Improving Asset Care Plans in Mining: Applying Developments from Aviation Maintenance

by

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December 2012

Declaration

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Date: 2012/09/03 . . . .

Abstract

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The aim of this thesis is to compare the aviation derived reliability metric known as the Maintenance Free Operating Period (MFOP), with the traditionally used, and commonly found, reliability metric Mean Time Between Failure (MTBF), which has over the years shown some innate disadvantages in the field of maintenance. It will be shown that this is mainly due to MTBF's inherent acceptance of failure and the unscheduled maintenance therewith directly connected. Moreover, MFOP is successfully applied to a mining specific case study, as to date, no other application of the MFOP concept to the mining sector is known.

An extensive literature study is presented, which covers concepts relevant to the overall study and which helps to contextualise the problem, revealing the major shortcomings of the commonly accepted MTBF metric. A methodology to analyse systems MFOP performance, making use of failure statistics to analyse both repairable and non-repairable systems, is presented. Validation makes use of a case study which applies the MFOP methodology to a system, specifically in the mining sector.

It was shown that MFOP could be applied to the data obtained from the mining sector, producing estimates which were accurate representations of reality. These findings provide an exciting basis on which to begin to facilitate a paradigm shift in the mind set of maintenance personnel, setting reliability targets and dealing with unscheduled maintenance stops.

KEYWORDS: Maintenance Free Operating Period, Mean Time Between Failure, Maintenance, Mining

Uittreksel

Verbetering van Batesorgplanne in Mynbou: Toepassing van Ontwikkelinge uit die Lugvaart Onderhoud

("Improving Asset Care Plans in Mining: Applying Developments from Aviation Maintenance")

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Desember 2012

Die doel van hierdie tesis is om die Onderhoudvrye Bedryf Tydperk (OBT), 'n betroubaarheidsmaatstaf afkomstig van die lugvaart industrie, te vergelyk met die Gemiddelde Tyd Tussen Falings (GTTF) maatstaf wat tradisioneel in algemene gebruik is, maar wat oor die jare inherente nadele met betrekking tot instandhouding geopenbaar het. Dit sal bewys word dat hierdie nadele hoofsaaklik ontstaan as gevolg van die GTTF se inherente aanvaarding van failure en die ongeskeduleerde instandhouding wat daarmee gepaard gaan. OBT word ook suksesvol aangewend in 'n mynwese-spesifieke gevallestudie, wat aaangegaan is aangesien geen ander sooortgelyke aanwending in die mynwese sektor tot datum bekend is nie. 'n Breedvoerige literatuurstudie word voorgelê wat relevante konsepte dek en die probleem binne konteks plaas, en daardeur die hoof tekortkominge van die algemeen aanvaarde GTTF metriek ontbloot.

'n Metodologie waardeur analise van die stelsel werkverrigting van die OBT uitgevoer kan word met gebruik van onderbrekings statistiek om herstelbaar sowel as onherstelbare stelsels te analiseer, word voorgestel. Geldigheid word getoets deur 'n gevallestudie wat die OBT metodologie aangewend word spesifiek vir 'n stelsel in die mynwese.

Dit is bewys dat OBT toegepas kan word op data afkomstig van die mynwese sector, en skattings lewer wat akkurate voorstellings is van die werklikheid. Hierdie bevindinge is opwindend, en dit dien as die basis vir 'n die aanwending van 'n paradigmaskuif in die benadering van instandhoudingspersoneel tot die daarstelling van teikens vir betroubaarheid en ook in hul hantering van ongeskeduleerde instandhoudingsophoud.

SLEUTELWOORDE: Onderhoudvrye Bedryf Tydperk, Gemiddelde Tyd Tussen Falings, Onderhoud, Mynbou

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To my family, especially my brother Karim, for their continued support for the project.

To my friends, especially Jan, Cedric and Thys, for their constant motivation and for keeping the office an entertaining place to be.

The Author
September, 2012

Dedications

This thesis is dedicated to my father, Hamid, may he forever rest in peace.

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Acronyms and Abbreviations

ACP	Asset Care Plan
AM	Asset Management
cdf	Cumulative Distribution Function
CM	Corrective Maintenance
DOM	Design-out Maintenance
EAM	Engineering Asset Management
FAA	Federal Aviation Authority
FFOP	Failure Free Operating Period
FMEA	Failure Mode and Effects Analysis
HPGR	High Pressure Grinding Roller
HPP	Homogenous Poisson Process
ISO	International Organisation for Standardisation
KPA	Key Performance Area
MFOP	Maintenance Free Operating Period
MFOPS	Maintenance Free Operating Period Survivability
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
MRP	Maintenance Recovery Periods
MSG	Maintenance Steering Group

NHPP	Non-homogenous Poisson Process
OED	Oxford English Dictionary
OEE	Overall Equipment Effectiveness
PAM	Physical Asset Management
PAS 55	Publicly Available Specification 55
pdf	Probability Density Function
PdM	Predictive Maintenance
PM	Preventive Maintenance
ROCOF	Rate of Occurrence of Failure
RCM	Reliability Centred Maintenance
TLOC	Total Life Operating Cost
TPM	Total Productive Maintenance

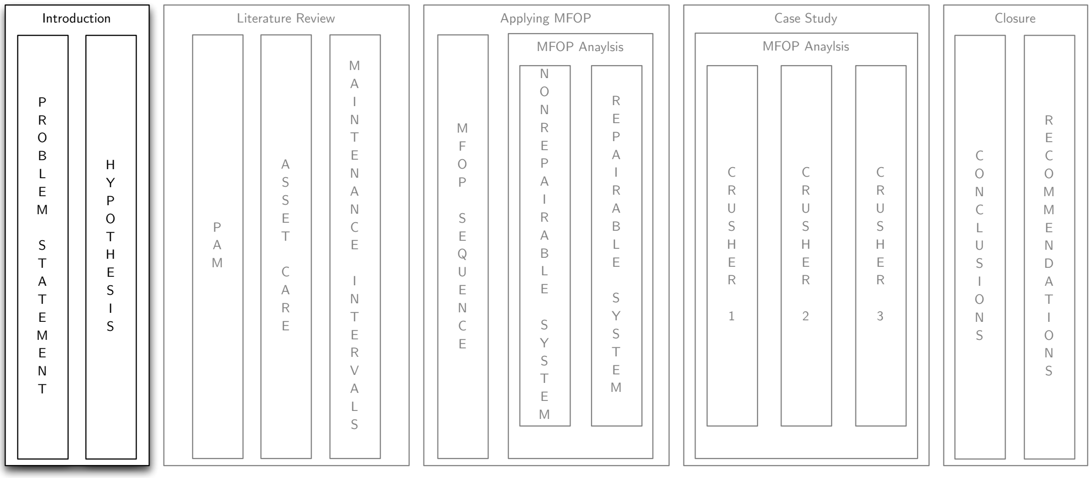
Notation

β	Shape parameter for the Weibull distribution
η	Scale parameter for the Weibull distribution
λ	Parameter required for the Power Law NHPP
δ	Parameter required for the Power Law NHPP
r	Total number of observed events
m	Total number of observed failures
x	Continuous time
X	Discrete event time measured in local time
T	Discrete event time measured global time
U_L	Laplace trend test
U_{LR}	Lewis–Robinson trend test
$f(x)$	Weibull Probability Density Function
$F(x)$	Weibull Cumulative Probability Function
$R(x)$	Weibull Reliability Function
$\mathrm{E}[\,]$	Expected value
$\rho_1(t)$	Power Law NHPP
$R(t_1 \to t_2)$	Reliability of a repairable system from t_1 to t_2
MTBF_{ρ_1}	Mean time between failure estimated by power law NHPP
MFOP	Maintenance Free Operating Period
MFOPS	Maintenance Free Operating Period Survivability
t_{mf}	Length of Maintenance Free Operating Period

$CR1$	Crusher 1
$CR2$	Crusher 2
$CR3$	Crusher 3

Chapter 1

Introduction



Chapter Aims:

This chapter aims to introduce the reader to the basic topics of this thesis and to provide an overview of the study conducted. Specifically it sets out the problem, which an attempt will be made to solve in the chapter that follows. An overview of the research design and methodology is also included in this chapter.

Chapter Outcomes:

⇒ Develop an understanding of the domain of the thesis.
⇒ Gain an overview of the research design and methodology employed.
⇒ Obtain a perspective of the problem that was presented.

1.1 Introduction

Physical Asset Management (PAM) is one of the fastest growing engineering disciplines in the world. With the recent conception and implementation of the the British Standard Publicly Available Specification 55 (PAS 55) (discussed in detail in Chapter 2), specifically dealing with PAM, the matter has become an area of much research and discussion for both industry and academia. This has been even further bolstered by the upcoming creation of an International Organisation for Standardisation (ISO) standard on PAM from the PAS 55 standard, to be known as ISO 55000, which at the time of writing this thesis is still under development. Within PAM and PAS 55 there are certain primary requirements for the optimisation of asset management activities, these are: acquire, utilise, maintain and renew.

The scope of the research with which the PAS 55 realm concerns itself is the "maintain" asset management activity. Maintenance engineering only truly began to be taken seriously by the majority of industry, in the early 1980s with the formulation and introduction of maintenance management theories such as, Total Productive Maintenance (TPM) and Reliability Centred Maintenance (RCM).

As with most industries, in maintenance, there is a drive for constant improvement of the status quo. Mobley (2002) points out that maintenance is one of the driving factors behind reliability and efficient operation. However, many industries still knowingly perform ineffective maintenance action. Due to this fact there is a constant push, especially in the engineering discipline, to optimise methodologies and practices. Heng *et al.* (2009) state that plants in the United States spent more than US $600 billion (R5 trillion) to maintain their critical plant systems in 1981 and this figure has doubled in the last 20 years. Thus maintenance today is not a multi-billion dollar industry, but actually a trillion dollar industry.

This is a massive industry, not only in terms of expenditure, but also maintenance activities, and therefore there is a need for optimised maintenance activities in order to gain maximum benefit for the operator at the lowest cost. Old concepts therefore need to be challenged with new thinking, in order to best perform this task and to continue to improve maintenance, and thereby the greater scope of PAM.

A number of key themes in this thesis are introduced in the next sections, thereafter only the problem statement is outlined.

1.2 Physical Asset Management

The formalisation of Physical Asset Management (PAM–or sometimes also known as Engineering Asset Management (EAM)) has in recent years come into the spotlight, increasingly being seen as providing the paradigm shift needed to bridge organisational gaps between higher and lower level management, in the field that used to be simply known as “maintenance”. It has been noted that in order to have a lasting and profound effect on the field of Asset Management (AM) requires an interdisciplinary approach in order to achieve the suitable mix of skills that are essential to solving complex issues of AM. AM (expanded upon in Chapter 2) has been defined by Hastings (2010) as the set of activities associated with the identification of which assets are needed, identification of funding requirements, actually acquiring assets, providing logistics and maintenance support and disposing of assets. The above mentioned activities are performed in order to effectively and efficiently meet the desired objective. The Asset Management council of Australia has provided another definition of PAM: “The life cycle management of physical assets to achieve the stated outputs of the enterprise”. From both these definitions it is important to note the holistic approach (also alluded to by Amadi-Echendu *et al.* (2010)) that PAM takes. Here the entire life-cycle of activities is considered and taken into account. A mixture of applying technical and financial judgement, together with management’s decision making, is used to decide what assets are needed by the organisation in order to meet the company’s goals.

Within the context of an asset intensive organisation, PAM attempts to address what Hastings (2010) identifies, as the “grey area” between senior management and maintenance management. Through the cross-functional alignment of these of an organisation-wide asset management strategy can be obtained. In the greater scheme of things, PAM deals with the productive use of assets at the disposal of the organisation, in order to provide value to the entire organisation, this therefore necessitates the broad-based view PAM has taken.

In order to help with the improvement of PAM performance and provide benchmarking capability, a number of Key Performance Areas (KPA) have been identified in literature, these are set out in detail in Chapter 2.

1.3 Publicly Available Specification 55

Stemming from the increased interest and need for a formalised AM arrangement, and the previously mentioned "grey area" between the senior management and lower level maintenance management, (led by the Institute for Asset Management), a standard for AM has been created, and published by the British Standards Institution. This standard is known as the Publicly Available Specification 55 (PAS 55). Work on what would eventually become the PAS 55 standard was first conducted in 1995, when the UMS Group, and a number of its clients, started creating an Asset Management Model. This was later formalised into the the PAS 55 standard on AM in 2004, and in 2008 the standard was given a substantial revision with input from over 50 organisations from 15 industry sectors.

The PAS 55 standard is split into two parts, the first (PAS 55-1) called "Specification for the optimised management of physical assets", the second (PAS 55-2) called "Guidelines for the application of PAS 55-1". The British Standards Institution (2008) states that PAS 55 is applicable to all sizes of organisations, from small or medium sized companies through to multinational organisations, and is applicable to any organisation that wishes to:

- Implement, maintain and improve an asset management system;
- Assure itself of compliance with associated asset management policy and strategy;
- Demonstrate such compliance to others.

With the wide spread acknowledgement of the PAS 55 standard within industry, the standard is now being formalised into a International Organisation for Standardisation (ISO) standard and will be known as ISO 55000 once published. PAS 55 is elaborated on in further detail in Chapter 2.

1.4 Maintenance

The term maintenance has a number of different meanings and definitions, AMCP (1975) defines maintenance as "all actions appropriate for retaining an item/part/equipment in, or restoring it to, a given condition". All in all the act of maintenance can be summed up to be a *cause to continue* an operation. Pintelon and Gelders (1992) give as the objective of maintenance: to maximise equipment availability in an operating condition permitting the desired output quantity and quality. Maintenance can be a significant factor within an organisation's profitability. According to Ben-Daya *et al.* (2009), in a manufacturing organisation maintenance can consume up to 10 % of the company's revenue. Maintenance used to be a completely separate entity within an organisation and was only called upon when it was needed. In recent years there has been a common acceptance that there is a lot more to maintenance than that. Waeyenbergh and Pintelon (2002) point to the fact that maintenance contributes more than ever to the achievement of total business objectives.

There are a number of different types of maintenance activities, (discussed in Chapter 2), which can be grouped under the greater term of asset care. Asset care or an Asset Care Plan (ACP) is the term coined to describe the mix of different maintenance types, it allows an organisation to plan, repair and replace its assets, in order to achieve the organisation's greater operational strategic goals. Moubray (2001) put forward a number of maxims on maintenance management, one maxim states that maintenance not only affects plant availability and cost, but also all aspects of business effectiveness such as safety, environment, energy efficiency and quality. This again shows how maintenance has become an intrinsic part of organisation success or failure, and can no longer be overlooked.

1.5 Maintenance Management Methodologies

In the 1970s, maintenance began to be taken ever more seriously and old phases such as, "fix it when it breaks" or "I operate–you fix", appeared to be finally cast aside and maintenance management was formalised. One of the first maintenance management methodologies was Reliability Centred Maintenance (RCM). This was originally designed for the aircraft industry, it was formed at a time when maintenance was beginning to be accepted as a profit contributor.

RCM can be defined as establishing minimum safe levels of maintenance, thereby changing operating procedures and strategies and maintenance plans. RCM is a highly structured process that in turn provides advantages in terms of traceability in that it rationalises the maintenance process, thereby yielding plant improvement. RCM uses a number of other concepts to improve maintenance performance, these include: a system-wide level, instead of component-based level, it uses a top down approach and function preservation, and consequence driven. RCM has been criticised at times for being too complex and cumbersome due to its extremely structured process. It also demands the extensive use of data in order to bear appropriate results. Even though the RCM methodology has been very successful by solely focusing on reliability, it does not, however, completely accept that maintenance is also an economic problem. RCM is further discussed in detail in Chapter 2.

Another major and successful maintenance methodology is Total Productive Maintenance (TPM). TPM was formalised in the late 1970s, early 1980s. TPM attempts to bridge the traditional gap between the operators and the maintenance department. Operators used to only operate the machine and not take any other responsibility, and the maintenance department was always solely responsible for the maintenance of machines. This created friction between these two groups within the organisation, thus degrading performance. This approach therefore creates a relationship between all functional departments within the organisation, especially the production and maintenance departments, which have traditionally stood apart. Under the TPM methodology, operators perform so called “autonomous” maintenance, thereby putting more responsibility into operators’ hands for individual machines. Further details of the TPM methodology are provided in Chapter 2. TPM provides a number of unique advantages, by increasing productivity and quality, providing cost reductions and increasing safety, it also attracts the involvement of lower level operators.

1.6 Maintenance Interval Metrics

A maintenance interval metric, also called a reliability metric, can be broadly defined as a unit of measurement displaying something about the reliability of the system in question. A number of different maintenance interval metrics are available for use in different situations. One of the most common maintenance interval metrics, used in industry today, is called Mean Time Between Failure (MTBF). MTBF can be simply defined as the mean length of time between consecutive failures. The MTBF can be calculated as a historic value, usually done in industry, on past failure data. It can also be calculated as a future or predicted value, by making use of failure statistics.

Other maintenance interval metrics have been defined, one such metric stemming from the aviation sector is called Maintenance Free Operating Period

(MFOP), and is meant to be a replacement of the MTBF metric. MFOP can be simply defined as a period of operation when a said system needs to be able to carry out of its allocated duties, without requiring any maintenance action. This way of thinking and underlying maintenance philosophy could greatly enhance operational effectiveness, as equipment would be available when needed, and maintenance downtimes can be better aligned around the equipment's operator. It also reduces the need for unscheduled maintenance or reactive maintenance that is usually far more expensive than planned or scheduled maintenance. Section 2.6 in Chapter 2 outlines maintenance interval metrics in additional detail.

1.7 Terminology

A number of terms are set out in this section that are used later in the study.

Probability

Probability is defined as the expectation that an event will occur.

Density Functions

Defined as the Probability Density Function (pdf), denoted by $f(x)$, this function indicates the failure distribution over the entire time range, the larger the value of $f(x)$, the more failures occur in a small interval around x. From the pdf the Cumulative Distribution Function (cdf) can be derived, the cdf, denoted by $F(x)$, is the probability of failure, and is the integral of $f(x)$. Equation 1.1 shows $F(x)$.

$$F(x) = \int_{-\infty}^{x} f(x)\mathrm{d}x \tag{1.1}$$

The reliability function, denoted $R(x)$, also called the survival function, is the probability of success, $R(x)$ is the complement of $F(x)$, and is shown in Equation 1.2.

$$R(x) = 1 - F(x) = \int_{x}^{\infty} f(x)\mathrm{d}x \tag{1.2}$$

Item Distinction

It is also necessary to distinguish between different types of items within an asset system, these are split into four distinct levels:

- *Part:* this is the lowest level of the system at which equipment can be disassembled without damaging the item.
- *Component:* this constitutes a grouping of parts into a package, this collection of parts will perform at least one function on their own.
- *System:* a logical grouping of components, the system will perform a series of key functions that are required of the plant.
- *Plant:* the logical grouping of systems, these function together in order to provide output as a whole.

