., & Sheu, C. (2015). *Decision model for corrective maintenance management*. (April).

Kullawong, T., & Butdee, S. (2015). Integrating reliability-centered maintenance with cost optimization & application in plant of hard chrome plating. *International Journal of Industrial Engineering and Management*, *6*(2), 85–92.

Levitt, J. (2008). *Lean Maintenance*.

Lewis, M. . (2000). Remote-control monitoring cuts maintenance cost. *Mining Engineering*, *52*(8), 15–19.

Love, R. E. (2011). Reliability Centered Maintenance. In *Terror from the Sky: The Bombing of German Cities in World War II*. https://doi.org/10.1109/TR.1987.5222285

Masue, O. S., Swai, I. L., & Anasel, M. G. (2013). The qualitative-quantitative “disparities” in social science research: What does qualitative comparative analysis (QCA) brings in to bridge the gap? *Asian Social Science*, *9*(10), 211–221. https://doi.org/10.5539/ass.v9n10p211

Matteson, T. (1995). “The Air Transportation Industry: Birthplace of Reliability-Centered Maintenance,.” *Substation Reliability Centered Maintenance Conference*, 12. Newport Beach, CA.

McDermott, R. E., Mikulak, R. J., & Beauregard, M. . (2008). *The Basics of FMEA* (2nd ed.; CRC Press, Ed.). Taylor & Francis Group.

Mitchell, J. . (2002). *Physical Asset Management Handbook* (3rd ed.). Clarion Technical Publishers.

Mobley, R. K. (1943). *An Introduction to Predictive Maintenance* (Second).

Morello, B., Karray, H., & Zerhouni, N. (2019). *New Perspectives of Maintenance Systems : “ Towards S-Maintenance .”* (1), 223–236.

Moubray, J. (1997). *Reliability-Centered Mainteannce*. Butterworth Heinemann.

*Moving Back On the P-F Curve to Maximize Maintenance Effectiveness _ RCM Blitz Blog*. (n.d.).

Muller, A., Marquez, C., & Iung, B. (2008). On the concept of e-maintenance: Review and current research. *Journal of Reliability Engineering and System Safety*, *93*(6), 1165–1187.

Nabhan, M. B. (2010). Effective implementation of reliability centered maintenance. *AIP Conference Proceedings*, *1239*(August), 88–95. https://doi.org/10.1063/1.3459791

Nakajima, S. (1988). *Introduction to TPM: Total Productive Maintenance* (Cambridge, Ed.). Manchester: Productivity Press.

NAVAIR. (2005). *MANAGEMENT MANUAL RELIABILITY-CENTERED MAINTENANCE*.

Neely, A. (1999). "The performance measurement revolution: why now and what next?" *International Journal of Operations & Production Management*, *19*(2), 205–228.

Niu, G., Yang, B. S., & Pecht, M. (2010a). Development of an optimized condition-based maintenance system by data fusion and reliability-centered maintenance. *Reliability Engineering and System Safety*, *95*(7), 786–796. https://doi.org/10.1016/j.ress.2010.02.016

Niu, G., Yang, B. S., & Pecht, M. (2010b). Development of an optimized condition-based maintenance system by data fusion and reliability-centered maintenance. *Reliability Engineering and System Safety*, *95*(7), 786–796. https://doi.org/10.1016/j.ress.2010.02.016

Nowlan, F. ., & Heap, H. . (1978). Reliability-centered maintenance. Technical report AD/A066-579. *National Technical Information Service,*.

Nowlan, & Heap, F. (1979). Reliability Centered Maintenance. In *Defense Documentation Center*. Washington DC.

Nowlan, S., & Heap, H. (1978). *What is Reliability Centered Maintenance ?* Retrieved from http://www.mainsaver.com/pdf/Reliability_Centered_Maintenance_White_Paper.pdf

Okwuobi, S., Ishola, F., Ajayi, O., Salawu, E., Aworinde, A., Olatunji, O., & Akinlabi, S. (2018). A Reliability-Centered Maintenance Study for an Individual Section-Forming Machine. *Machines*, *6*(4), 50. https://doi.org/10.3390/machines6040050

OREDA Consortium. (1997). *OREDA Consortium - Reliability data handbook* (3rd ed.).