System Distinction

Two types of systems are defined in this study:

1. *Non-Repairable:* Is a system that is discarded once it fails.
2. *Repairable:* Is a system that can be reinstated again to perform all of its functions, rather than a complete replacement of the system.

1.8 Problem Statement

Physical Asset Management (PAM) has become an increasingly important area of research and discussion within industry and academia. The British Standards Institution (2008) PAS 55 states that PAM constitutes those systematic and coordinated practices that support an organisation, to optimally and sustainably manage their asset systems over their entire life cycle. Due to the interdisciplinary nature of PAM, PAS 55 emphasises an integrated and holistic view of PAM, in order to come to terms with its complexity. A detailed overview of PAM and PAS 55 is given in Chapter 2, and the overall high level research influence is given in Figure 1.1 .

In order to help with the assessment of this complexity and the overarching nature of the field, seventeen Key Performance Area (KPA) have been defined in literature. These shine a light on the current status of an organisation's AM performance and AM maturity. One of the KPAs defined is called an Asset Care Plan (ACP). ACP is the high level term coined to describe the mix of tactical and non-tactical maintenance activities performed within a maintenance strategy. Here tactical maintenance is the group of Preventive Maintenance (PM) activities, and non-tactical is the group of Corrective Maintenance (CM) activities, PM being favoured among maintenance specialists. Maintenance management strategies such as RCM and TPM also fall under ACPs and can even be said to operate on the same level as an ACP.

In order to schedule and specify maintenance activities, but also to analyse historical failure data on equipment, statistical maintenance interval metrics are defined and used. The most notable maintenance interval used today is Mean Time Between Failure (MTBF) or Mean Time To Failure (MTTF), depending on whether the system is repairable or non-repairable, respectfully. The use of MTBF to predict and specify failures goes back nearly half a decade and it is used extensively in industry.

The aviation industry is widely considered to be at the forefront of maintenance methods. In recent years, a study commissioned by the Royal Air Force found a number of underlying and fundamental problems with the use of the maintenance interval metric MTBF, specifically for aircraft. Long *et al.* (2009) highlight the fundamental problem with MTBF. The author states that the use of MTBF in predicting failure, already accepts that failure cannot be accurately forecast or avoided. It assumes random failures and this assumption has negative knock-on effects, as it creates the need for unscheduled maintenance activities to be performed during normal operating hours. Other problems have been highlighted by Knowles (1995), Appleton (1996), Hockley and Appleton (1997) and Dinesh Kumar *et al.* (1999), for example that it is almost impossible to predict MTBF if the failure distribution does not follow an exponential one. The exponential distribution is used within the prediction of MTBF not for scientific reasons, but mainly because of its mathematical simplicity. In a very clear assessment from Trindade and Nathan (2006) state that there is a need for better reliability metrics that account for trends in the failure data.

The above stated problems with MTBF have resulted in the Royal Air Force defining a new maintenance interval that addresses the elementary problems that arise when using MTBF. The interval or reliability metric that has been defined is called MFOP, Appleton (1996). MFOP, which is elaborated on in Chapter 2, is a period of operation where no unscheduled maintenance activities are allowed, thereby replacing unscheduled maintenance activities with scheduled ones, essentially making it a warranty period. It exploits systems that are fault-tolerant and that have redundancies.

There exists a problem, specifically within asset intensive industries, in the application and use of MTBF for the scheduling of maintenance activities. Characteristically the mining industry needs machines and equipment to work continuously, and any unscheduled downtimes or interruptions during production time, create massive losses in revenue and hamper the quality of the final product. It would therefore be advantageous to use MFOP as a reliability metric and give machines or equipment a set MFOP, within a predefined confidence interval. This would potentially allow for better production scheduling, better downtime planning, could reduce the logistic footprint and yield a steadier throughput within a plant or system.

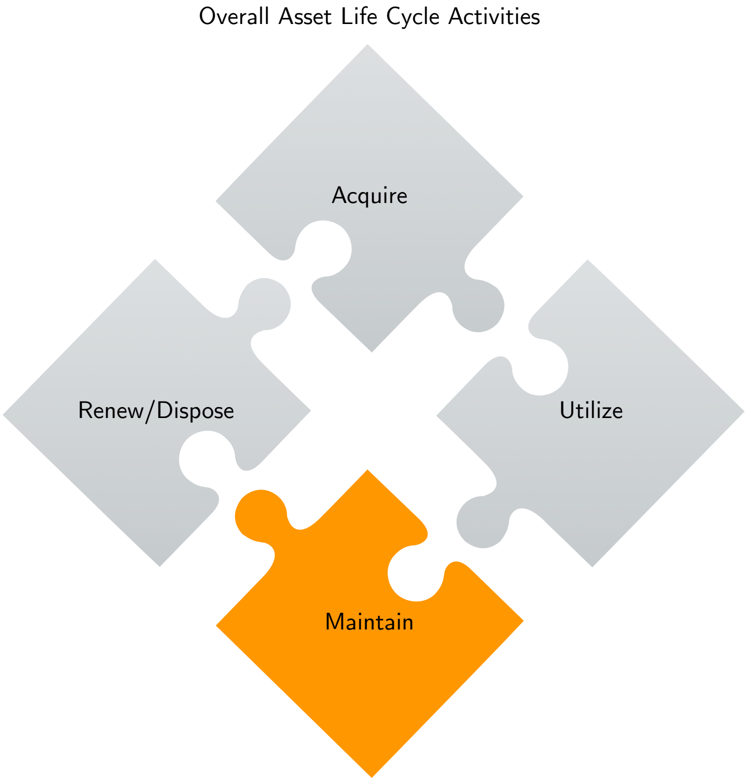


Figure 1.1: Asset life cycle activities, highlighting overall area of research.

1.9 Hypothesis

Leading on from the problem statement in Section 1.8, the central research question can be developed. The central research question is defined below:

> *Is the use of Maintenance Free Operating Periods a more appropriate reliability metric for the assessment of physical assets in the mining sector?*

From the central research question the null hypothesis can be derived, it is defined in Table 1.1:

Table 1.1: The Null Hypothesis (H_0)

H_0:	*The use of Maintenance Free Operating Periods is not a more appropriate reliability metric for the assessment of physical assets in the mining sector.*

1.10 Research Design and Methodology

This section provides an overview of the specific research design methodology used in this thesis.

1.10.1 Research Design

Mouton (2001) and Creswell (2009) state that there are three classifications of research design: *qualitative, quantative* and *mixed methods*. However, the author makes the point that studies cannot just be easily grouped into one of these categories, instead, studies can be better described as leading or tending to be more qualitative or quantitative.

The research conducted in this study can be clearly described as tending to the quantitative side. Creswell (2008) defines quantitative research as a means for testing objective theories, by examining the relationship amount through variables. Here the theory being tested is MFOP, the variables analysed within the theory will come from the environment in which the testing takes place, in this case the mining industry.

Table 1.2: Exploratory research design. Adapted from Creswell (2009).

Characteristic	Technique
Research design:	Quantitative Approach.
Philosophical world view:	Post-positivist knowledge claims.
Strategy of inquiry:	Experimental research including a case study.
Research methods:	Statistical based analysis, performance data and instrument based questions.
Practices of research:	Tests theories or explanations, identifies variables to study, observes and measures information numerically and makes use of statistical procedures.

In terms of the philosophical aspects of the research design Slife and Williams (1995) state that these remain hidden within the research, however, as they do influence the research, the author states that they should be identified. Creswell (2009) makes a similar point, and defines four philosophical world views or scientific methods called, post-positivism, constructivism, advocacy and pragmatism. From the four world views mentioned, post-positivism can be identified as the philosophy best describing the scientific research conducted in this study. Post-positivism is illustrated by Creswell (2009) as being comprised of the following elements: determination, reductionism, empirical observation and theory verification. Research done by post-positivists begins with a theory, then collects data which supports or refutes the theory, and then makes the necessary changes before more experiments are done. Table 1.2 gives an overview of the exploratory research design and a schematic diagram of the research design is shown in Figure 1.2.

The research design will therefore use a post-positive worldview, which will be validated using a quantitative experimental strategy model that will be elaborated on in section 1.10.3.

1.10.2 Research Objectives

The research objectives are to master the relevant literature, in order to gain a detailed understanding of maintenance, reliability metrics and how the solution to the above stated problem can benefit the PAM fraternity. Ultimately, the research will test the school of thought of MTBF against that of MFOP. A

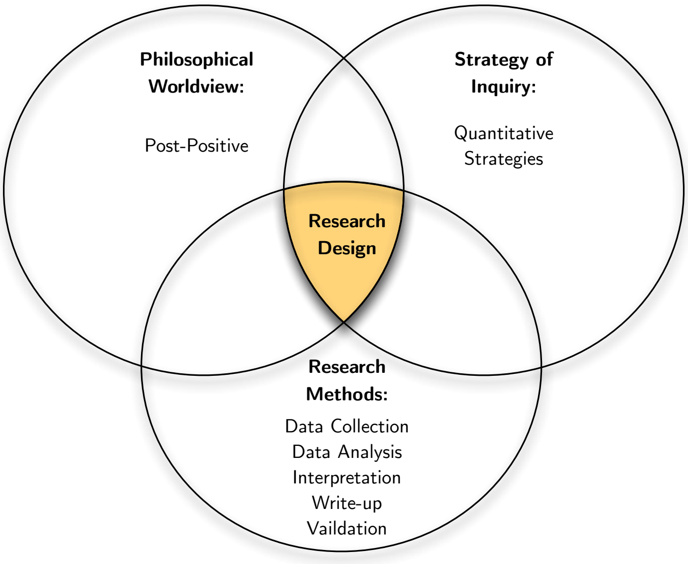


Figure 1.2: Schematic representation of the research design interactions.

methodology is to be set out for the calculation of MFOP lengths, thereby modelling a chosen system. This methodology is then applied in an industry case study, here the research can be validated and the null hypothesis can be either rejected or accepted.

1.10.3 Research Methodology

The research methodology will be conducted in order to fill the research objectives and ultimately answer the problem set out in Section 1.8. The problem statement is set out in this chapter and will be used to guide the research towards a proposed solution. An exhaustive and in-depth literature review is conducted thereafter and attempts to contextualise the problem, thereby providing perspective and an outlook to the proposed solution. Chapter 3 will present the proposed solution and the methodology behind it, thereby building towards the application thereof. As alluded to, Chapter 4 will apply the proposed methodology of Chapter 3 onto a real life Case Study conducted on site. Here, results are analysed (mainly using the software packages, Microsoft Excel and Matlab), presented and then discussed. In the final chapter of this document, the conclusions and secondary validation are expounded, thereby bringing to a close this thesis.

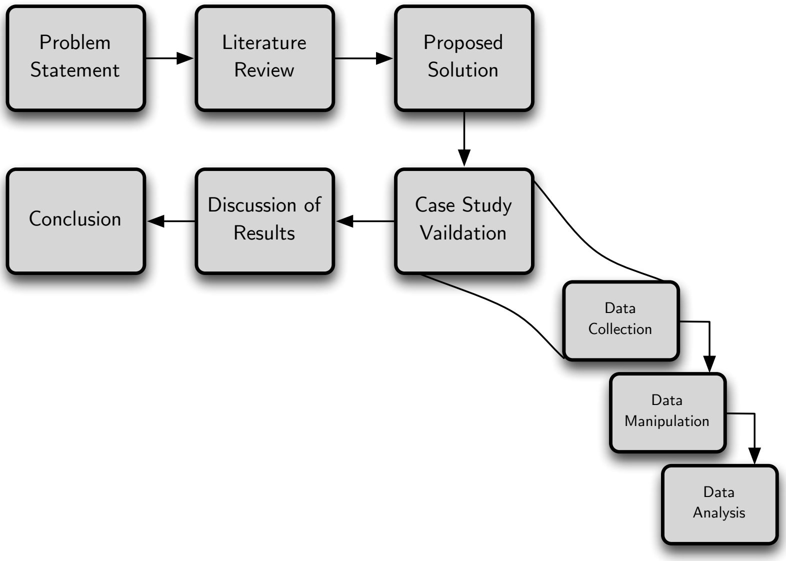


Figure 1.3: Research methodology and flow.

1.11 Thesis Outline

It can be seen from this chapter that the fields of PAM and maintenance are cross-functional and increasingly complex. As economies grow, and therewith consumption is increased, maintenance demands will naturally increase in tandem. It therefore needs constant new research and discussion in order to affect and gain the improvement that ultimately drives the profit of the organisation or institution. This thesis will attempt to follow the research objectives outlined in Section 1.10.2.

The remainder of this thesis is constructed as follows. Chapter 2 provides a literature study and contextualises the problem, it introduces the fundamentals of PAM and PAS 55, and thereafter the topic of asset care, along with maintenance. The current state of maintenance interval metrics used in mining, is shown, after which developments from aviation maintenance are contrasted. Finally, overviews of both TPM and RCM are given, together with MFOPs possible application within these.

Chapter 3 presents the application methodology that is later used within the specific case study presented in this document. The chapter outlines the framework as well as the study design, providing failure statistics, in order to finally calculate MFOP lengths for either a non-repairable or repairable system.

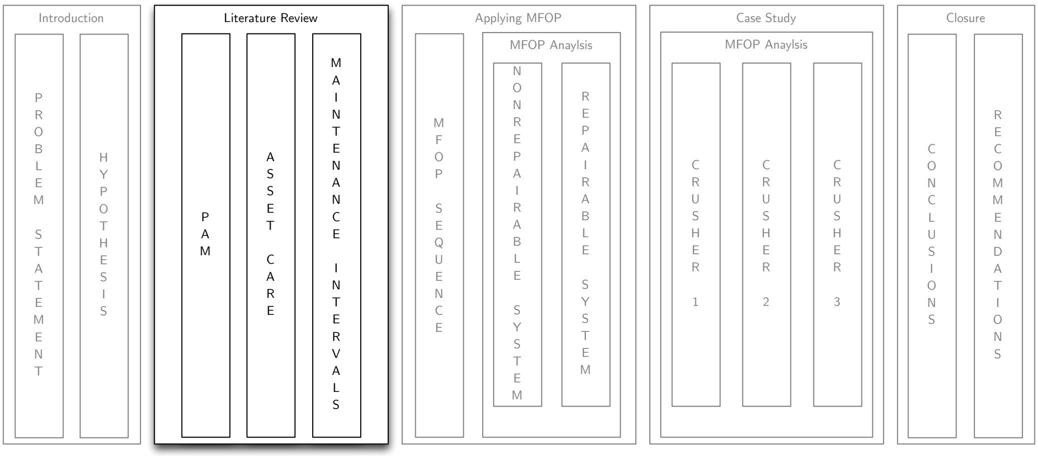
After this the application methodology is set out in Chapter 3. Chapter

4 applies the methodology on a real life Case Study, conducted at a mine in South Africa. Results are presented and reviewed, in order to validate the research. The practical value of the research in industry is also obtained from a number of external sources.

Chapter 5 sums up and reviews the research that was conducted, providing the limitations of the study. Final conclusions are made and linked back to the central research question and hypothesis. Lastly, an outlook and recommendations for future research are given.

Chapter 2

Literature Review and Contextualisation of Problem



Chapter Aims:

The literature review aims to introduce the reader to the relevant literature, in order to contextualise the problem set out in Chapter 1. Fundamental concepts are introduced that provide the reader with the correct background, in order to continue with the remainder of the thesis.

Chapter Outcomes:

⇒ Understand the domain and holistic view of Physical Asset Management.
⇒ Understand maintenance and the relevant subsegments.
⇒ Gain an overview of both MTBF and MFOP.

2.1 Introduction

This chapter introduces relevant literature, and attempts to contextualise the problem described in Chapter 1. PAM, the umbrella under which this research falls, is looked at first, Asset Management (AM) and an overview of the holistic approach to AM is then described. After gaining an overview of AM, the PAS 55 standard is briefly discussed in the following subsection. Due to the fact that strategy plays an important role in maintenance management, it is examined in detail in Section 2.4, with a section on asset management strategy. After this, ACPs are reviewed and a number of relevant subsections follow. Maintenance interval metrics play a central role in this study and are elaborated on after ACPs, together with relevant items regarding maintenance intervals. Thereafter, two important maintenance management philosophies are discussed, in order to place the research in context and to show its wider application.

2.2 Physical Asset Management

To begin to understand the term AM in the context of engineering, an engineering specific definition is provided by Davis (2007):

> *A continuous process-improvement strategy for improving the availability, safety, reliability, and longevity of plant assets, i.e., systems, facilities, equipment and processes.*

However, in order to gain an understanding of the complete and more general application of the term AM, it would be appropriate to compare the above definition to the definitions of the word pair, given by the Oxford English Dictionary (OED), first the definition of an asset is given as:

> *All the property of a person or company which may be*
> *made liable for his or their deaths.*
>
> –OED (2007)

Management is defined by the OED as:

> *Organisation, supervision, or direction; the application of skill or care in the manipulation, use, treatment, or control (of a thing or person), or in the conduct of something.*
>
> –OED (2007)

An authoritative definition of AM is the so-called accountant's view of assets. In the accountant's definition, assets are split into fixed and current assets. Hastings (2010) defines a fixed asset as a physical item which has value over a period exceeding one year, examples of these include: land and buildings, as well as plant and machinery. Faster moving assets such as: cash and inventory, are defined as current assets. Amadi-Echendu *et al.* (2010) states that one should have a clear differentiation from "engineering" asset objects to "financial" asset objects, as all assets can be classified into one of these two object categories. Financial objects, for example, could be securities traded on the stock exchange or patent rights, both of which only exist as contracts between legal entities. Engineering objects can be items such as inventories, equipment, land and buildings. These objects can exist independently of any organisation or contract. Amadi-Echendu *et al.* (2010) point to a diagram, reproduced in Figure 2.1 below, in which the author describes the base of a pyramid comprising of the realm of Engineering Asset Management (EAM), with financial and all other assets being built on top of it. The OED also more specifically defines AM as:

> *...the active management of the financial and other assets of a company, etc., esp. in order to optimise the return on investment.*
>
> –OED (2007)

Hastings (2010) gives another definition of AM that is more aligned with a business' objectives, here AM is the set of activities associated with:

- identifying what assets are needed,
- identifying funding requirements,
- acquiring assets,
- providing logistic and maintenance support systems for assets,
- disposing or renewal of assets.

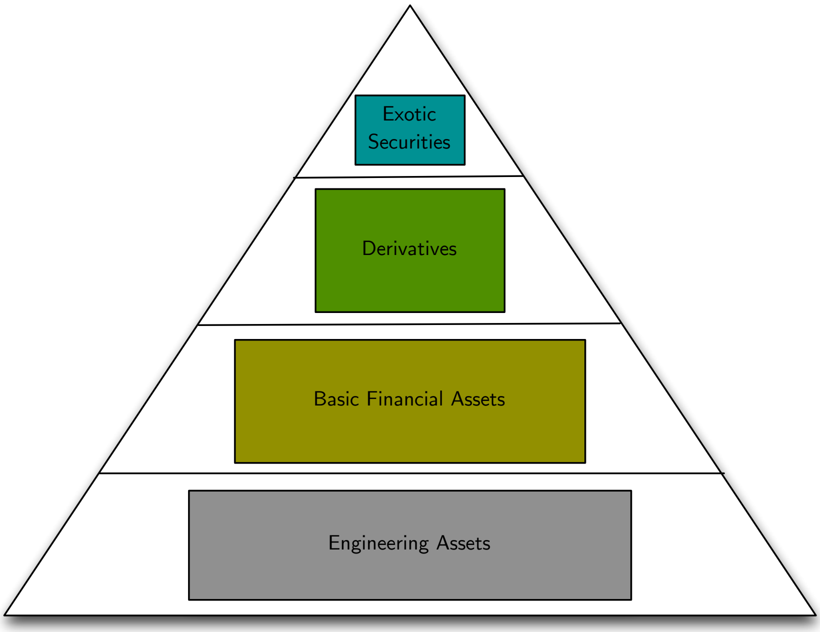


Figure 2.1: Nature of EAM within the context of other assets.

Adapted from Amadi-Echendu *et al.* (2010)

These activities are done to meet the organisation's greater objective or goal. This definition goes to show that asset management, when compared to the single term, maintenance, is far broader and encompasses an entire life cycle of activities, Ma (2007). Maintenance is only concerned with the act of keeping an asset in its original working condition. An integrated view of asset management is shown in Figure 2.2, Amadi-Echendu (2004) explains the primary processes, value-chain and life-cycle stages of physical asset management. The value-chain comes from the basic definition of an asset, with the key attributes being ownership, management and utilisation. The value-chain is usually independent of the life-cycle stages, also shown in Figure 2.2, however, this is influenced by the nature of the physical asset and organisational objectives. Amadi-Echendu (2004) and Woodhouse (2003) also state that aligning utilisation and management towards stakeholder-desired performance is a key challenge for physical asset management. Effective asset management requires: (i) the appropriate integration of the corporation between established disciplines and emerging technologies; and (ii) the application of the integrated synergies towards achieving the value profile, desired at the respective life-cycle stages of the asset. Amadi-Echendu (2004) also points out that PAM is fundamentally accountable for the triple bottom line of business reporting of economic, environmental and social responsibilities. In this regard, Woodhouse (2003) mentions that integrated AM represents the best sustained mix of both asset care (maintenance and risk management) and asset exploitation (use of the asset to meet some organisational objective). Vanier (2000) presents the "Six Whats" of asset management, in order to describe examples of decision support tools for asset management, as well as to show the discrete levels for asset management implementation:

1. What do you own?
2. What is it worth?
3. What is the deferred maintenance?
4. What is its condition?
5. What is the remaining service life?
6. What do you fix first?

Vanier (2000) suggests that the "Six Whats", or levels, can be used as a sequential program in order to implement an asset management plan. The Institute of Asset Management (2011) further states that more and more people have understood that AM is not so much about "doing things to assets", but about using assets to deliver value and achieve the organisation's explicit purposes, which also confirms Vanier (2000). The Institute of Asset Management (2011) goes on to say that AM converts the fundamental aims of the organisation into practical implications for choosing, acquiring, utilising and looking after, appropriate assets to deliver those aims. This is done while seeking the best total value approach, meaning the optimal combination of costs, risks, performance and sustainability.

The British Standards Institution (2008) PAS 55 (elaborated on in section 2.3) defines PAM as "–those systematic and coordinated activities and practices through which an organisation optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organisational strategic plan". Important to note here are the final words "achieving its organisational strategic plan", these call for the complete alignment of the organisation's assets and therewith the associated systems, to be aligned with the organisation's strategy. Woodhouse (2001) defines PAM in a similar way: "The set of disciplines, methods, procedures and tools to optimise the whole life business impact of costs, performance and risk exposures (associated with the availabil-

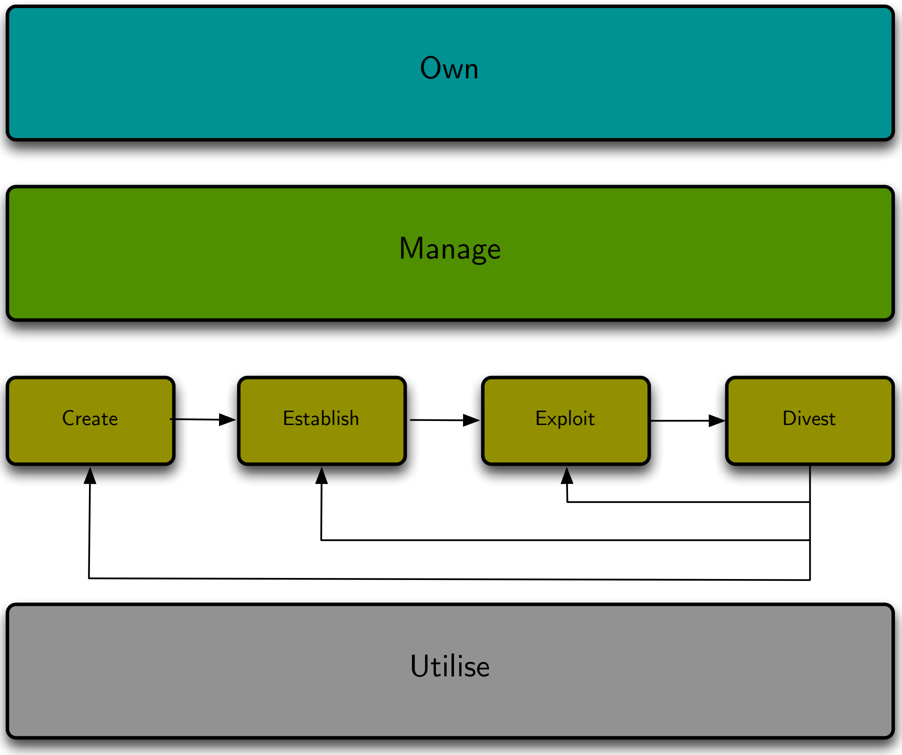


Figure 2.2: Integrated view of physical asset management.

Adapted from Amadi-Echendu (2004)

ity, efficiency, quality, longevity and regulatory compliance) of the company's physical assets." The British Standards Institution (2008) PAS 55 standard on physical asset management, also defines five key asset management areas within organisations:

1. Financial Assets
2. Physical Assets
3. Human Assets
4. Information Assets
5. Intangible Assets

Vanier (2001) and FHWA (1999) define asset management as "... a systematic process of maintaining, upgrading and operating physical assets cost-effectively. It combines engineering principles with sound business practices and economic theory, and it provides tools to facilitate a more organised, logical approach to decision-making. Thus, asset management provides a framework

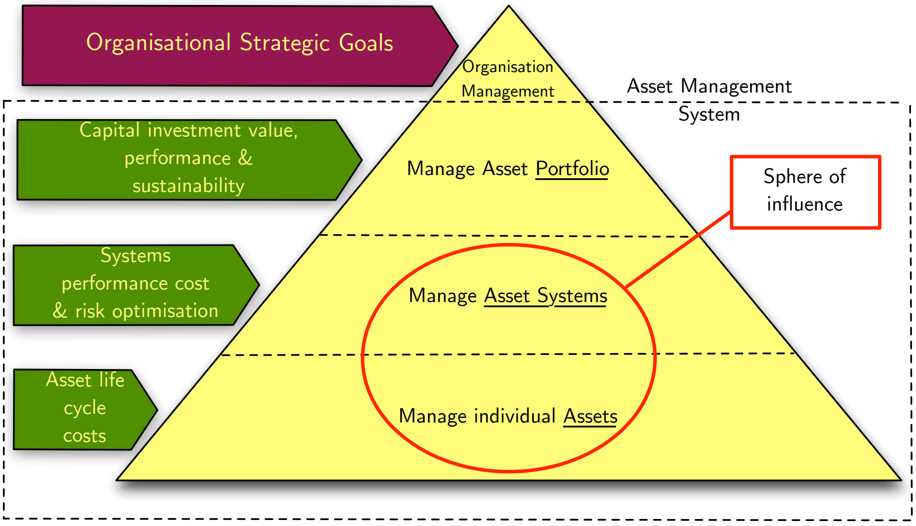


Figure 2.3: Hierarchy of a asset management system.

Adapted from British Standards Institution (2008)

for handling both short- and long-range planning". Even though this definition is older, similarities can still be drawn to PAS 55 and Woodhouse (2001).

Though these definitions differ in their wording, the overall theme is very similar and commonalities can be seen in the use of the words and phrases such as "systematic", "technical and financial judgement", "best practices", "business aims" and "life cycles". The above definitions show that asset management circumscribes a much broader and different set of objectives and activities, than those traditionally seen and clichéd as associated with maintenance. Figure 2.3 shows the hierarchy of an asset management system, as well as displaying the sphere of influence of the research conducted in this study.

Thus it can be seen that PAM is an extremely inter-disciplinary field, where balancing different conflicting drivers is key to success. These factors include compliance, performance and sustainability. Due to this, seventeen key performance areas, have been found in literature that support PAM and therefore PAS 55, these are shown in Figure 2.4. From the seventeen KPAs shown in Figure 2.4, four were identified as being the most relevant to this study. These four KPAs are:

1. Strategy Management
2. Risk Management
3. Asset Care Plans
4. Life Cycle Management

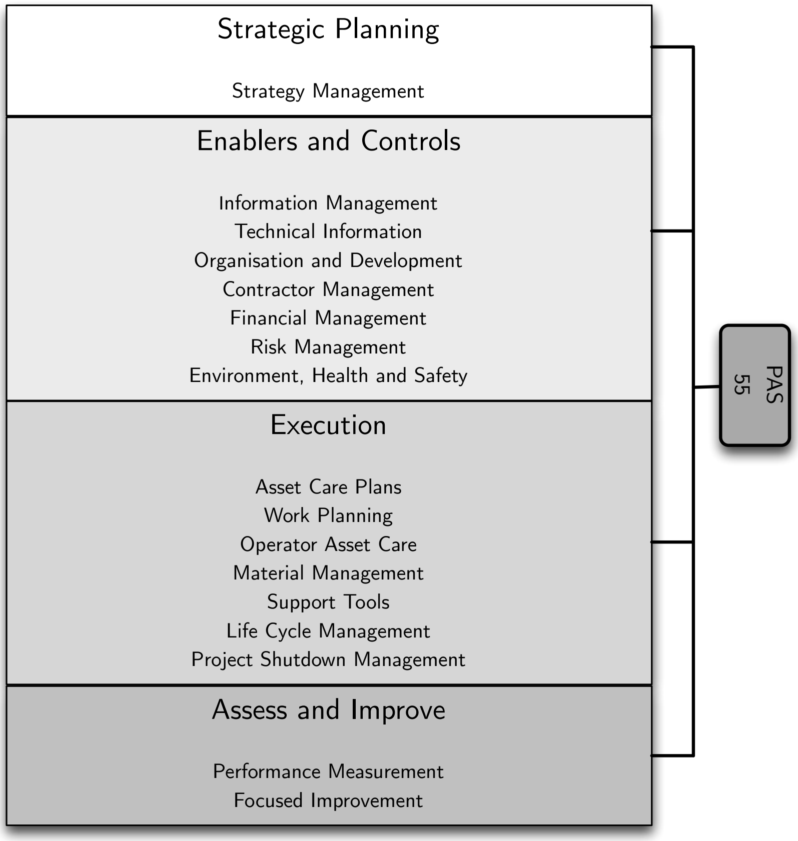


Figure 2.4: 17 Asset Key Performance Areas of Physical Asset Management.

Amadi-Echendu *et al.* (2010) provide five requirements and challenges–or in the author's words "generalities"–for EAM, namely: spatial, time, measurement, statistical and organisational generality. These are further explained in Table 2.1. By looking at the five generalities, it becomes clear that EAM or AM needs a very diverse skill set and is multi-disciplinary, as it requires input from a variety of different disciplines. Since EAM requires alignment throughout the entire organisation, as stated by, British Standards Institution (2008), Amadi-Echendu (2004) and Amadi-Echendu *et al.* (2010), decisions that range from operational, tactical and strategic aspects are necessary.

Table 2.1: Five generalities within EAM.

Generality	**Explained**
Spatial generality	Due to the multi-disciplinary nature of EAM, it extends across all types of physical assets.
Time generality	EAM extents over all time periods from short term (utilisation) to long term (complete life cycle).
Measurement generality	Three measurement dimensions: financial, social and physical.
Statistical generality	First moment estimates such as asset performance as well as risk and other higher moment estimates are important.
Organisational generality	Due to the significance of alignment of EAM with all levels of the organisation, from contact to strategic decisions.

According to Amadi-Echendu *et al.* (2010)

2.3 Publicly Available Specification 55

PAS 55 began in 1995, when key players within asset management and the Institute of Asset Management (industry and academia), met to decide the direction of a new set of guidelines, which would later become the PAS 55 standard. The formalisation, review and publishing of the PAS 55 standard took 9 years and its application first gained traction in 2006 in the United Kingdom's utilities sector. PAS 55 has since spread into a wide variety of industries including transport, facilities management, pharmaceuticals and natural resources. PAS 55 is published in two separate parts, the first, "PAS 55-1: Specification for the optimised management of physical assets" provides recommendations for establishing, documenting, implementing, maintaining and continually improving an Asset Management System. Part two, "PAS 55-2: Guidelines for the application of PAS 55-1", comprises guidelines for the application of PAS 55-1. Hereinafter, it is consistently referred to PAS 55, as a specification, rather than to the standard's individual publications. The standard is now heading towards becoming an ISO standard, ISO 55000, this will bring even further credibility and more momentum to the field of asset management, as well as to the PAS 55 standard.

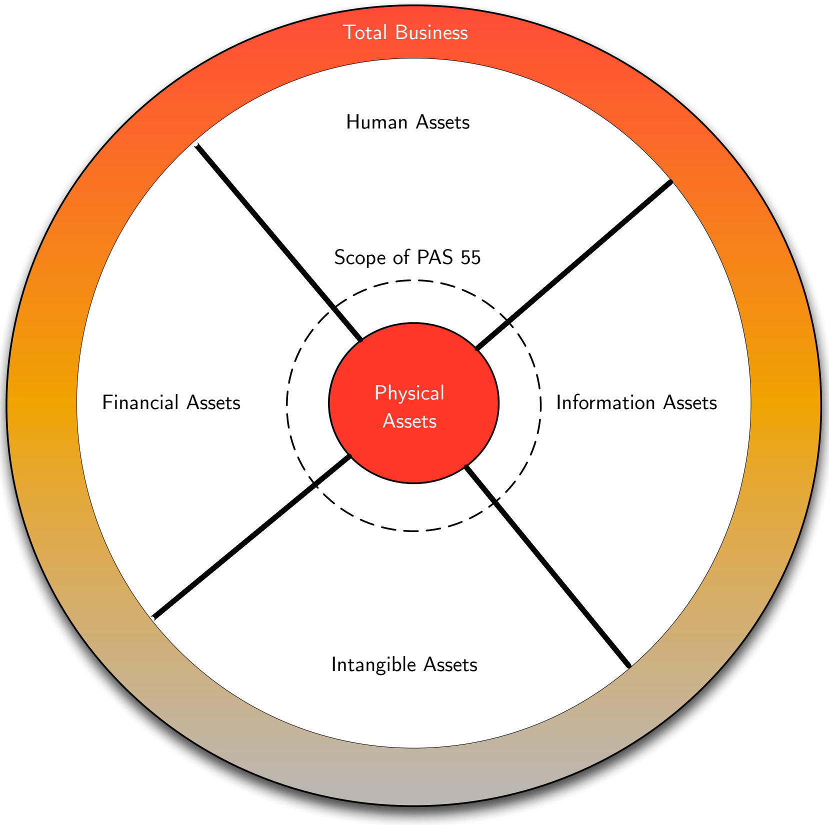


Figure 2.5: Focus and business context of PAS 55.

Adapted from British Standards Institution (2008)

Hastings (2010) says PAS 55 aims to ensure that an organisation's physical assets are effectively and efficiently managed over time. PAS 55 does this by setting certain frameworks that define what exactly an asset is and what it is not. An organisation using PAS 55 is therefore enabled to develop good practices for long-term asset administration. The requirements set out in PAS 55 help an organisation to identify improvement opportunities and create an improvement plan. These requirements therefore lead to real ground level improvements of the bottom line and also improve asset stewardship within the organisation. PAS 55 defines asset management as:

> *The systematic and coordinated activities and practices through which an organisation optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organisational strategic plan.*

Hastings (2010) further states that maintaining an asset or asset system correctly and managing this asset from its initial inception, through its usage stage and finally to its decommissioning, is of great importance to asset intensive organisations. There are already many approaches to solving these problems, however, through PAS 55 there is a realisation that greater performance could be achieved if a more holistic approach is used. Ma (2007) highlights the fact that that EAM entails the integration of business processes and practices, including supporting mechanisms and record systems across the entire organisation. PAS 55 "is applicable to any organisation where physical assets are a key or a critical factor in achieving its business goals". According to Woodhouse (2007), PAS 55 uses a bottom up approach in order to deliver change within the organisation, specifically using a bottom up cost, risk and performance evaluation of individual activities. PAS 55 provides a 28–point auditable set of requirements of good practices in physical asset management. According to Hastings (2010), the adoption of PAS 55 can provide:

- A structured view of asset management;
- Effective relationships between top management, asset management, operations and maintenance and cross functional communications;
- Improvements in asset financial returns;
- Improvements in asset management organisation;
- Safety and regulatory benefits, and
- Improvements in training and development.

In the introductory clause 0.5 of British Standards Institution (2008), PAS 55, states clearly that PAS 55 defines only what has to be done but not how to do it, therefore the method and tools used to achieve the PAS 55 requirements are left up to each individual organisation. Reyes-Picknell (2011) explains that the flexibility with the PAS 55 standard allows every organisation to use tools that suit their requirements and industry, at that particular time. This can be compared to a company complying with financial accounting standards, the company does it in a way that suits itself. The same is true for PAS 55, the organisation complies to the standard's requirements by doing things in its own way. The Institute of Asset Management (2011) states that PAS 55 provides a checklist of requirements for an AM system, it covers the establishment of clear policy and strategic direction, specific asset management plans, operational controls and continual improvement activities.