Paprocka, I. (2018). The model of maintenance planning and production scheduling for maximising robustness. *International Journal of Production Research*, *0*(0), 1–22. https://doi.org/10.1080/00207543.2018.1492752

Paraszczak, J., Komljenovic, D., & Kecojevic, V. (2010). Potential for Improvement of Reliability and Maintenance in Mining Operations Based on Nuclear Industry Know-How and Experience. *International Mining Forum 2006, New Technological Solutions in Underground Mining*, (May 2015), 143–152. https://doi.org/10.1201/noe0415401173.ch17

Pascu, C. ., & Paraschiv, D. (2016). Study about Improving the Quality Process Performance for a Steel Structures Components Assembly using FMEA Method. *Applied Mechanics & Materials*, *822*, 429–436.

Pierpoint, T. J. (2001). RCM - The Driver for T&D condition-based maintenance—Autility perspective. *2001 IEEE/PES Transmission and Distribution Conference and Exposition*, 957–959.

Pintelon, L, Puyvelde, N., & Nagarur Van, F. (1996). “Case study: RCM – yes, no or maybe?” *Journal of Quality in Maintenance Engineering*, *5*(3), 182–192. Retrieved from https://doi.org/10.1108/13552519910282638

Pintelon, Liliane, Parodi-Herz, A., Kobbacy, A. ., Khairy, N., & Prabhakar Murthy, D. (2008). *Maintenance: An Evolutionary Perspective*. https://doi.org/10.1007/978-1-84800-011-7

Rahman, M. S. (2016). The Advantages and Disadvantages of Using Qualitative and Quantitative Approaches and Methods in Language “Testing and Assessment” Research: A Literature Review. *Journal of Education and Learning*, *6*(1), 102. https://doi.org/10.5539/jel.v6n1p102

Ramlan, R., Ngadiman, Y., Omar, S. S., & Yassin, A. M. (2015). Quantification of machine performance through Overall Equipment Effectiveness. *2nd International Symposium on Technology Management and Emerging Technologies, ISTMET 2015 - Proceeding*, (August), 407–411. https://doi.org/10.1109/ISTMET.2015.7359068

Rausand, M. (1998). Reliability centered maintenance. *Reliability Engineering and System Safety*, *60*(5), 121–132. https://doi.org/pn:sO951-8320(97)00092-6

Reliability Analysis Center. (1993). *Failure Mode , Effects and Criticality Analysis*.

ReliabilityWeb.com. (2019). WHAT IS MAINTENANCE 4.0? Retrieved February 18, 2020, from The reliability Conference website: https://reliabilityweb.com/the-reliability-conference-2020?publisher_status=open

Riis, O., Luxhøj, J. & T., James, Thorsteinsson, & Uffe. (1997). A situational maintenance model. *International Journal of Quality & Reliability Management*, *14*(4), 349–366. Retrieved from 10.1108/02656719710170620.

Romera, R., Carretero, J., Maria, J., & Menor, P. (2006). *Optimal railway infrastructure maintenance and repair policies to manage risk under uncertainty with adaptive control*. (April).

Saad, G. H., & Siha, S. (2000). “Managing quality: critical links and a contingency model.” *International Journal of Operations & Production Management*, *20*(10), 1146–1164. Retrieved from https://doi.org/10.1108/01443570010343717

Sandtorv, H., & Rausand, M. (1991). Closing the gap loop between design reliability and operational reliability. *Maintenance*, *6*(1), 13–21.

Schwan, C. A. (1999). Introduction to Reliability Centered Maintenance. *Reliability Centered Maintenance for Substations, Transmission and Distribution Conference*, 3–12.