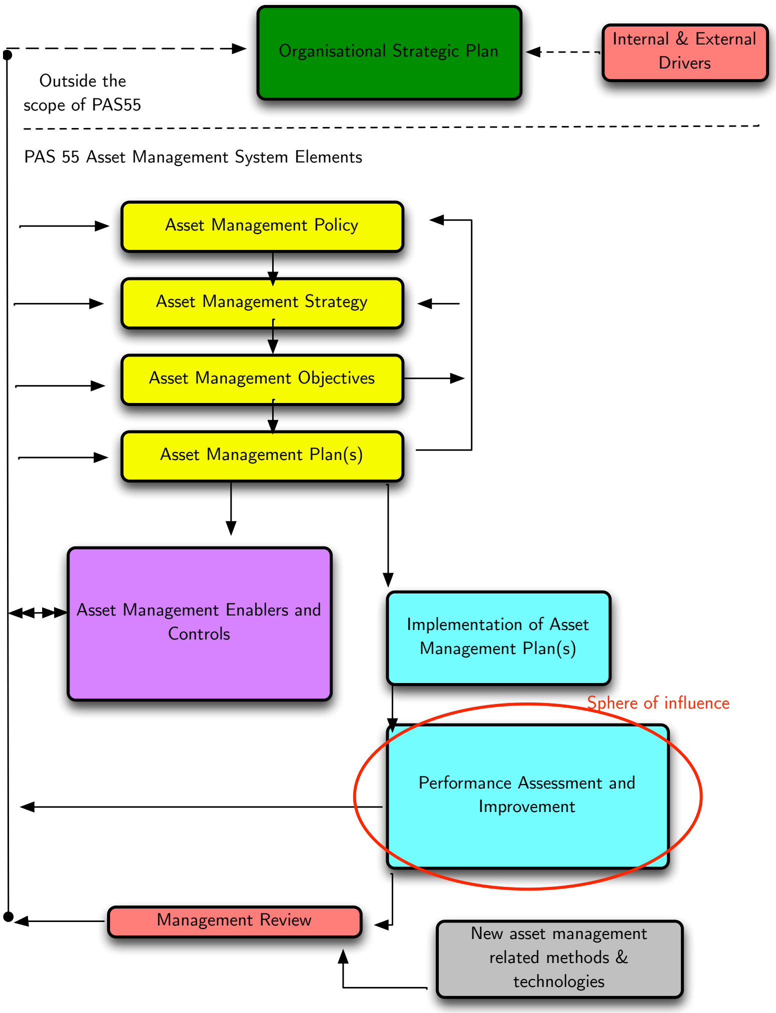


Figure 2.6: Typical elements of an asset management system.

Adapted from British Standards Institution (2008)

It also identifies a range of enablers that have been found by the many organisations participating in PAS 55 development. According to The Institute of Asset Management (2011) and the British Standards Institution (2008) it is important that the backbone of any good management system for assets is, clear connectivity and communication between the organisation's strategic plan, and the on-the-ground daily activities of individual departments. The Institute of Asset Management (2011) calls this "line of sight", as people on the "front line" need to have direct visibility of the reasons for their activities. It is important for people to know why the task is needed and not just how to do it. This philosophy can also help to stimulate creativity and innovation within processes in the organisation.

2.4 Asset Management Strategy

An asset management strategy should define what the organisation intends to achieve from its specific AM activities and within what time. According to The Institute of Asset Management (2011), certain factors should be included within this strategy, namely, the current and future demand; condition and performance requirements of the organisation's assets, also the current and future AM capabilities of the organisation, such as processes, information, systems, people, tools and resources; and how the organisation intends to develop its future capabilities to a level of maturity necessary to deliver its organisational goals. Wenzler (2005) states that there are four key challenges for an AM strategy to live up to its expectations: (1) alignment of strategy with stakeholder values and objectives; (2) balancing reliability, safety and financial considerations; (3) benefiting from performance based rates; and (4) living with the output based penalty regime. The British Standards Institution (2008) PAS 55 standard makes the point that an asset management strategy should ensure that activities carried out on physical assets, are aligned with the organisational strategic plan, thereby achieving optimal performance.

British Standards Institution (2008) emphasises that the AM strategy should be SMART–meaning that its objectives should be Specific, Measurable, Achievable, Realistic and Time-bound. PAS 55 of the British Standards Institution (2008) sets a list of 12 requirements for an AM strategy, which fall into seven broad categories:

1. *Consistency:* The AM strategy should be consistent with the AM policy.
2. *Risk-based approach:* The AM strategy should be risk-based in its approach, meaning that it should prioritise activities according to the criticality of the asset.
3. *Life cycle approach:* The life cycle of assets should be specifically considered in the AM strategy.
4. *Framework:* A clear unambiguous framework should be included within the AM strategy, in order to develop AM objectives and plans that set forth the correct level of optimisation, prioritisation and the management of information.
5. *Stakeholders:* Involvement of stakeholders is needed within the AM strategy.
6. *Functional, performance and condition requirements:* The AM strategy

should include present and future functional, performance and condition requirements for the assets, a roadmap should also be included as to how these will be met.

7. *Continual improvement:* Support from top management, effective communication and regular reviews of the AM strategy is needed.

Davis (2007) states that an integrated asset management strategy does not just apply to the maintenance department as it did in the past, but must involve the entire organisation. The author lists a number of ways in which an asset management strategy supports the organisation:

- Enables the organisation to know precisely which assets it has and who is responsible for which asset.
- Enables the organisation to know exactly where assets are situated.
- Enables the organisation to determine the condition of its assets at any time.
- Enables the organisation to understand its assets better, in terms of operations.
- Forces the organisation to develop and create a formal asset care plan that confirms that all its assets perform correctly and reliably.
- Enables the organisation to operate its assets most cost effectively and extend their operating life.

According to The Institute of Asset Management (2011), one of the greatest challenges to any asset-intensive organisation, is creating an AM strategy that clearly maintains the line of sight initiated by the AM policy. The asset management strategy is therefore of vital importance, as it sets the tone for asset care and maintenance activities that are performed within the organisation and provides the framework for maintenance activities that are performed on the organisation's physical assets. Asset care and maintenance are expanded on in the next section.

2.5 Asset Care

British Standards Institution (2008) PAS 55 asset management standard states that an organisation must improve and maintain processes during all stages of the asset life cycle and thereby perform asset care. Van der Westhuizen and

Van der Westhuizen (2009) cite Peterson (2007) describing AM as a process for asset care decision making. Wheelhouse (2009) says that an effective asset care program allows an organisation to plan, repair and replace its equipment in order to achieve the organisation's strategic goals. In the end, the optimisation of the following factors should be achieved: safety, cost, performance and availability, while keeping the greater organisational objectives in mind. Willmott and McCarthy (2001) define an asset care program as a systematic approach to keeping equipment in an "as new" condition. The author states that this consists of carrying out routine activities such as: cleaning and inspecting; checking and monitoring and; PM and servicing. Woodhouse (2007) connects asset care to AM by pointing out that optimised and integrated AM is the best sustained mix of asset care and asset exploitation, and these should be optimised over the entire life cycle of the asset. Sachdeva *et al.* (2008) draws attention to the fact that asset care should involve direct and active participation across the hierarchy of the organisation, from top management to shop floor workers. Wenzler (2005) names keeping assets healthy and operational as a core activity. Wheelhouse (2009) also states a number of items that should be included within a plant asset care plan:

- Servicing and Maintenance
- Inspection
- Shutdowns
- Spares Management
- Asset Strategy
- Performance Monitoring

Mitchell *et al.* (2007) speak of a number of challenges facing asset care planning, these include:

- selecting the best suited tactic,
- dealing with each unique type of failure,
- fulfilling and balancing the expectations of both the owners and operators of the assets, and
- performing asset care in the most cost effective and enduring manner.

From these challenges Mitchell *et al.* (2007) identifies three key concepts most relevant to asset care: cost effective, failure and tactic. Cost effectiveness

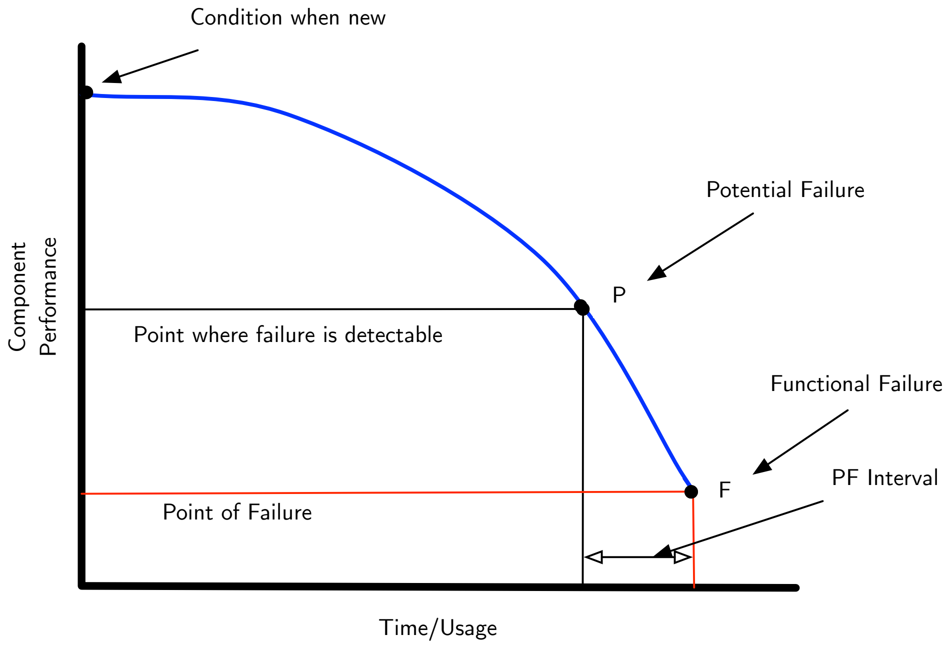


Figure 2.7: Failure progression of a component, showing the PF interval.
Adapted from Moubray (2001)

has two sub-factors that need to be considered in tandem, firstly the cost of preventative asset care and secondly, the cost of the penalty linked to asset care in terms of loss of revenue, recovery and opportunity loss costs.

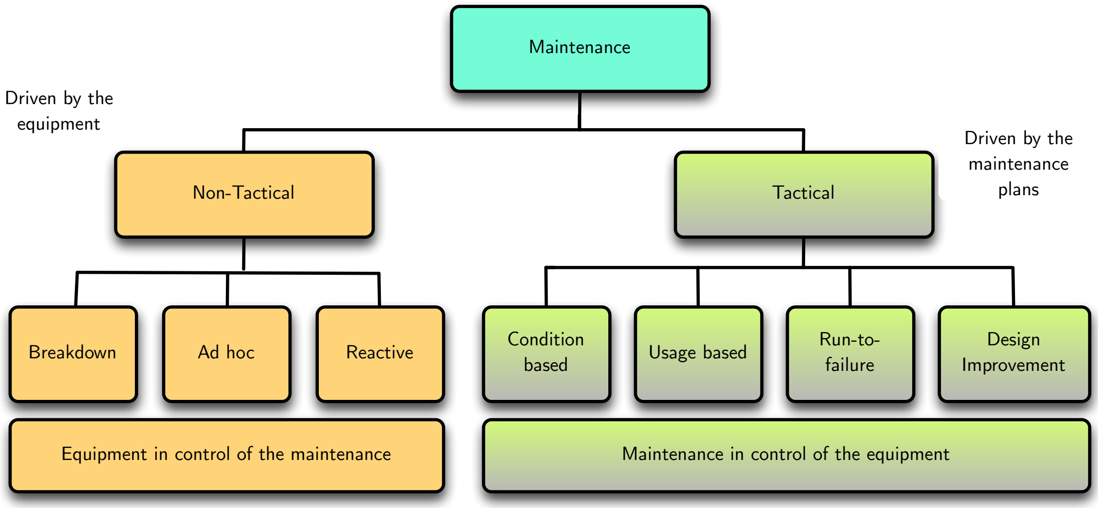


Figure 2.8: Overview of tactical and non-tactical asset care.

Wheelhouse (2009) states that in order to create value for the shareholder, five things need to be done: reduce the cost of capital; reduce the tax burden; invest for growth; improve asset performance and influence stock market judgement. Asset care can positively influence the last two. It positively improves asset performance, which yields a strategic advantage, as equipment that is reliable and has extended life will mean that future investments can be postponed. Efficient asset utilisation also lowers costs, thereby increasing profitability; it also has a favourable effect on the reputation of the organisation, adding value to the share price. Davis (2007) highlights that a asset care plan should ensure that each asset performs its designated task reliably whenever it is required. Davis (2007) also points out that the function of an asset care plan is to verify that assets function at or near to their design parameters over their entire life cycle. This will ensure that the cost of operating the organisation's assets is optimised. Even basic shop floor level asset care can lead to great improvements in overall plant reliability, according to Khan (2001).

Wheelhouse (2009), Mitchell *et al.* (2007) and Davis (2007) all state that in order for an asset care plan to be effective and create value, deliberate decisions must be taken early in the life of the equipment, with regards to its maintenance programmes. Davis (2007) points out that an asset care plan needs to be proactive and not reactive, using modern computer software to capture events and conduct data mining, the use of statistical process control is also encouraged. According to Wheelhouse (2009), it comes down to doing the "right things at the right time". This is becoming increasingly important.

2.5.1 Maintenance

According to Organ *et al.* (1997), the dictionary definition of maintenance is to "to keep in existence". However, traditionally maintenance was only performed when the equipment or system was already broken. British Standards Institution (1984) standard 3811 defines maintenance as "the combination of all technical and associated administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function." Kiyak (2011) says maintenance is the process that involves all procedures and operations carried out to fix any mechanical or electrical device, should it become broken or out of order. Waeyenbergh and Pintelon (2002) explain that maintenance contributes "more than ever" to the achievement of business objectives, it keeps life cycle costs down and improves the performance of the the organisation. Dhillon (2002) states that over US $300 billion dollars (R 2.5 Trillion) are spent annually on plant maintenance and operations in the US alone and that 80% of this amount is spent on correcting the chronic failure of machines, systems and people. Maintenance does however also include performing routine actions in order to keep the device in question in working order, this is labeled scheduled maintenance. Geraerds (1985) defines maintenance as "all activities aimed at keeping an item in, or restoring it to, the physical state considered necessary for the fulfilment of its production function". This definition presupposes that maintenance also includes proactive maintenance activities such as preventive maintenance, inspection and condition-monitoring. Kelly (1984) estimated that better maintenance practices in the UK could have saved approximately £300 million (R3.8 billion) annually in lost production, due to equipment failure. Maintenance activities in a company need to be monitored, controlled and improved in order to produce an effective system and therefore, according to Parida and Kumar (2006), the efficiency and effectiveness of a maintenance system plays a central role in a company's success. Chelsom *et al.* (2005) state that within most engineering firms maintenance is self-evident, as without maintenance equipment within the plant would not survive. The central objective of maintenance is to maximise equipment availability in an operating condition, permitting the desired output quantity and quality, Pintelon and Gelders (1992). Different maintenance types according to EN 13306:2001 (2001) are shown in Figure 2.9.

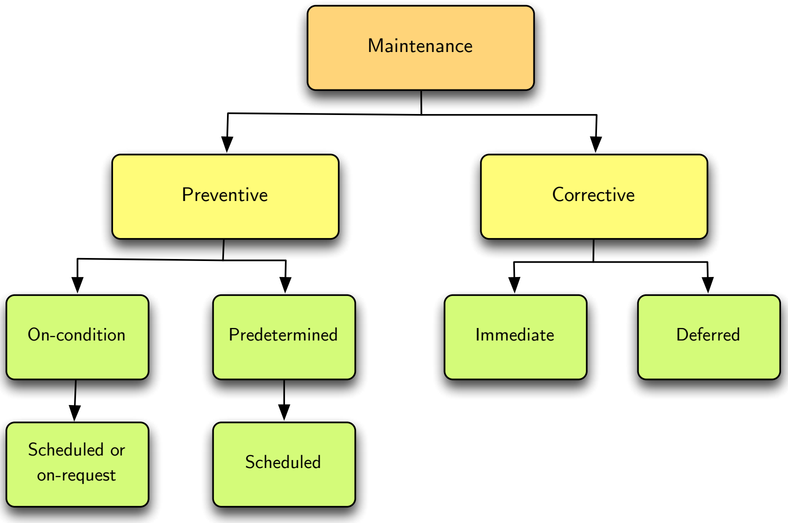


Figure 2.9: Maintenance types according to EN 13306:2001 (2001)

In general, there are two major types of maintenance, namely:

1. Preventive Maintenance (PM) and,
2. Corrective Maintenance (CM).

PM is the process of maintaining equipment before a break down occurs. CM is the process of performing maintenance after a break down has occurred. For obvious reasons, the latter type of maintenance is often more expensive than PM. Smith and Hinchcliffe (2004) define PM as the performance of inspection tasks that have been preplanned or scheduled at specific points in time, in order to retain the functional capabilities of equipment or systems. Smith and Hinchcliffe (2004) also define CM as the performance of unplanned or unscheduled maintenance tasks, to restore the functional capabilities of already out of order equipment or systems. Márquez (2009) provides an interesting analogy, the author names "Retention" and "Restoration" as the designations for action types that are then translated into "preventive" and "corrective" maintenance types, within the maintenance body of knowledge. Campbell *et al.* (2011) state a useful rule of thumb to illustrate and roughly estimate the cost saving potential of preventive and planned maintenance, shown in equation (2.1):

$$\begin{aligned} &\$\ 1.00 \text{ Predictive, Preventive, Planned} \\ =\ &\$\ 1.50 \text{ Unplanned, Unscheduled} \\ =\ &\$\ 3 \text{ Breakdown} \end{aligned} \tag{2.1}$$

This simple rule puts forward the claim that the ratio of costs, for different kinds of maintenance, is \$1 for one unit of effective maintenance if it is planned, \$1.50 in an unplanned environment and \$3 if a machine or system breaks down. This concept is further illustrated by Kiyak (2011) on a global level in Figure 2.10, within the context of time.

Kiyak (2011) defines a maintenance concept as a set of a number of maintenance tasks (corrective, preventive, etc.) and the general structure in which these tasks are implemented.

Pintelon *et al.* (1997) point out three important components that lead to a successful maintenance concept: (i) the entire maintenance personnel and maintenance workers need to have a complete and thorough knowledge

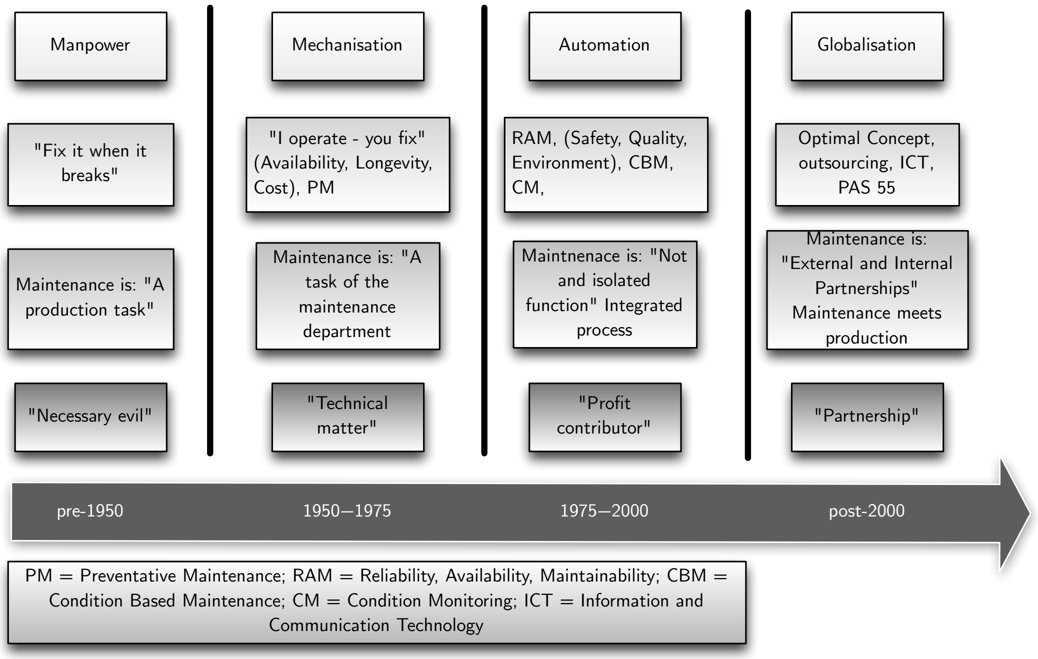


Figure 2.10: Different maintenance strategies over time.

Adapted from Waeyenbergh and Pintelon (2002)

of maintenance technologies; (ii) long-term maintenance plans, organisational wide maintenance awareness and cross functional participation in the planning of maintenance; and (iii) expanding and making better use of information and communications technology within a maintenance context. Chelsom *et al.* (2005) provide two objectives for the design and operation of a maintenance system:

1. Minimise the chance of failure where such failure would have undesirable consequences.
2. Minimise the overall cost or maximise overall profit of an operation. Balance the cost of setting up and running the maintenance operation and savings generated by increased efficiency, this allowing for the prevention of downtime.

Dhillon (2002) makes the point that due to various factors, it was established in the previous century that “maintenance” must be an intrinsic part of production strategy. Therefore it becomes a pivotal point in the success of an organisation. Profitable maintenance operations will be, according to Dhillon

(2002), ones that effectively use modern thinking that takes advantage of new advances in the areas of information, technology and methods.

Another important aspect of maintenance within an organisation, is the overall maintenance policy, according to Dhillon (2002), Chelsom *et al.* (2005), Márquez (2009) and Ben-Daya *et al.* (2009), it is one of the most important elements of effective maintenance management. It becomes critical in the continuity of operation and in the clear understanding of the maintenance management program, at all levels of the organisation.

2.5.2 Corrective Maintenance

Well designed systems are devised by engineers to be as reliable as possible, however, from time to time they do fail. They must then be repaired and brought back to a serviceable state. This makes repair, or Corrective Maintenance (CM), an important and necessary action of any maintenance activity. AMCP (1975) and McKenna and Oliverson (1997) define CM as the remedial action carried out, due to a failure discovered during PM, to repair equipment to its operational state. Dhillon (2002) states that corrective maintenance by its very nature is comprised of unscheduled maintenance action and unpredictable maintenance needs that cannot be preplanned, and usually require immediate action Mobley (2002) describes CM as event driven. A CM policy according to Nakagawa (2005), is adopted in the case where units can be repaired and their failures do have detrimental effects on the entire system. Garg and Deshmukh (2006) say that during the 1950s, CM was undertaken under the premise of “fix it when it breaks”. This, over time, gradually changed into PM and then into various other forms of predictive maintenance. A system with several units forms semi-Markov processes and Markov renewal processes in stochastic processes.

AMCP (1971, 1975) classify CM into five major categories, shown visually in figure 2.11, these are fail–repair, salvage, rebuild, overhaul and servicing. They are described below:

1. *Fail–Repair:* The failed item or component is restored to its operational state.
2. *Salvage:* This element of corrective maintenance is concluded with the disposal of non-repairable systems or components.

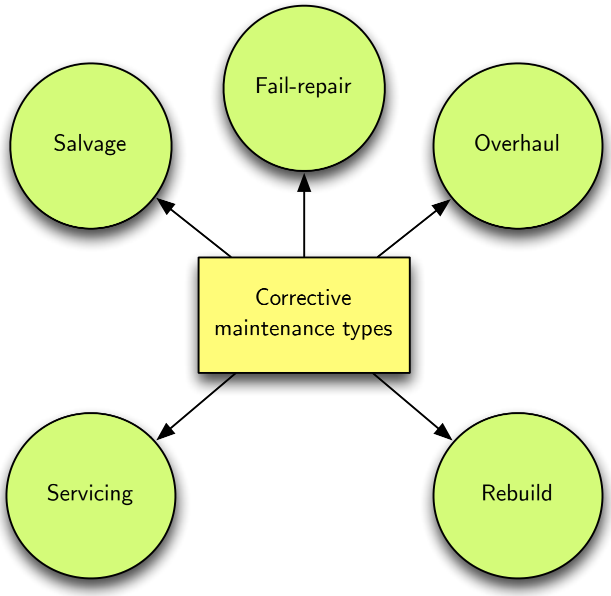


Figure 2.11: Elements of CM.

Adapted from AMCP (1975)

3. *Rebuild:* Here an item is restored as close as possible to the original state in terms of performance, life expectancy and appearance.
4. *Overhaul:* Inspect and repair only what is necessary, restoring an item to a set maintenance standard.
5. *Servicing:* The servicing that is required due to the corrective action that was taken.

Márquez (2009) states that major failures under CM should be fully investigated, to identify preventive and corrective actions, this could also include performing a root cause analysis. CM is carried out after fault recognition and its immediate concern is to put the equipment in question back into a state where it can perform its assigned task. CM, according to Márquez (2009), can be either immediate or deferred:

- *Immediate maintenance:* This is maintenance that is carried out without delay, as soon as possible after the fault has occurred.
- *Deferred maintenance:* This maintenance task is not done immediately after the fault detection, it needs to be performed within the given maintenance rules.

2.5.3 Preventive Maintenance

There are many different versions and definitions of Preventive Maintenance (PM), but according to Mobley (2002) they all have one common factor, that of time. This means that maintenance tasks are performed based on the hours of operation of a machine or system. Omdahl (1988) defines PM as all actions carried out on a planned, periodic, and specific schedule, to keep an item or equipment in the stated working condition through the process of checking and reconditioning. Nakagawa (2005) points out that every time a unit is repaired only after a failure, it requires large amounts of time and high cost, this was described in the previous section on CM. The downtime when a system is repaired should be kept as short as possible, by decreasing the number of system failures. Maintaining a unit to prevent failures, thereby doing PM is the best way of achieving this. In order to further distinguish PM and CM tasks, Smith and Hinchcliffe (2004) argue that the purpose of a PM task is to perform actions that will retain functional capabilities, therefore to repair or restore is a preventive action, and is not a corrective action as often thought. AMCP (1975) shows seven elements in a PM program, these are shown in figure 2.12. Long *et al.* (2009) and Mobley (2002) state that the MTTF for non-repairable systems or MTBF for repairable systems are used within preventive maintenance to schedule machine repairs or rebuilds. According to Mann *et al.* (1995) the common objective of any PM program is the minimisation of the total cost of inspection and repair, as well as equipment downtime.

Niebel (1994) details a number of characteristics of a plant that is in need of a good preventive maintenance program:

- Low equipment use due to failures;
- Large volume of scrap or rejects, due to unreliable equipment;
- Rise in equipment repair costs, due to negligence in lubrication, inspection, and replacement of worn components;
- High idle operator times, due to equipment failure;
- Reduction in capital equipment expected productive life, due to unsatisfactory maintenance.

Nguyen and Murthy (1981) present two motivations for a preventative maintenance policy: (i) the replacement or repair cost of a failures system is usually far higher than the replacement or repair cost of a non-failed system; and (ii) the continuing repair of a system is normally far more costly

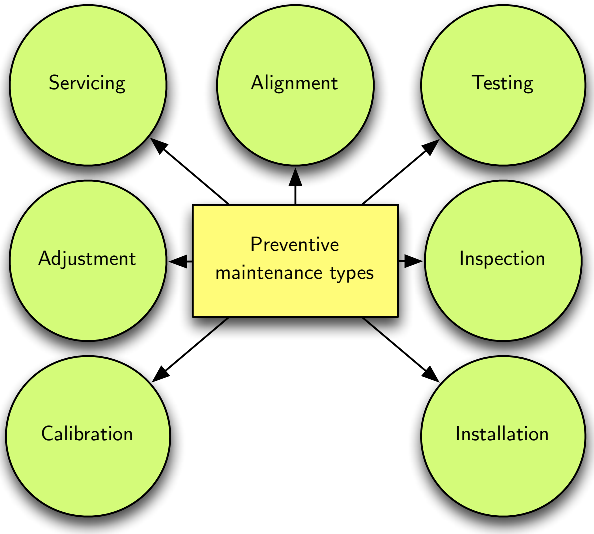


Figure 2.12: Elements of PM.

Adapted from AMCP (1975)

than the replacement after an established number of years. Levitt (1997) and Patton (1983) propose a simple formula to use when deciding to go ahead with a PM program, shown in equation 2.2

$$(\mathrm{NB})(\mathrm{ACPBD})(\alpha) > \mathrm{CPMS} \tag{2.2}$$

where,

$$\begin{aligned} \mathrm{CPMS} &= \text{total cost of PM system,} \\ \alpha &= \text{a factor whose values are proposed to be taken as 70\%} \\ & \text{of the total cost of breakdowns,} \\ \mathrm{NB} &= \text{number of breakdowns,} \\ \mathrm{ACPBD} &= \text{average costs per breakdown.} \end{aligned}$$

Smith and Hinchcliffe (2004) identify four different factors in making decisions to define and choose preventive maintenance actions:

- Prevent failure occurrence.
- Detect the onset of failure.
- Discover a hidden failure.
- Do nothing, due to valid constraints.

Smith and Hinchcliffe (2004) state that, using the four factors shown above, one can define the task categories from which a PM action can be specified. These four task categories are as follows:

- *Time-directed (TD):* aimed directly at failure prevention.
- *Condition-directed (CD):* aimed at detecting the onset of a failure.
- *Failure-finding (FF):* aimed at discovering a hidden failure before an operational demand.
- *Run-to-failure (RTF):* a deliberate decision to run a part or component to failure because other tasks are not possible or the economics are not favourable.

PM programs assume that all machinery degrades with time, therefore machinery is removed from service and rebuilt or serviced before its expected failure point. Mobley (2002) says that the applications of PM differ substantially. In some cases it could be constrained to lubrication only. However, common to all PM programs, is the time factor or scheduling suggestion. Sherwin (2000) and Pun *et al.* (2002) both state that time-based preventive maintenance is conducive to the indiscriminate use of overhaul and preventive procedures in many maintenance programs. According to Swanson (2001), PM interrupts production time to perform maintenance tasks, it does, however, reduce the probability of equipment failure. Raymond and Joan (1991) state a number of advantages of preventive maintenance, for example that maintenance costs can be reduced by avoiding the cost of resultant damage. The general health and safety of the equipment user is also increased.

The problem with using these statistics is that the mode of operation and plant specific variables directly affect the normal operating life of machinery. It can therefore, according to Mobley (2002), be deduced that the MTBF is not the same for identical systems used in different contexts. For example a pump that handles water and one that handles abrasive fluids will not have the same MTBF. Due to these statistics, Mann *et al.* (1995) say that PM allows for unplanned machine failures and therefore emergency maintenance which often comes at a much higher cost.

Mobley (2002) states that the use of MTBF or MTTF statistics, to plan maintenance, usually results in unnecessary repairs or catastrophic failure. Long *et al.* (2009) suggest that MTTF accepts that failures cannot be accurately forecast and avoided, and that this leads to unscheduled maintenance activities being performed during operating periods.

2.5.4 Predictive Maintenance

Predictive Maintenance (PdM) entails in starting a maintenance operation only when required by the state of the system, meaning when a potential failure is detected. This type of maintenance policy is often achieved through condition monitoring. Mobley (2002) attributes the PdM philosophy that uses the actual operating condition of the plant equipment and systems, to the optimisation of total planet operation. Heng (2009) defines condition-based maintenance as the method to replace or repair when necessary, based on the non-intrusive measurement of current unit condition. The author points to three major elements of condition-based maintenance detailed below:

1. *Data acquisition*: collection and storage of machine health information.
2. *Data processing*: conditioning and feature extraction/selection of acquired data.
3. *Decision making*: recommendation of maintenance actions through diagnosis and/or prognosis.

Heng (2009) points out some distinct advantages of condition-based maintenance: easy identification of the faulty component, prevention of failures and increased asset availability, a reduction in maintenance costs and improved safety. A comprehensive PdM policy uses the most cost effective tools, such as vibration monitoring, thermography and tribology, in order to obtain the actual operating condition of plant systems, based on actual collected data, Mobley (2002).

2.5.5 Design-out Maintenance

Another type of basic maintenance policy found is called the Design-out Maintenance (DOM). The principle focus of DOM, according to Pintelon and Gelders (1992), is improvements in the equipment's design in order to simplify maintenance operations and to increase reliability. A machine or equipment that is subject to a high frequency of failure, coupled with a high length of downtimes should, according to both Labib (1998) and Scarf (2007), be submitted to a DOM policy.

In a case study conducted by, Pintelon *et al.* (1999), it was found that far better PM results could be achieved by realising some rewarding DOM projects. These engineering DOM projects yielded some interesting results that also had benefits in future equipment purchasing. Pintelon *et al.* (1999) did, however, find some drawbacks, including the fact that DOM is very time intensive and applying this policy requires not only management commitment but also organisational openness. Therefore DOM can be seen as the last resort within maintenance activities and due to this, not performed very often.

2.6 Current use of Maintenance Interval Metrics in Mining

Mining can clearly be characterised as an asset centric or asset intensive industry. With large amounts of physical assets that need to be kept running in order to generate a profit for the organisation. PAS 55 has already shown the need for overall organisational alignment with regards to all levels of the organisation in order to achieve the PAM strategy, this includes maintenance. Mining processing operations needs a high level of reliability from its equipment in order to generate constant volumes of product, otherwise no revenue is generated. In order to specify reliability, the mining industry, as with other industries, have used the best practice for reliability characterisation is the maintenance interval metric Mean Time Between Failure (MTBF), according to Wessels (2012) and Krellis and Singleton (1998). MTBF, defined and elaborated on in the following sections. The definition of a *maintenance interval metric*, or also called *reliability metric*, is given by Relf (1999), as a numerical figure that describes the reliability level associated with an item, component or system. Hastings (2010) in the book *Physical Asset Management*, also states that the most commonly used measure of reliability is the MTBF. Both Campbell *et al.* (2011) and Van der Lei *et al.* (2011) state in books on PAM state that MTBF is an important tool in PAM.

Before MTBF is defined and expanded upon, two generally relevant and important terms are defined, Rate of Occurrence of Failure (ROCOF) and reliability.

2.6.1 Rate of Occurrence of Failures

Rate of Occurrence of Failure (ROCOF) is defined by Trindade and Nathan (2005) as the probability that a failure (not necessarily the first) occurs in a small time interval, and is used in repairable systems. Failure rate, according to Trindade and Nathan (2005), used in non-repairable systems, for a certain component, equipment or plant can be expressed in a number of ways such as failure per hours, failure per thousand or even per million. Chelsom *et al.* (2005) show in Figure 2.13 that failure rates are a function of time, typically exhibiting a "bathtub" curve, characteristic of many types of electrical and mechanical equipment.

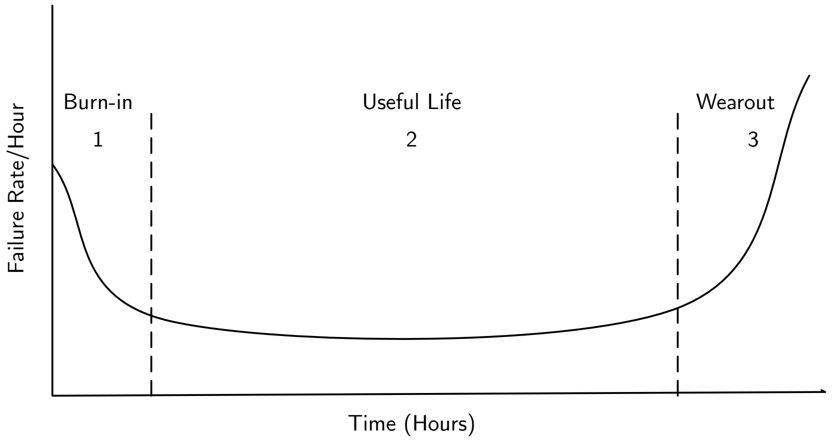


Figure 2.13: The "bathtub" curve failure rate.

Adapted from Chelsom *et al.* (2005) and Smith (2005)

From Figure 2.13 it can be seen that there are three distinct phases within the bathtub curve during the life of a component. Chelsom *et al.* (2005) state that their boundaries are often not as well defined in practice. According to Smith (2005), the bathtub curve describes the variation of failure rate of components during their life, by treating more than one failure type by a single classification.

Phase 1: called the burn-in phase, the failure rate is initially high but reduces rapidly over a short time. Failures that occur in this phase can be attributed to manufacturing faults or flaws within the design of a component.

Phase 2: this is the useful life of the component or system, the failure rate within this phase is characterised by a constant and low failure rate. The length of this phase can also be called, according to Chelsom *et al.* (2005), the durability of a component, and will vary. It is important to note that within this phase, the MTTF or MTBF is the reciprocal of the failure rate.

Phase 3: called the wear-out phase, here the failure rate increases rapidly again due to ageing, wear, erosion, corrosion, etc. of the component. The rate of increase in failure rate depends largely on the component.

2.6.2 Reliability

The OED defines reliability as:

> *consistently good in quality or performance.*
> –OED (2007)

Cătuneanu and Mihalache (1989) describe reliability as an inter-disciplinary theory for treating the degradation laws of physical elements. The author also states that the general property of a system, to conserve its performance in time, has become the specific notion, that is reliability today. Another more specific definition is given as:

> *The probability that an item will perform a required function under stated conditions for a stated period of time.*
> –O'Connor and Kleyner (2011)

Reliability can be defined by the equation below, which also shows how reliability is related to the failure rate λ:

$$\mathrm{R}(t) = e^{-\lambda t} \tag{2.3}$$

A system, if designed correctly should initially, according to Chelsom *et al.* (2005), have a reliability of 1.0 and will eventually tend to 0. At that point the system will not be able to perform its assigned and intended duty. Figure 2.14 shows a typical reliability function, according to the equation defined above.