Shaomin, W., & Ming, J. Z. (2011). Linear and Nonlinear Preventive Maintenance Models. *Linear and Nonlinear Preventive Maintenance Models*, *59*(1), 3–100. https://doi.org/10.1007/978-0-85729-215-5_1

Sharma, K., Kurma, D., & Kurma, P. (2006). Manufacturing Excellence Through TPM Implementation - A Practical Analysis. *Industrial Management & Data Analysis*, *106*(23), 256–280.

Silverman, D. (2010). *Doing qualitative research: A practical handbook. Thousand Oaks, CA: Sage.*

Singh, R., Shah, D. B., Gohil, A. M., & Shah, M. H. (2013). Overall equipment effectiveness (OEE) calculation - Automation through hardware & software development. *Procedia Engineering*, *51*(December 2012), 579–584. https://doi.org/10.1016/j.proeng.2013.01.082

Siregar, I., Muchtar, M. A., Rahmat, R. F., Andayani, U., Nasution, T. H., & Sari, R. M. (2018). Method of calculation overall equipment effectiveness in fertilizer factory. *IOP Conference Series: Materials Science and Engineering*, *308*(1). https://doi.org/10.1088/1757-899X/308/1/012053

Smith, A. (1993). *Reliability Centered Maintenance* (First). McGraw-Hill.

Smith, A. . (1993). *Reliability Centered Maintenance*. New York: McGraw-Hill.

Smith, A., & Hinchcliffe, G. (2003). *RCM--Gateway to World Class Maintenance*. Butterworth-Heinemann: Butterworth-Heinemann.

Soiferman, L. K. (2010). Inductive and Deductive Research Approaches. *University of Manitoba*, (April), 1–23. Retrieved from https://eric.ed.gov/?id=ED542066

Swanson, L. (1997). An empirical study of the relationship between production technology and maintenance management. *International Journal of Production Economics*, *53*(3), 191–207.

Tarar, M. A. (2014). Study Reliability Centered Maintenance (RCM) of Rotating Equipment Through Predictive Maintenance. *International Journal of Industrial Engineering Research and Development*, *5*(1), 976–6979. https://doi.org/10.15242/IIE.E0314595

Thobiani, F. Al, Tran, V. T., & Tinga, T. (2017). An Approach to Fault Diagnosis of Rotating Machinery Using the Second-Order Statistical Features of Thermal Images and Simplified Fuzzy ARTMAP. *Engineering*, *6*(9), 132–155.

Tombari, H. (1983). Designing a Maintenance System. *Productio and Inventory Management*, *23*(4), 139–147.

Usrey, M. (2000). Reliability-Centered Maintenance : A Case Study EVALUATING A RELIABILITY CENTERED MAINTENANCE PROGRAM. *Engineering Management Journal*, *34*(5). https://doi.org/10.1080/10429247.2000.11415089

Vishnu, C. R., & Regikumar, V. (2016). Reliability Based Maintenance Strategy Selection in Process Plants: A Case Study. *Procedia Technology*, *25*(Raerest), 1080–1087. https://doi.org/10.1016/j.protcy.2016.08.211

Wilmeth, R. G., & Usrey, M. W. (2000). Reliability-centered maintenance: A case study. *EMJ - Engineering Management Journal*, *12*(4), 25–31. https://doi.org/10.1080/10429247.2000.11415089

Wilmeth, R. G., & Usrey, M. W. (2015). Reliability-centered maintenance: A case study. *EMJ - Engineering Management Journal*, *12*(4), 25–31. https://doi.org/10.1080/10429247.2000.11415089

Worledge, D. (1993). A breakthrough in reducing RCM costs. *Neclear News*, *36*.

Yamashina, H. (2000). “Challenge to world-class manufacturing.” *International Journal of Quality & Reliability Management*, *17*(2), 132–143. Retrieved from https://doi.org/10.1108/02656710010304546

Zajicek, J. (2018). *Analysis and some improvements of FMECA*. (March).