According to Cătuneanu and Mihalache (1989), a theoretical approach to reliability is purely connected to the fact that modern systems are becoming far more complex. But however high the investment in reliability of a complex

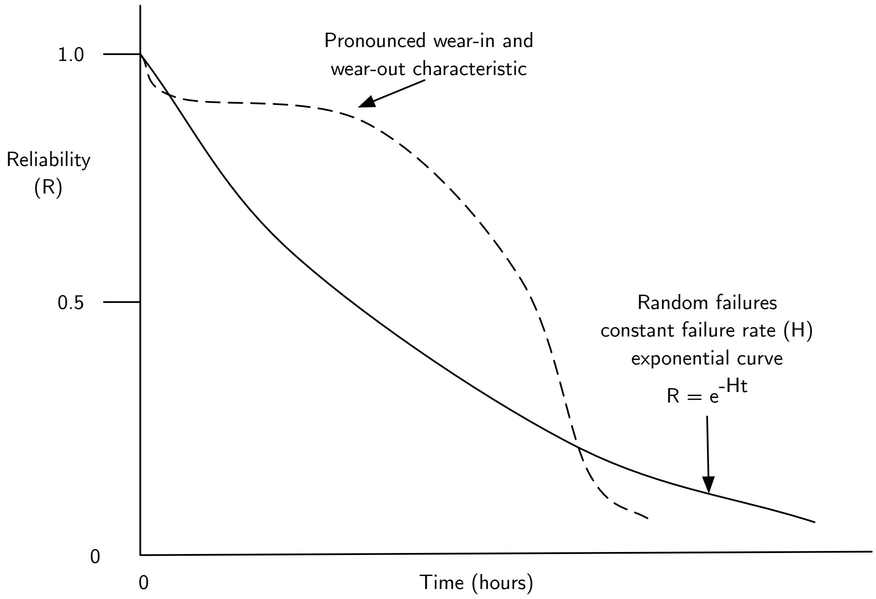


Figure 2.14: Example of a typical reliability curve.

Adapted from Lewis (1987)

system, absolute reliability cannot be achieved or guaranteed. Due to this fact, the reliability of a system must be known, in order for a correct operation length to be determined and a renewal or maintenance strategy to be developed. It is therefore desirable to have a certain level of control over the reliability of the system, this is illustrated in Figure 2.15.

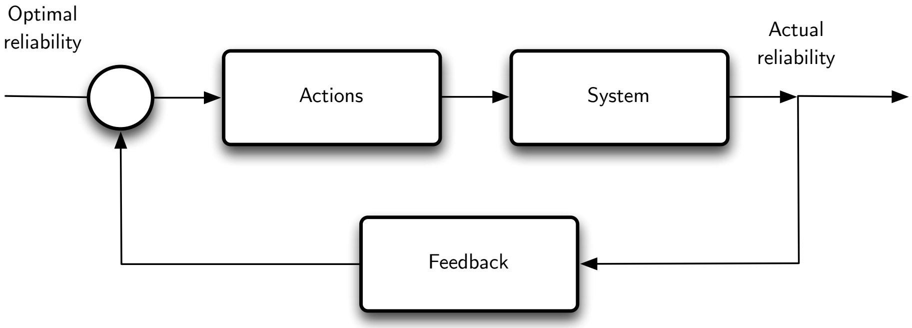


Figure 2.15: Reliability feedback control loop.

Adapted from Cătuneanu and Mihalache (1989)

2.6.3 Mean Time Between Failure (MTBF)

The MTBF is a reliability metric that is often used to describe equipment or system reliability. Smith (2005) defines MTBF as

> *a stated period in the life of an item, the mean value of the length of time between consecutive failures, computed as the ratio of the total cumulative observed time to the total number of failures.*

Modarres *et al.* (1999) defines the MTBF as the Probability Density Function (pdf) of time, between the first failure and the second failure, the second failure and the third failure, etc. The unit of MTBF is hours per failure, however, most statements about MTBF are made in terms of some time unit, Ireson *et al.* (1996).When an item goes through a renewal process, it is assumed to be perfect. This means that when the item goes through repair or maintenance it is assumed to exhibit the characteristics of a new item. Modarres *et al.* (1999) states that the *as-good-as-new* assumption made here is sufficient for the vast majority of reliability cases.

As previously stated, in both mining and PAM, MTBF is commonly applied to assess reliability of equipment, MTBF can be determined by the following equation:

$$\text{MTBF} = \frac{\sum X_i}{m} \tag{2.4}$$

Here, X_i represents the inter-arrival times of the failures and m the number of failures. It should be noted that the MTBF calculation shown here is a historic, backward looking one. Even though not often performed in industry, it is possible to predict a future MTBF value, this is shown in Chapter 3.

A number of disadvantages have been found to be associated with the use of MTBF. According to Dinesh Kumar *et al.* (1999) MTBF, or its reciprocal “failure rate”, is used by many organisations as their reliability specification, without realising that in most cases it is almost impossible to demonstrate. Ireson *et al.* (1996) argues that MTBF does not indicates how high the failure rate is, nor does it indicate how long the infant-mortality period will last. Knowles (1995) also mentions that defining reliability in terms of MTBF is neither beneficial to the customer or the supplier. Kumar (1999) says that MTBF has been widely used for the past five decades in many commercial and defence industries for measuring reliability, but there are many difficulties in using MTBF for maintenance planning and it fails to engineer a solution to maintenance problems. The use of MTBF has received censure from a number of researchers, Knowles (1995), Dinesh Kumar *et al.* (1999) and Hockley and Appleton (1997) name a number of drawbacks of MTBF: (1) It is almost impossible to predict MTBF if the time-to-failure distribution is not exponential; (2) The methodology used most widely to predict MTBF and the failure rate, is based on the exponential distribution. This distribution is used to model failure times, not for any scientific reason, but primarily because if its mathematical simplicity.

Hockley (1998) states that MTBFs assume that there is an allowable constant failure. This constant failure rate is then understood in such a way that random failures becomes inescapable. Long *et al.* (2009) mention that MTBF accepts that failure cannot be accurately forecast and avoided and therefore has the negative impact that unscheduled maintenance activities have, especially when they need to be performed during operating hours. This statement can be taken further as the high costs of the consequences of failures and the unscheduled nature of the maintenance activities therefore make a notable contribution to the Total Life Operating Cost (TLOC) of the equipment or machine. Mitchell (2000) states that the traditional MTBF approach to reliability specification, has often been based on unrealistic reliability predictions and resulted in endless product testing to provide assurance. This is done without acknowledging that many failures can be prevented by, attention to basic design details.

Mitchell (2000) also makes a similar statement to both Knowles (1995) and Dinesh Kumar *et al.* (1999), in that MTBF assumes an exponential failure-rate, meaning that random failures are inevitable. Hockley (1998) and Mitchell (2000) make the point that MTBF and the use thereof, has created a culture of acceptance of failure with little or no motivation to understanding the mechanisms of when and why failures occur, but instead to concentrate on random failure.

In order to completely understand the impediments associated with the use of MTBF, it should be understood on a conceptual level, this is discussed in the next section.

2.6.4 Conceptual Evaluation of MTBF

As previously defined by the British Standards Institution (1984) standard 3811, maintenance is the combination of all technical and associated administrative actions intended to retain an item in, or restore it to, a state in which it can perform its required function. Maintenance is normally classified into two distinct categories, namely preventive and corrective maintenance. These have been defined and discussed in Chapter 2. These maintenance types have a direct impact on the reliability and ultimately the performance of the system, Yeung *et al.* (2007).

The UK Defence Standardisation (2008) Defence Standard 00-40 defines reliability as "the ability of an item to perform a required function under stated conditions for a specified period of time". Hockley (1998), however, found that reliability has often been incorrectly defined as "the allowable number of faults in a given time". This definition clearly does not support the customer's needs, the author holds the use of MTBF directly accountable for this.

It is necessary, in the context of this study, to genuinely understand MTBF conceptually. The conceptual definition necessitates an allowable constant failure rate. Hockley (1998) and Mitchell (2000) point out that this is then naturally translated into a firm belief that random failures are prescribed during the life cycle of the equipment. Hockley and Appleton (1997) state that the indiscriminate use of MTBF has given rise to a perception of belief in and acceptance of failure, which leads to no impetus to understand when and why the failure occurs in the first place. Todinov (2003) states that the classic reliability measure, MTBF, can be misleading for the non-constant hazard rate. Figure 2.16 reveals this misleading nature of MTBF. In this figure, three systems are shown, however, they all have the same 1000 hour MTBF. System 1 has three early failures, System 2 has three failures in a 1000 hour interval and System 3 has three very late failures. Campbell *et al.* (2011) states that, generally, an operation is better off with fewer downtime incidents. Looking at Figure 2.16 all three systems have few failures, however, they behave strikingly different, but the MTBF is the same for all systems. This illustrates that MTBF does not show any material information.

This definition has resulted in an entire area of engineering devoted to it and has animated people to believe that failures have become permissible. This has, according to Hockley (1998), had the psychological effect that there is no transcending motivation to understand why and when failures occur. Due to

MTBFs simplicity, it caters to the *one number syndrome* that so often exists, and is actually a over simplification of the problem. The entire concept of MTBF ostracises the efforts made by design engineers, as they do not design things to fail. Brown and Hockly (2001) make a similar statement, in that the classically used reliability matrices such as MTBF are delusive and frequently mishandled, causing ambiguity and wasted effort. Standard MTBF calculations, according to Brown and Hockly (2001), lack the ability to forecast the next failure, and assume a constant failure rate which is often untrue. Following Relf (1999), the MTBF methodology conveys the impression that there is an “allowable” level of failure, which can be classified as random, therefore the term “mean” is used.

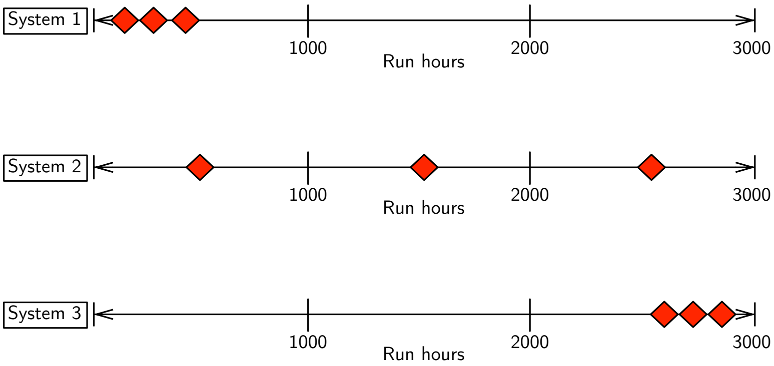


Figure 2.16: Schematic displaying how MTBF hides information. Adapted from Trindade and Nathan (2006)

MTBF can only realistically be applied to an entire fleet of equipment as an average and it therefore, according to Brown and Hockly (2001), fails to engineer a solution to the customer’s requirements as a reliability metric for specific equipment. It would be of far greater use to see the performance of individual systems. Once equipment has been given reliability, all efforts and undertakings focus on amplifying the belief in random failures.

Bottomley (2000) points to the well known fact that unscheduled maintenance is disruptive to the availability of equipment, as well as creating a dilemma in the cost effective and efficient use of assets, this in turn has a negative overall effect, as it increases the life cycle cost of the asset in question.

It can be seen from the above that the maintenance interval metric MTBF is flawed by its very definition. MTBF makes the presumption that failure is inevitable and thus creates the collective premise for a lack of strive towards reliability excellence. It is essential that there is an elementary change in the definition of the maintenance interval metric. The aviation industry also identified these inherent shortcomings of MTBF and came up with a new maintenance interval metric that address these issues, this will be presented in the following section.

2.7 Developments from Aviation Maintenance

The aviation maintenance industry, due to the innate risks within the sector, have been at the forefront of maintenance technology and practices. One such example is the Reliability Centred Maintenance (RCM) maintenance methodology (discussed in detail in Section 2.8.2), which originated from the aviation industry and is now widely used in other industries, sometimes under different names. This section outlines the history of aviation maintenance and the industries, proposed solution to the problems with the maintenance interval metric MTBF.

2.7.1 History of Aviation Maintenance

Prior to the 1950s, technical items were more inherently simple and therefore easier to maintain. According to Ahmadi *et al.* (2007) and Smith and Hinchcliffe (2004), maintenance principles in this time were a set of skills learnt over time, through experience and not based on scientific knowledge. Due to the fact that technology was not as complex and advanced as it is today, items were more reliable, therefore the most common maintenance strategy was CM. This was born out of the idea that the failures were mostly caused by wear and tear. This maintenance is reactive and is used in order to restore functionality.

After the 1950s a new era of maintenance started. Ahmadi *et al.* (2007) state that the technological advances of World War II made industry more competitive, it also improved design standards and the performance requirements of the products and services. This natural progression led to ever more complex systems in a closer and more globalised world. The increase in complexity led to an increase in downtime and thus, maintenance costs became ever more increasing. These forces led to a change in thinking, as maintenance went from reactive to proactive and PM was applied instead of CM.

According to Ahmadi *et al.* (2007), Preventive Maintenance tried to reduce the number of failures during operation by using an accepted “wear and tear” model of failure. Every item has a "fixed age" at which to overhaul the part in question or replace it completely, in order to guarantee the safe and reliable operation of the system. This time-based maintenance became the industry standard for PM.

This approach, which used overhauling and PM for all parts, no matter what their function, naturally increased maintenance costs substantially, as well as in some cases increasing the failure rate. This led airlines to rethink their maintenance programs, Ahmadi *et al.* (2007) note.

Ahmadi *et al.* (2007) further state that the FAA, concerned with developments in preventive maintenance in ever more complex aircraft systems in the 1960s, launched a task force in order to evaluate the effectiveness of time-based maintenance and to investigate the capabilities of scheduled maintenance. This research, and research done by United Airlines at the time, led to the first structured maintenance programs called MSG-1 and MSG-2. RCM was then later, in the 1970s, developed as a follow-on and extension of MSG-2. MSG-2 has since again been revised and developed into MSG-3. Shown in Figure 2.17 is an overview of the timeline of different maintenance strategies in the aviation sector.

The aviation industry has now taken it upon itself to find a solution to the deep-rooted problems with the widely used and known maintenance interval metric MTBF. Its disadvantages are discussed in Section 2.6.4, the solution is called Maintenance Free Operating Period (MFOP). MFOP is a maintenance interval metric that was born out of the military aviation environment in 1996, by the Royal Air Force, Appleton (1996) put forward the concept as a new reliability metric, in a constant drive for improvement in the areas of reliability and availability, two very important factors in the military aviation environment. MFOP is not a new concept as it can be very simply described as a warranty period. According to Dinesh Kumar *et al.* (1999), what is new is that operators are now starting to consider the concept throughout the life of the system. Chew (2010) states that MFOP attempts to satisfy the needs of dependable systems that work over long periods of time with maintenance-free operating periods, in order to carry out all assigned missions, without any loss in capability. The military roots of MFOP can also be seen, according to Chew (2010), in the fact that it caters for the ability to plan and predict, with a high probability of success, all aspects of mission and support thereof. Thereby allowing for quick deployment and the spreading of fighting across several areas. MFOP is discussed in greater detail in the next sections.

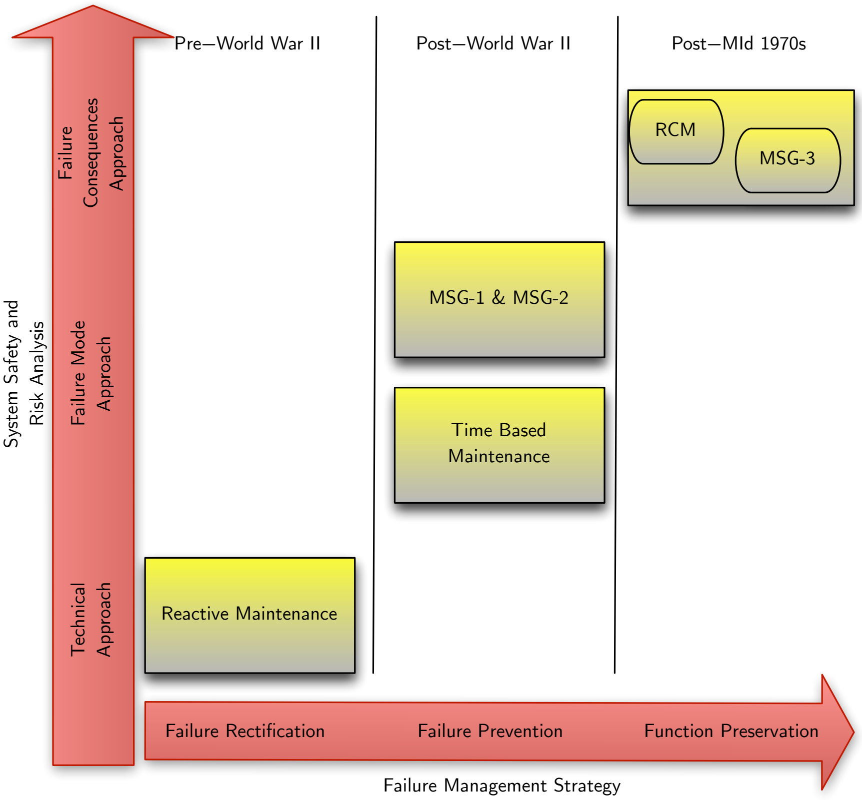


Figure 2.17: Overview of the development of the different maintenance methodologies in the aviation sector.

Adapted from Ahmadi *et al.* (2007)

2.7.2 Maintenance Free Operating Period (MFOP)

As stated in the previous section, the Maintenance Free Operating Period (MFOP) maintenance interval metric, is the aviation derived solution to the numerous problems identified with MTBF, and can simply be defined as a warranty period. However, more accurately MFOP is defined by Mitchell (2000), Brown and Hockly (2001), Dinesh Kumar *et al.* (1999), Manzini *et al.* (2009) and Long *et al.* (2009) as follows:

> *A period of operation during which the system must be able to carry out all of its assigned missions without any maintenance action and without the operator being restricted in any way due to system faults or limitation.*

Another term that goes hand in hand with MFOP is the Failure Free Operating Period (FFOP), which can be equated to ROCOF vis-à-vis MTBF. FFOP is defined by Brown and Hockly (2001) and Mitchell (2000) as:

> *A period during which the equipment shall operate without failure, however, faults and maintenance both planned and unplanned are permissible, i.e. all planned operations and cycles are completed unchanged.*

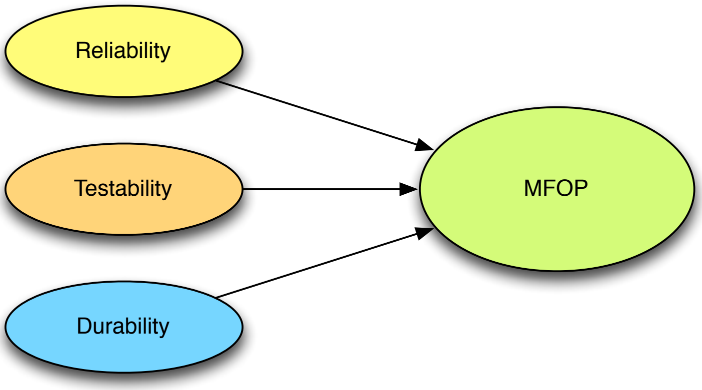


Figure 2.18: The fundamental elements of MFOP.

Adapted from Brown and Hockly (2001)

Brown and Hockly (2001) state that MFOP also utilises the employment of fault-tolerant, redundant and re-configurable systems that therefore allow for continuous operation. The fundamental elements of MFOP are shown in Figure 2.18. It is very importantly noted by Dinesh Kumar *et al.* (1999), Kumar (1999) and Mitchell (2000) that during a MFOP, the system is allowed to undergo any planned minimal maintenance, and also that redundant components can fail during an MFOP, without forcing any corrective maintenance, this ties into Brown and Hockly's previous statement. Manzini *et al.* (2009) also refers to this by mentioning that corrective maintenance under a MFOP policy has to be bypassed. Only major preventive maintenance should be carried out in previously arranged and provisioned Maintenance Recovery Periods (MRP). During a MRP, the platform would be recovered and repaired to its full operational state, prior to the beginning of the next MFOP. The length of the MRP is flexible and would be dependent on the previous and the next MFOP and also the level and depth of maintenance that is required. A MRP is defined by Brown and Hockly (2001) and Dinesh Kumar *et al.* (2006) as:

> *A period of a certain specified duration dependent upon the maintenance task that is required. The requirements for periodic maintenance tasks to be of different duration for minor and major activities would not change.*

MFOP together with FFOP are shown graphically in Figure 3.1. Each MFOP is defined as a finite period of operation, which is followed by a MRP, of a specified duration, dependent on the maintenance tasks required. It can therefore be said that the duration and content of each MRP could be directly predicted by the duration and content of the MFOP.

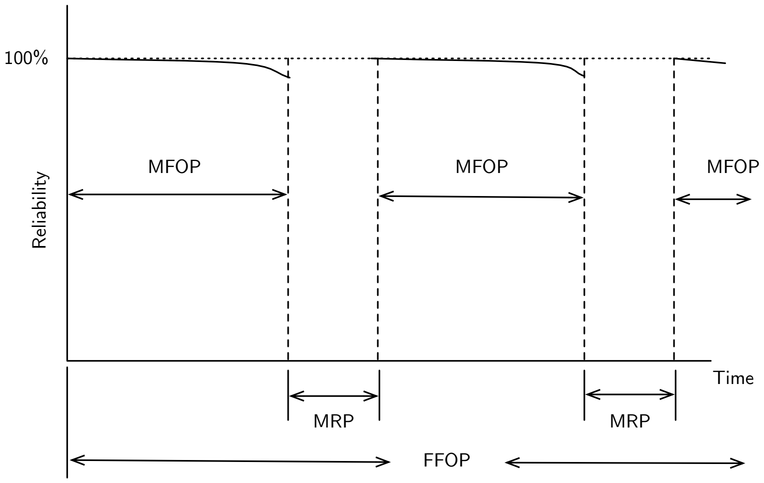


Figure 2.19: Breakdown of ideal MFOP over time, including FFOP.

Adapted from Brown and Hockly (2001)

Mitchell (2000) and Chew (2010) state a number of key benefits that accompany a MFOP maintenance interval philosophy:

1. The equipment would only need particular levels of maintenance at predetermined intervals that would greatly enhance operational effectiveness. Equipment would be available when needed and operational failures would be greatly reduced.

2. Maintenance downtimes could be programmed around operational times and according to the equipment's operator.

3. Reduced random component failures, and thereby a reduction in the probability of emergency or reactive maintenance.

4. Even though MFOP is still based on statistical failure analysis, as in MTBF, it is a more physical approach and therefore more likely to identify the true causes of failure.

5. The assumption of a constant failure rate would be challenged, thereby giving a more realistic bottom-up approach, rather than a top-down one.

6. The use of MFOP, rather than MTBFs, and the acceptance of random failures, would improve logistical planning, thus a more realistic provisioning of spares would be possible, as unscheduled maintenance is minimised or even eliminated.

7. The MFOP approach would provide a far simpler and more confident prediction of total life cycle costs of the equipment or system.

8. There would be improvement in the availability of the system, as the successful application of MFOP will create a greater chance of completing a certain mission, thus reducing the time spent in the down or failed state.

This section introduces the MFOP principle and defines accompanying terminology in order to understand the complete concept. It has already been seen that the MFOP philosophy stands in stark contrast with MTBF philosophy. In the end it is the philosophy and mindset that MFOP encompasses that will hold the majority of the benefit and not the metric itself. The dissimilarity between the two can be seen on the most fundamental levels of definition, this theme is further explored in the next section.

2.7.3 Conceptual Explanation of the MFOP – The Paradigm Shift

In order to gain a better understanding of MFOP, one should analyse the fundamental concepts behind its origin. Beginning with the fact that random failures inherently mean corrective maintenance must be carried out, which in turn has a significant contribution to the TLOC. Taking this into account, it would be advantageous to be able to guarantee a MFOP that diminishes the monetary risks related to the costs of failures and unscheduled corrective maintenance. MFOP therefore boils down to being a maintenance philosophy obtained from the operational requisite of needing periods of guaranteed availability and reliability.

Long *et al.* (2009) point out some MFOP concept change drivers, these being changes in design, operation and maintenance planning. This is done to realise success in the operational environment with minimal maintenance inside a MFOP, achieved through the use of failure anticipation, avoidance and maintenance delay. Brown and Hockly (2001) state that MFOP measures the probability of being able to successfully complete an operation or a series of operations, without maintenance degrading the ability to conduct the next operation or series of operations. A key point differentiating the reliability metric or maintenance interval MFOP from that of MTBF is that MFOP assumes, from the outset, that success is attainable and that the probability of success can be accurately forecast from entry into service, Brown and Hockly (2001) state that MFOP specifies customer needs in unambiguous terms. Levitt (2003) provides a quote for the mission of maintenance:

> *The mission of the maintenance department is to provide reliable physical assets and excellent support for its customers by reducing and eventually eliminating the need for maintenance services.*

Looking at this statement, it is important to note the word “eliminating”. The MFOP philosophy, as stated previously, attempts to remove unscheduled maintenance actions from equipment operation. Levitt (2003) statement of “eliminating the need for maintenance service” is an ideal case or the so called “holy grail”, MFOP provides a substantial first step towards this goal.

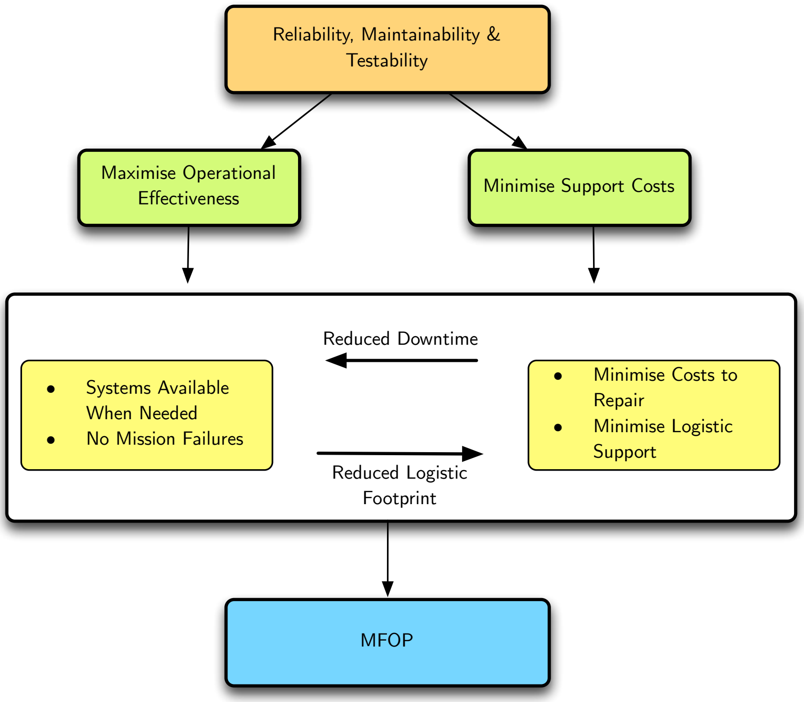


Figure 2.20: Motivators for MFOP.

Adapted from Hockley (1998)

Hockley (1998) points out the reality that, in large projects, procurement costs are normally the only factor taken into consideration when analysing affordability, however, these should be coordinated with accomplishing the least through life support costs or TLOC: MFOP can achieve this. Curbing and capping random failures may result in a significant reduction in corrective maintenance performed, hence, according to Hockley (1998), substantially increasing a company's asset effectiveness and lowering the supportability costs for their assets. Brown and Hockly (2001) state that MFOP would yield more reliable equipment, the author goes further by stating that in the MFOP methodology, maintenance needs would be more accurately known, thus shrinking the logistical footprint and spares consumption. Equipment reliability, according to Khan (2001), is a competitive advantage in today's global environment, this should align more with corporate and shop floor maintenance strategies, as also suggested by the British Standards Institution (2008) PAS 55 standard. Figure 2.20 shows graphically the advantages of using a MFOP philosophy. Table 2.2 summaries the major differences between MFOP and MTBF.

Table 2.2: Summary of advantages between MFOP and MTBF

MFOP	MTBF
MFOP assumes success is attainable and failures can be accurately forecast.	MTBF accepts failure cannot be accurately forecast or avoided.
Does not allow and tries to eliminate unscheduled maintenance.	Accepts random failure therefore accepts unscheduled maintenance activities.
Replaces expensive unscheduled maintenance with cheaper scheduled maintenance.	MTBF endorses unscheduled maintenance by accepting failure.
Bottom-up approach to maintenance.	Top-down approach to maintenance.
Helps operators/organisations understand their equipment better, a more detailed, focused and customised approach to maintenance	MTBF is by definition an average calculation and not as focused as MFOP.
Exploits systems that are fault-tolerant, redundant and reconfigurable.	Treats all systems the same.
Using MFOP maintenance downtime can be programmed or scheduled around the specific operational commitments.	MTBF does not directly provide for this.
Using a MFOP maintenance strategy a far better and more accurate TLOC can be forecast.	Due to random failure acceptance, TLOC can not be forecast accurately.
Could potentially reduce logistics footprint by more accurately forecasting which spares will be needed.	Due to random failures, spares will not always be available or known.
The philosophy behind MFOP could potentially tie in better with existing maintenance management strategies such as Total Productive Maintenance (TPM) and Reliability Centred Maintenance (RCM)	MTBF is traditionally used within TPM and RCM.

2.8 Wider Application of MFOP

As seen in the previous sections, the definition, philosophy and concept of MFOP maintenance interval metric holds some unique advantages over the traditionally used MTBF. Over the years, a number of different maintenance management methodologies have been defined for industry application and often refreshed and renamed. Two major and dominating methodologies, Total Productive Maintenance (TPM) and Reliability Centred Maintenance (RCM) are discussed in the following Sections 2.8.1 and 2.8.2 respectively, Section 2.8.3 shows how the MFOP philosophy fits in with these methodologies.

2.8.1 Total Productive Maintenance (TPM)

Total Productive Maintenance (TPM), unlike many other maintenance methodologies, directly links maintenance to business performance and practices. According to Hutchins (1998), TPM challenges the view that maintenance is done in the background and only appears when it is needed – meaning when something is broken.

History and Formation of TPM

The concept of TPM comes from Japan, according to Venkatesh (2007) the origins of TPM can be traced back to 1951. At the time, preventive maintenance was introduced to Japan after the Second World War from the United States. Nippondenso, a large automobile supplier, was one of the first Japanese companies to introduce complete PM in 1960. The PM used entailed operators producing goods and the maintenance group dedicated to the maintaining of machines. This, however, very soon became a problem within Nippondenso, due to their high level of automation. Management then decided to make routine maintenance the responsibility of the operator, this became known as autonomous maintenance, a predominant feature of TPM.

This decision caused Nippondenso to have an active preventive maintenance program and an added autonomous programme performed by operators. The maintenance crew then only performed essential maintenance work, the total company wide maintenance program then consisted of revertive maintenance, together with maintenance prevention and maintainability improvement. This gave rise to Total Productive Maintenance.

The TPM Framework

Ever increasing global competitiveness has, according to Brah and Chong (2004), raised the importance of TPM in gaining and sustaining a competitive advantage. Organisations are seeking proactive tools such as TPM, in order to boost their competitive position. TPM, as detailed by Brah and Chong (2004), covers the entire life of equipment in every division of the organisation including planning, manufacturing and maintenance. It creates a relationship between all organisational functions but particularly between production and maintenance that have traditionally stood apart. The Japan Institute of Plant Maintenance (1990) argues that both operations and maintenance departments should accept the responsibility of keeping equipment in a good condition. Nakajima (1988) states that this relationship between production and maintenance departments drives continuous improvement of product quality, operational efficiency, capacity assurance and safety.

Nakajima (1988) also puts forward a definition of the word “total” that forms part of the name TPM, he states that it has three meanings:

1. *Total effectiveness:* pursuit of economic efficiency and profitability.
2. *Total maintenance system:* includes maintenance prevention, maintenance improvement and PM.
3. *Total participation:* refers to the fact that all employees, including operators, are expected to take responsibility for maintenance activities and that maintenance is a team effort.

Nakajima (1988), being the founder of TPM as we know it, also provides us with the five pillars of TPM, these are:

1. Maximise overall equipment effectiveness.
2. Establish a thorough system of preventive maintenance for the equipment’s entire life span.
3. Implement TPM by involving all departments.
4. Involve every single employee, from top management to line worker.
5. Promote TPM through so called *motivation management*; autonomous small groups.

As one can see from the above mentioned five pillars, the TPM methodology is very much tuned to a heavy manufacturing environment, as it originated from this industry. McKone *et al.* (1999) state that TPM provides a comprehensive company-wide approach to maintenance management that involves all employees of the organisation, it is usually split into a short-term and long-term element. The short-term focuses on the autonomous maintenance programme within the production department and a planned maintenance programme within the maintenance department. In the long-term view, the focus is on new equipment design and a concerted effort to get rid of lost equipment time. In his book, Hartmann (1992) describes many differences between TPM as used in Japan and how it is used in the United States. The author states that it is very important to customise the TPM process to work for a specific environment and the cultures of different people. He suggests that there are unique external and specific factors, such as country, plant and management aspects, to any TPM implementation. Both Powell (1995) and Brah *et al.* (2002) suggest that top management support and planning leads to the success of a TPM program.

Autonomous Maintenance

Both Suzuki (1992) and Nakajima (1988) state that autonomous maintenance is one of the most important steps within the short-term effort. At the core of Autonomous maintenance is the 5 S's strategy: *seiri, sexton, seiso, seiketsu* and *shitsuke.* These are Japanese words and can be translated as: organisation, tidiness, purity, cleanliness and discipline. The 5 S's concept is essentially a housekeeping notion. Hutchins (1998) compares the cleaning activities to steam cleaning the engine of a car. When the car is dirty, it is impossible to tell if any screws are missing or if there are any fluid leaks. However, when clean, missing screws and leaking fluid can easily be identified. The added benefit to this procedure, according to Hutchins (1998), Suzuki (1992) and Nakajima (1988), is that the operator will begin to gain a better understanding of the machine and how it works. Brah and Chong (2004) state that TPM depends on operators to perform autonomous routine maintenance and, continuous improvement being a fundamental element of a TPM program, this again depends on the worker's willingness to accept changes and adapt to new environments.

Overall Equipment Effectiveness

Overall Equipment Effectiveness (OEE) is one of the main goals and measures of TPM. The OEE ratio is defined by both Willmott and McCarthy (2001) and Hutchins (1998) in equation 2.5.

$$\text{OEE} = \text{availability} \times \text{performance} \times \text{quality rate} \tag{2.5}$$

where,

availability = proportion of the total time during which the equipment is available.

performance = measures of how close the average cycle time is to the theoretical minimum.

quality rate = proportion of the processed quantity that is of acceptable quality.

According to Hutchins (1998), typical OEE calculations range between 40% and 50% before implementation, and can rise up to between 80% and 90%. Nakajima (1988) states that the basis for OEE comes from the fact that the objective of any production improvement activity is to increase productivity by minimising input and maximising output. By output the author also includes quality, reducing costs and meeting delivery dates, while increasing worker morale and improving health and safety.

Nakajima (1988) defines input as labour, machine and materials. Output is defined as production (P), quality (Q), cost (C), delivery (D), safety, health and environment (S) and morale (M). In the end, TPM attempts to maximise the PQCDSM output, this is achieved by creating and maintaning optimal operating conditions and running machines effectively. In order to achieve OEE, the TPM methodology defines "six big losses" that TPM works to reduce and eliminate. These losses are defined by TPMs founder, Nakajima (1988) as:

Downtime:

1. Equipment failure (breakdowns)
2. Setup/adjustment

Speed losses:

3. Idling and minor stoppages
4. Reduced speed

Defect:

5. Process defects
6. Reduced yield

Hutchins (1998) states that cost effectiveness is a result of an organisation's ability to eliminate the causes of the above mentioned losses that reduce the OEE. Chan *et al.* (2005) state that OEE is an effective way of analysing the efficiency of a single machine, as well as a complete and integrated manufacturing system. Willmott and McCarthy (2001), however, state that OEE cannot only be used to assess machinery, but should be applied to the entire business, monitoring the effectiveness of the whole value chain. OEE is a direct help to the operator and the core TPM team, to focus their efforts in limiting and eliminating the six losses stated above.

2.8.2 Reliability Centred Maintenance (RCM)

Smith and Hinchcliffe (2004) state that during the early days of the Industrial Revolution, designers of industrial equipment were also the operators of the equipment. Out of this was born a very close relationship between the hardware and the designer, the designer knew what worked, when and for how long. When something broke the designer would know how to fix it. This experience led to, early formulation of PM actions.

According to Smith and Hinchcliffe (2004) and Wessels (2011), during the 1940s and 1950s the early roots of reliability engineering were found in the form of the bathtub curve. It was observed that electronic sample populations had a high but decreasing rate of failure, until they reached a point where there would be a long period of a low constant failure rate. Finally, there would be a point where the failure rate would once again begin to increase sharply, due to ageing and wear-out. These findings quickly worked their way into the maintenance strategies from non electronic industries, and this was called the bathtub curve. This led to the fact that until the 1960s most equipment maintenance strategies were PM strategies based on the bathtub curve.

The Bathtub Curve Fallacy

It was found that many components do not comply with the bathtub curve, in terms of failure rate. According to Smith and Hinchcliffe (2004) and Wessels (2011), a lot more has been assumed than actually measured. In order to prove such a curve, a very large sample size is needed with recorded data on failures, these are of course very hard to come by.

Fortunately, within the aviation industry, there are large populations of identical or very similar aircraft components in use. It is often the case that there are common components to many aircraft types. Also, according to Smith and Hinchcliffe (2004), within the industry, there have been concerted and successful efforts to develop databases of the operating history of components and to share this information globally.

As a prelude to RCM, United Airlines commissioned a study using failure databases to find age-reliability patterns, specifically for non-structural components in their fleet. The study was meant to explore whether aircraft components indeed follow the bathtub curve. The results from the the study are shown in Figure 2.21 and Table 2.3.