Zambon, I., Piergentili, A., Salvati, L., Monarca, D., Matyjas-Łysakowska, P., & Colantoni, A. (2018). Applied Research for a Safer Future: Exploring Recent Job Accidents in Agriculture, Italy (2012–2017). *Processes*, *6*(7), 87. https://doi.org/10.3390/pr6070087

Zio, E. (2009). Reliability engineering Old - problems and new challenges. *Reliability Engineering & System Safety*, *94*(2), 125–141. https://doi.org/https://doi.org/10.1016/j.ress.2008.06.002

# 9. Appendices

## 9.1 Letter of permission to contact research

No 10 Montego Lodge
Victoria Street
Little Falls
Johannesburg
Cell: +27 74 580 5040
Landline: +27 11 475 6785
Email: saul.machingauta@gmail.com

Shane Tilka
Chief Operating Officer
Sierra Rutile Limited
Moriba Town
Moyamba District
Sierra Leone

11 January 2019

Dear Shane

**REF: REQUEST FOR PERMISSION TO CARRY OUT RESEARCH AT SRL**

I am a registered student at the University of Pretoria, Department of Engineering - Center of Asset Integrity Management studying for a Masters in Mechanical Engineering supervised by Prof Jasper Coetzee.

The proposed topic of my research is ***The Implementation of a Reliability Centered Maintenance program on a Mineral Sizer to Increase availability and reduce costs***

The objectives of my research are:

- To establish availability improvements obtained as a result of implementing an RCM program on the mineral sizer
- To determine OEE improvements on the mineral sizer after RCM implementation
- To determine the level of downtime reduction brought about by implementing an RCM program on the mineral sizer
- To establish if there is a relationship between implementing an RCM program and maintenance cost reduction
- To recommend improvement programs to optimize mineral sizer operations

I do hereby seek request your permission to conduct the research within the organization. This research will involve soliciting opinions and participation of employees from predominantly Engineering, Maintenance and Engineering Departments

Should you require further information do not hesitate to contact me or my supervisor on the emails provided below:

- Saul.machingauta@gmail.com +27 74 580 5040
- Jasper.coetzee@up.ac.za +27 12 420 4746

Upon completion you will receive a copy of the research and you will receive consent from me to use my recommendations for process improvements in the business

Your assistance in this matter will be greatly appreciated

..............................

Yours sincerely

Saul Machingauta

| | |
|---|---|
| Permission Granted | ✓ |
| Permission rejected | |

..............................

Shane Tilka

Chief Operating Office

## 9.2 Sample Oil analysis Results for sizer gearbox

LubeAnalyst

| | | |
|---|---|---|
| **Sample Number** | : **4708958** | **LubeAnalyst Number : 01598027/ING01** |
| Site Name | : LANTI DRY MINING & MU01 EQUIPMENT | LANTI DRY MINING & MU01 EQUIPMENT |
| Equipment Ref ID | : 100-SZ-GB010A | 110 Wilkinson Road ,P.O Box 59 |
| Equipment Description | : 100-SZ-GB010A | Sierra Leone |
| Component Ref ID | : | |
| Component Description | : MINERAL SIZER DRIVE 1 GEARBOX | |
| Manuf./Model | : Mining Machinery Developments Ltd (MMD Group)/ GHPD1 LRN | |
| Lubricant Name | : Shell Omala 320 | |

**SHELL CONTACTS**

Focal point 1 : Mahir Bousselham — Focal point 1 phone : +233242514289

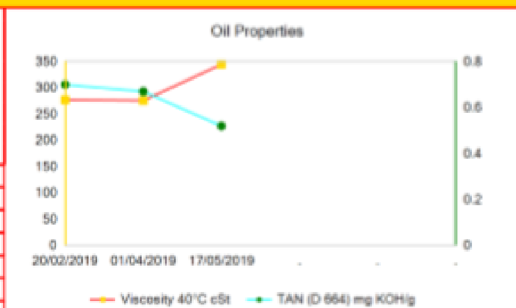
Shell Website : http://www.shell-lubeanalyst.shell.com/

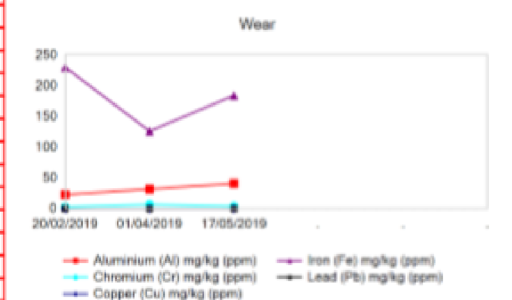
**COMMENTS**

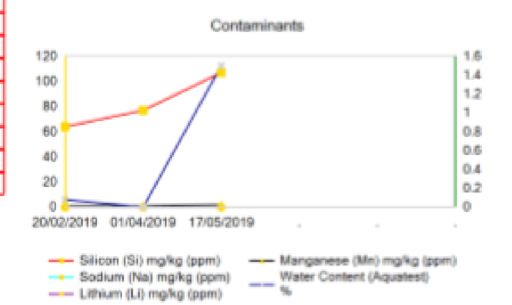
The oil contains an unsatisfactory amount of water with cloudy appearance and the silicon content (dust) is rather high. The aluminium content is slightly high. All the other results are within normal limits. Check and eliminate the source of the water contamination Check breathers and vents as possible causes of dirt ingress. We recommend that you send a further sample to the laboratory following the recommended actions.

**RESULTS**

| **Sample Number** | 4708883 | 4709011 | **4708958** |
|---|---|---|---|
| **Sample Condition** | Caution | Caution | **Caution** |
| **Sample Date** | 20/02/2019 | 01/04/2019 | **17/05/2019** |
| **Equipment Life** | - | - | - |
| **Lubricant Life** | 7 Months | - | - |
| **Top-up Volume** | - | - | - |
| **Oil Drain** | No | No | **No** |
| **Appearance (Special)** | | | |
| Appearance | Cloudy | Clear | **Cloudy** |
| **Viscosity 40°C** | | | |
| Viscosity 40°C cSt | 277.2 | 275.8 | **344.9** |
| **Acid Number ASTM D664** | | | |
| TAN (D 664) mg KOH/g | 0.70 | 0.67 | **0.52** |
| **Water Content (Aquatest)** | | | |
| Water Content (Aquatest) % | 0.08 | 0.00 | **1.50** |
| **Elemental Spectroscopy (Oils)** | | | |
| Iron (Fe) mg/kg (ppm) | 230 | 126 | **184** |
| Chromium (Cr) mg/kg (ppm) | 3 | 7 | **4** |
| Nickel (Ni) mg/kg (ppm) | 0 | 1 | **1** |
| Aluminium (Al) mg/kg (ppm) | 23 | 32 | **41** |
| Copper (Cu) mg/kg (ppm) | 0 | 0 | **0** |
| Lead (Pb) mg/kg (ppm) | 0 | 0 | **0** |
| Tin (Sn) mg/kg (ppm) | 0 | 0 | **0** |
| Titanium (Ti) mg/kg (ppm) | 3 | 5 | **6** |
| Vanadium (V) mg/kg (ppm) | 0 | 0 | **0** |
| Silicon (Si) mg/kg (ppm) | 64 | 77 | **107** |
| Sodium (Na) mg/kg (ppm) | 0 | 0 | **0** |
| Molybdenum (Mo) mg/kg (ppm) | 0 | 1 | **0** |
| Manganese (Mn) mg/kg (ppm) | 1 | 1 | **2** |
| Lithium (Li) mg/kg (ppm) | 0 | 0 | **0** |
| Boron (B) mg/kg (ppm) | 0 | 1 | **1** |
| Magnesium (Mg) mg/kg (ppm) | 0 | 2 | **1** |
| Calcium (Ca) mg/kg (ppm) | 5 | 159 | **7** |
| Barium (Ba) mg/kg (ppm) | 0 | 0 | **0** |
| Phosphorus (P) mg/kg (ppm) | 222 | 201 | **256** |
| Zinc (Zn) mg/kg (ppm) | 22 | 25 | **18** |



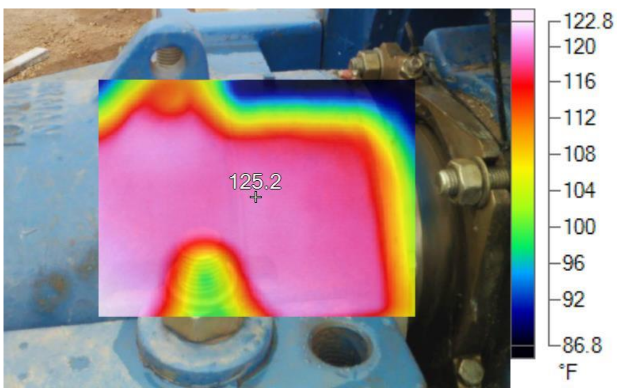



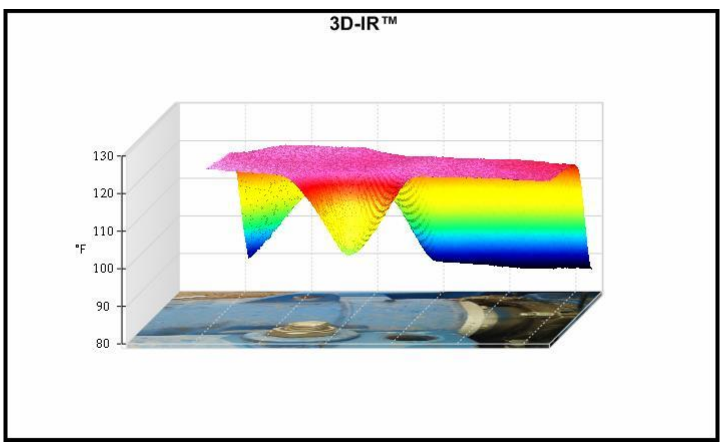



## 9.3 Sample Thermal imaging photos for Sizer Motors

Inspected By: Adjei Gyapong

| | | | |
|---|---|---|---|
| Inspection Date: | 2 May 2019 | Location | DM1 |
| Equipment | Mineral Sizer R/H motor | Equipment Name: | Mineral Sizer R/H motor |
| Ambient Air Temp: | | Wind Speed | |
| Load (%) | | Max Rated Load: | |
| Exception Temperature: | | Potential Problem | |
| Recommended Action | | Repair Priority: | |
| Emissivity: | 0.90 | Reflected Temperature: | 71.6 °F |
| Camera Manufacturer | Fluke Thermography | Camera: | Ti200-18020225 |



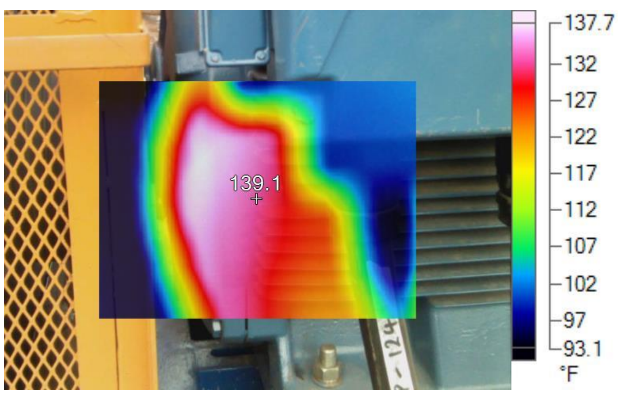



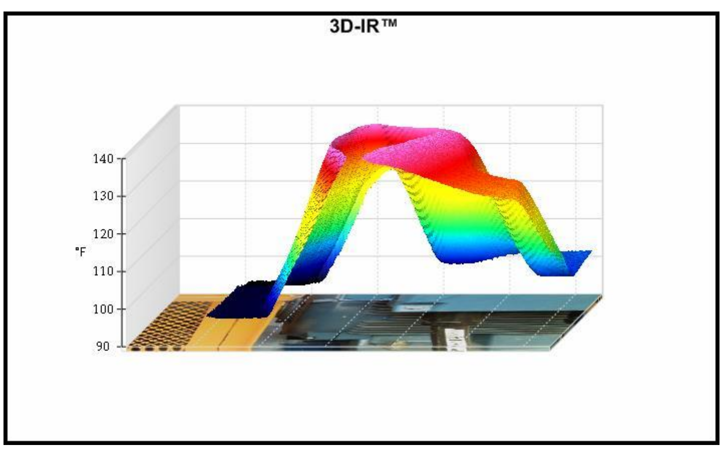

**Graph**

### Main Image Markers

| Name | Temperature | Emissivity | Background |
|---|---|---|---|
| Centerpoint | 125.2°F | 0.90 | 71.6°F |
| | | | |

| | | | |
|---|---|---|---|
| Inspection Date: | 2 May 2019 | Location | DM1 |
| Equipment | Mineral Sizer L/H motor | Equipment Name: | Mineral Sizer L/H motor |
| Ambient Air Temp: | | Wind Speed | |
| Load (%) | | Max Rated Load: | |
| Exception Temperature: | | Potential Problem | |
| Recommended Action | | Repair Priority: | |
| Emissivity: | 0.90 | Reflected Temperature: | 71.6 °F |
| Camera Manufacturer | Fluke Thermography | Camera: | Ti200-18020225 |
| | | | |

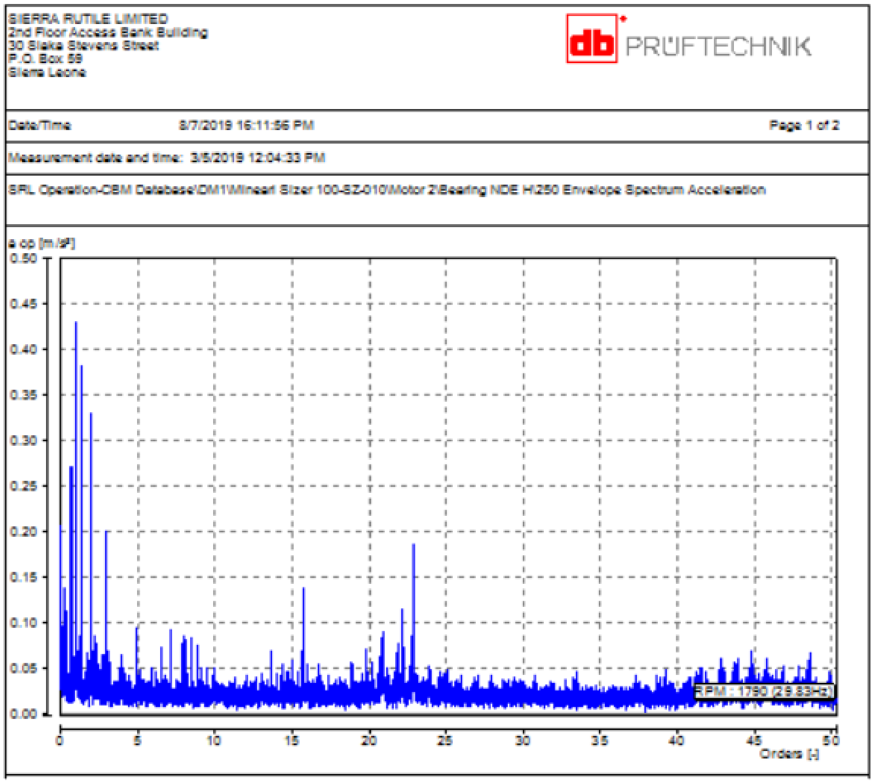


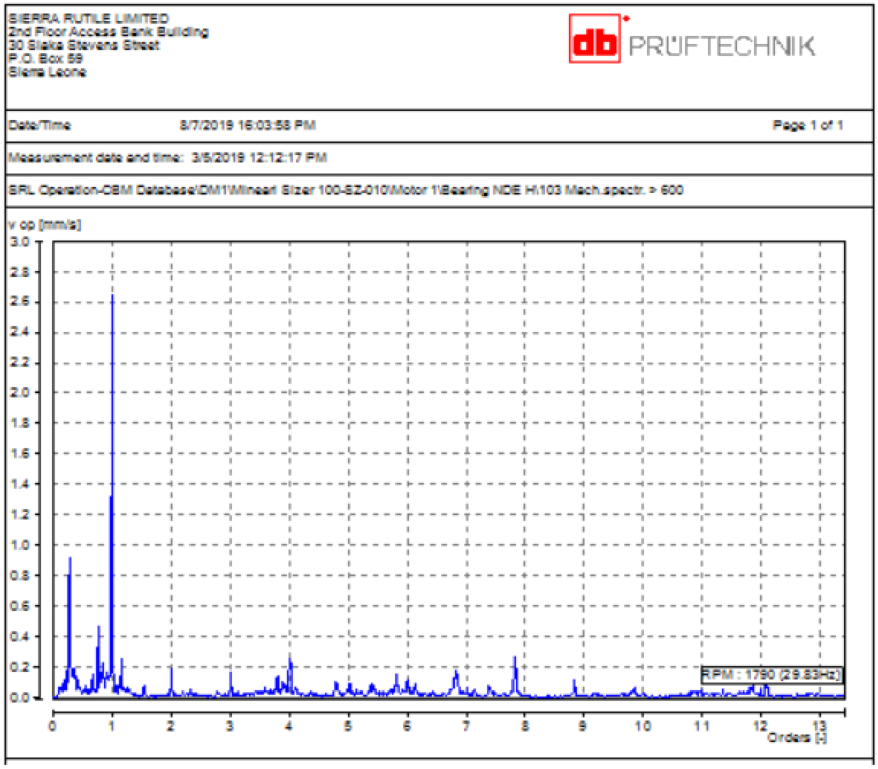



### Main Image Markers

| Name | Temperature | Emissivity | Background |
|---|---|---|---|
| Centerpoint | 139.1°F | 0.90 | 71.6°F |

## 9.4 Vibration analysis results for Sizer Gearbox and Motor






## 9.5 Table of Task Frequencies

| Task Frequency Table | |
|---|---|
| **Frequency Symbol (F)** | **Description** |
| S | Once per shift |
| D | Daily |
| W | Weekly |
| M | Monthly |
| Q | Quarterly |
| HY | Half yearly |
| Y | Yearly |
| B | Bi-Annually |
| HY | Hourly basis |
| 3Y | Three yearly |
| 6Y | Six yearly |

### 9.6 Table of Trade Descriptions

| Trade Description Table | |
|---|---|
| **Trade Symbol (T)** | **Trade Description** |
| B | Boiler Maker |
| CM | Condition Monitoring |
| EN | Engineer |
| E | Electrician |
| F | Fitter |
| O | Operator |
| PE | Production Engineer |
| R | Rigger |
| W | Welder |
| AS | Alignment Specialist |

### 9.7 Table of Scheduling Groups

| Scheduling Table | |
|---|---|
| **Scheduling Group Symbol (SG)** | **Scheduling Group Description** |
| CW | Condition Monitoring Weekly |
| CM | Condition Monitoring Monthly |
| OS | Operator Per Shift |
| OW | Operator Weekly |
| TD | Tradesmen daily |
| TW | Tradesmen Weekly |
| TM | Tradesmen Monthly |
| TQ | Tradesmen Quarterly |
| TY | Tradesmen Yearly |
| AQ | Alignment Specialist Quarterly |

## 9.8 Table of Production indicators

| Production Indicator Table | |
|---|---|
| **Production Indicator Symbol (P)** | **Production Indicator Description** |
| P | Work that can be done during production Run |
| O | Opportunistic - Minor work to be done during production stoppages |
| SD | Major work to be done during shutdowns |