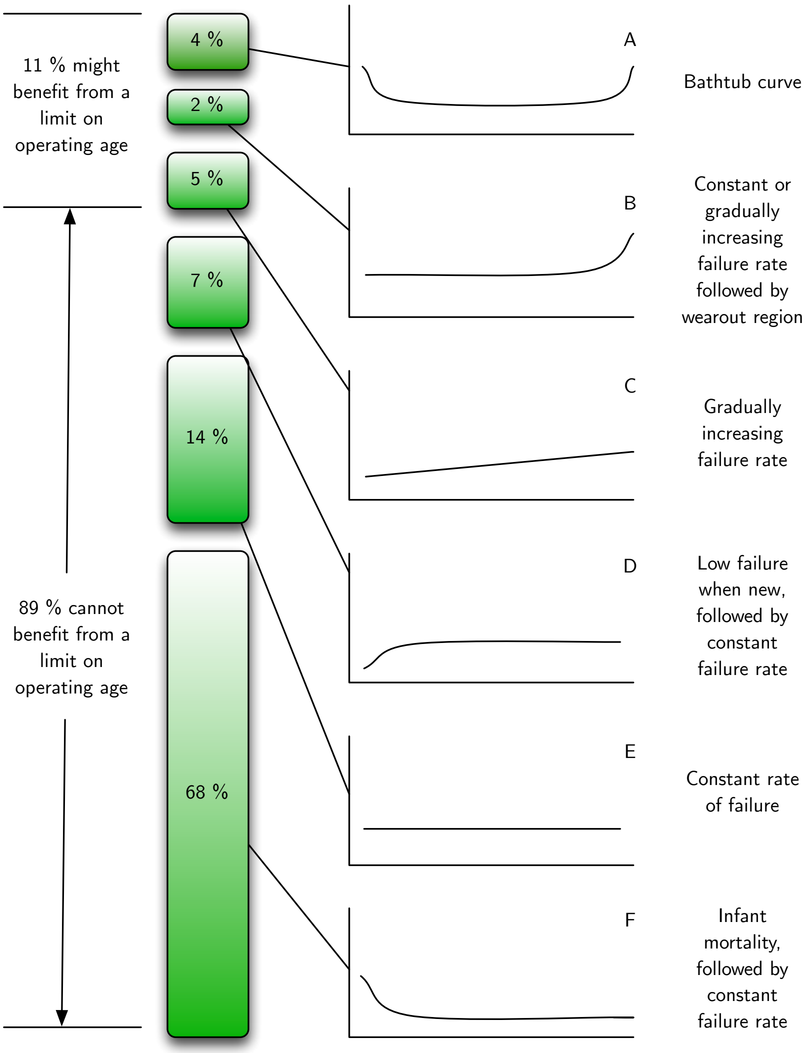


Figure 2.21: Age-Reliability patterns for non-structural components, United Airlines (UAL).

Adapted from Stanley and Heap (1979)

According to Smith and Hinchcliffe (2004), the results were surprising and unexpected. In later studies performed by the US Navy, essentially identical results were found. These included random failures accounting for 77–92 % of the total population, age related failures only made up the remaining 8–23 %.

The analysis by Smith and Hinchcliffe (2004) of Figure 2.21 show the following important points.

1. Only 3–4 % of the population actually followed the bathtub curve (A).
2. Importantly 4–20 % of components in the population experienced very distinct ageing during the useful life of aircraft fleets (A and B). One

Table 2.3: Age-reliability patterns.

Failure Rate by Type	UAL 1968	Bromberg 1973	U.S. Navy 1982
A	4 %	3 %	3 %
B	2 %	1 %	17 %
C	5 %	4 %	3 %
D	7 %	11 %	6 %
E	14 %	15 %	42 %
F	68 %	66 %	29 %

Adapted from Smith and Hinchcliffe (2004) and NASA (2008)

could also include curve C within this ageing pattern, which would mean that only 8–23 % of components show ageing characteristics.

3. Surprisingly, a majority of 72–92 % of all components in the population never saw any ageing or wear-out characteristics over the useful life of an aircraft. (D, E and F).
4. Some components also experienced infant mortality characteristics (A and F).

Important points regarding the bathtub curve fallacy exist, such as failure not being directly related to age or use. Failure is not easily predicted and therefore restorative maintenance based on time will not normally improve failure odds.

History of RCM

Ahmadi *et al.* (2007) write that the basis for RCM was developed in the 1970s within the aviation industry in response to the need for greater safety in ever more complex and technologically advanced aircraft. Smith and Hinchcliffe (2004) state that RCM epitomises the old adages that “necessity is the mother of invention”. With the Boeing 747 Jumbo Jet about to come into service, the US Federal Aviation Authority (FAA) needed to approve a preventive maintenance program to be used by operators of the aircraft. Due to the massive size difference (approximately by a factor of 3) between the Boeing 747 and the next largest aircraft, at the time, the Boeing 707, preventive maintenance strategies available at the time would not have allowed operators to be profitable.

The United States Department of Defence (DOD) started the process by sponsoring United Airlines, who already had some experience in the field, to write a comprehensive report titled "Reliability-Centred Maintenance (RCM)" (MIL-STD-2173). Smith and Hinchcliffe (2004) state that this came about because of concern with the failure statistics for some aircraft engines, which were being maintained under time-based and preventive maintenance strategies. Added to this, time-based maintenance, overhauling or disposal of all parts within the system were driving costs up for the aviation industry.

Before the RCM or Maintenance Steering Group (MSG) methodologies were created, the FAA analysed data that suggested that while under time-based maintenance the frequency of some failures had been reduced, the majority had remained the same and a small number had actually increased. At the time, concurrent research that analysed the failure data, indicated that the standard model of failure did not apply. The probability of failure did not increase over time and time-based strategies were not effective in this environment, Ahmadi *et al.* (2007) and Smith and Hinchcliffe (2004). It is based on this assumption that inherent reliability of the item or system is directly proportional to the design and build quality of that item. According to Rausand (1998), RCM is the tool that will insure this inherent reliability, but it cannot improve reliability. An improvement would only be possible through a redesign of the system. Today, many major corporations are in some stage of RCM usage and have thereby revamped their PM strategies through the implementation of RCM methodology, write Smith and Hinchcliffe (2004).

An FAA panel was tasked to investigate the effectiveness of traditional time based and scheduled maintenance, and the relationship between the scheduled maintenance and reliability. The panel came to the following conclusions, Ahmadi *et al.* (2007):

- Scheduled maintenance or overhauls had little or no effect on the overall reliability of complex systems, unless they had a dominant failure mode.
- A large number of items do not have an effective form of scheduled maintenance.
- Even with intense overhauls, many failures cannot be avoided.
- There is not always a direct correlation between cost and reliability, cost reductions can be achieved without decreasing reliability.
- Overhauls by their definition can play a leading role in unreliability.

After this, the MSG methodologies were written. RCM, as stated above, was an extension and shift from MSG-2. According to Ahmadi *et al.* (2007), RCM methodology supports a well structured and logical decision process, which is used to identify the policies that are needed to manage failure modes that could cause the functional failure of any physical item or system. RCM can be considered to be a complete solution or program which brings together preventive maintenance and predictive maintenance or redesign. PM is often misunderstood, the wrong belief is that the more an item is routinely maintained, the more reliable it will be. This is not the case and in many cases the opposite is actually true. RCM achieves inherent reliability by using an effective maintenance program and was designed to balance costs and benefits in order to create the most cost efficient maintenance program. An important point remains, a RCM program will never be a fix for poor design or poor build quality. RCM has a general guideline of questions that any RCM process should be able to answer, Rausand (1998):

1. What are the functions and associated performance standards of the item in its present operating context?
2. In what ways does it fail to fulfil its functions?
3. What are the causes of each functional failure?
4. What happens when each functional failure occurs?
5. In what way does each failure matter?
6. What can be done to prevent each failure?
7. What should be done if a suitable preventative task cannot be found?

The questions that are stated above are answered by the RCM methodology, by using a structured decision diagram. This includes the Failure Mode and Effects Analysis (FMEA) methodology to answer questions regarding function, functional failures and failure modes. FMEA classifies the severity of each identified failure effect, according to a classification criteria that is created for each program.

Major Features of RCM

According to Smith and Hinchcliffe (2004) and Dhillon (2002), there are four main features that make RCM completely unique, these are summarised below:

- Preserve functions;

- Identify modes that can defeat the functions of the system in question;
- Prioritise function need (failure modes); and
- Select applicable and effective PM tasks for the high priority failure modes.

RCM uses historical data when it is available, however, when this is not available, an age exploration program must be initiated for maintenance tasks. Independent auditing is also required under the RCM methodology. RCM is based on the following concepts:

- Acting on a system wide level instead of a component-based level;
- Top down approach;
- Function preservation technique;
- Task-oriented and not process-oriented; and
- Consequences of failures are far more important than technical attributes, therefore consequence driven.

As stated above, RCM is consequence driven and therefore, the consequences of every failure have to be analysed and evaluated. Events and failures must be distinguished from one another: hidden failures from evident failure modes. Also be categorised in terms of safety: environmental, operational and economic. Because RCM uses a system-wide method, each component is treated differently, in terms of its importance to the entire system function. Due to this system-level implementation, far better system performance can be realised, including improved safety and operating performance, as well as a better understanding of the failure modes and decreased maintenance costs.

Figure 2.22 shows the four different components of RCM. Any maintenance strategy labeled as a RCM must contain all four of the above stated features, to be a true RCM strategy.

Cost Benefit of RCM

As stated previously, one of the major driving forces behind the creation of RCM, was to have high system availability and safety at the lowest cost. This has been very successfully applied to the commercial aviation industry. Figure 2.23 shows the cost of maintenance per flight-hour for the first ten years of RCM use, when compared with the factors of fuel and flight crew costs. It should be noted that the large increase of fuel costs throughout the 1970s is due

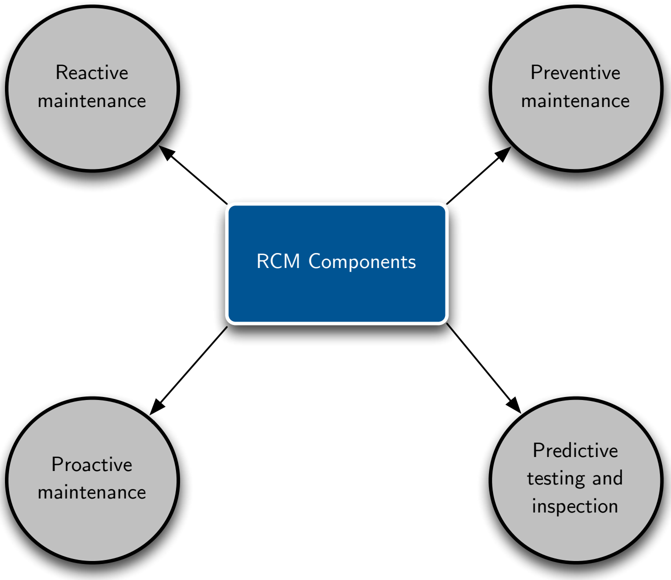


Figure 2.22: Overview of components of RCM.

Adapted from Naval Air Systems Command (1996)

to the Organisation of Petroleum Exporting Countries, (OPEC) oil embargo crisis, Smith and Hinchcliffe (2004).

In the period shown in Figure 2.23, the maintenance costs remained essentially constant, however, during this period, a number of large, new era commercial aircraft were introduced to the market including the Boeing 747, the McDonald Douglas DC-10 and the Lockheed L-1011 TriStar. Even though these new aircraft were about three times larger than the aircraft they replaced (Boeing 707 and McDonald Douglas DC-8), maintenance costs remained largely constant. According to Matteson *et al.* (1984), RCM was the main reason for the fairly constant maintenance costs.

Smith and Hinchcliffe (2004) also indicates another impact of RCM, illustrated in Table 2.4. Table 2.4 shows the maintenance processes in three different years. The first, 1964, is pre-RCM and the other two, 1969 and 1987, post-RCM. It clearly shows a massive reduction in the hard-time units over the entire period, hard-time tasks make up costly component overhauls. The hard-time tasks have been replaced with condition-monitored items. RCM provides the unique advantage of being able to use design features to the benefit of the final maintenance strategy, these include taking into account double and triple redundancy in newer design philosophies.

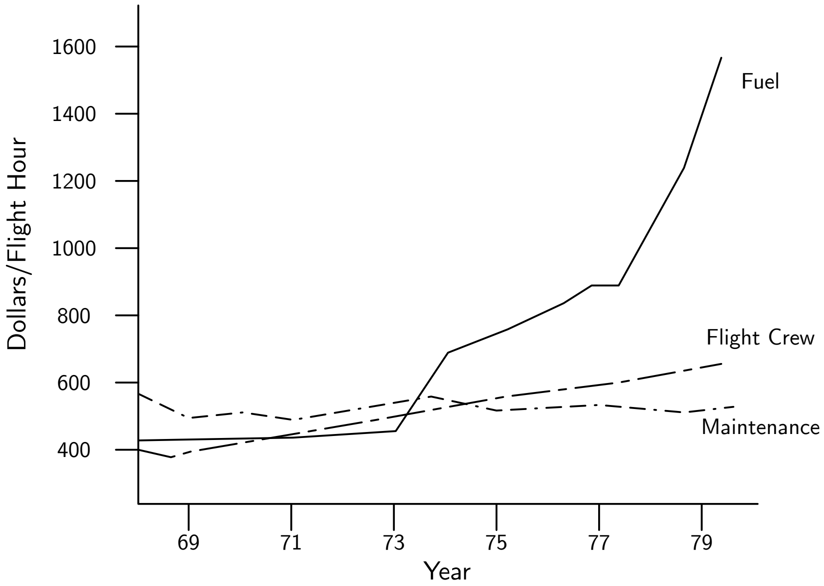


Figure 2.23: Costs per flight-hour in 1982 constant US dollars.

Adapted from Matteson *et al.* (1984)

Table 2.4: Commercial aircraft component maintenance policy.

	Component distribution		
Maintenance Process	1964	1969	1987
Hard-time Items	56 %	31 %	9 %
On-condition Items	40 %	37 %	40 %
Condition-monitired Items	2 %	32 %	51 %

Adapted from Smith and Hinchcliffe (2004)

2.8.3 Integration of MFOP into Maintenance Methodologies

From the two maintenance management methodologies discussed in this section, TPM and RCM, a number of comments can be made regarding the integration of MFOP into these, replacing the normally used MTBF.

Beginning with TPM, MFOP firstly uses a bottom-up approach to maintenance. By definition, it forces the maintenance personnel to know the system or equipment in question better. This ties in with TPMs methodology of autonomous maintenance and better understanding the equipment. Secondly, MFOP, by its very fundamental definition, believes that success is attainable and unscheduled failures should not be accepted and should be minimised as far as possible, this is in strong contrast to MTBF. This belief could bring about even further improvements to the OEE within TPM, as it brings advances to the "six big losses", such as equipment breakdowns and reduced yield. Searching literature does yield many specific applications of MFOP in TPM, only Long and Jiang (2011) was found to have integrated MFOP and TPM in order to improve the OEE.

The RCM maintenance management methodology also integrates well with the MFOP philosophy. MFOP aims to have a system with the highest reliability, for the longest time and at the highest probability. Even though MTBF ultimately also wants to achieve this, it does this in an ambiguous and contradictory manner. RCM also aims to achieve the highest reliability possible, while preserving functions. RCM prioritises the failures modes, focused improvements can thus be made in these areas and the direct effect can be seen by the improvement of the MFOP length. MFOP reasoning exploits systems that are fault-tolerant, RCM also reasons in this manner. Long *et al.* (2009) looked at integrating MFOP and RCM and were able to reduce the Total Life Operating Cost (TLOC) in doing so.

2.9 Summary

Ever since the industrial revolution, the practice of maintaining engineering systems has been a great challenge. In spite of this fact, there has been substantial progress in the effectiveness and efficiency of maintenance. However, many challenges remain in this field, such as, cost, complexity, competition and the interdisciplinary nature of organisational engineering maintenance. Factors such as complexity and competition, play an even larger role within today's ever increasing technological advanced organisations and in the "global village", which corporations find themselves in . Added to this, are further external factors such as, suppliers, and environmental and safety pressures. This not only calls for but also necessitates, a need for effective PAM and ancillary maintenance practices that will positively impact vital elements within an organisation.

It can be seen that the field of PAM is extremely diverse. It integrates many conflicting levels within an organisation, from the highest to the lowest levels, in order to achieve success. This fundamental complexity of PAM has been identified and the British Standard PAS 55 attempts to address these difficulties with a over arching framework. Due to the relative youth of the standard, there has been a large interest in research in the general implementation of PAS 55 but no real detailed supporting fields have been investigated.

Maintenance is a tremendously important part of PAM, and also thus PAS 55. Areas of constant interest are topics such as, asset care plans, preventive and corrective maintenance and condition monitoring, to name just a few. However, an area over looked only until recently, has been reliability metrics and more specifically Mean Time Between Failure (MTBF). There are certain fundamental problems with the way MTBF approaches and defines reliability, these have been detailed in this chapter. The aviation sector, a branch of industry that, just like the mining sector, is massively asset intensive, has looked at alternatives to these fundamental problems. The proposed solution stemming from this sector is in the form of the Maintenance Free Operating Period (MFOP). MFOP strives to attend to the fundamental flaws that MTBF has bestowed. The aviation sector, like the mining sector, is very safety conscious and is therefore relatively conservative when applying new concepts in practice. The beauty of the MFOP concept is that it defines existing failure statistics and reliability concepts in a different way, but still remains compatible, if not even better integrated, with existing maintenance methodologies such as RCM and TPM.

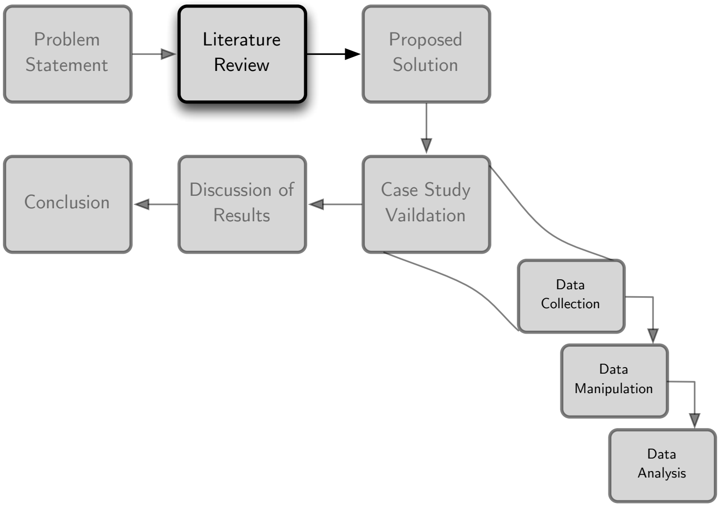
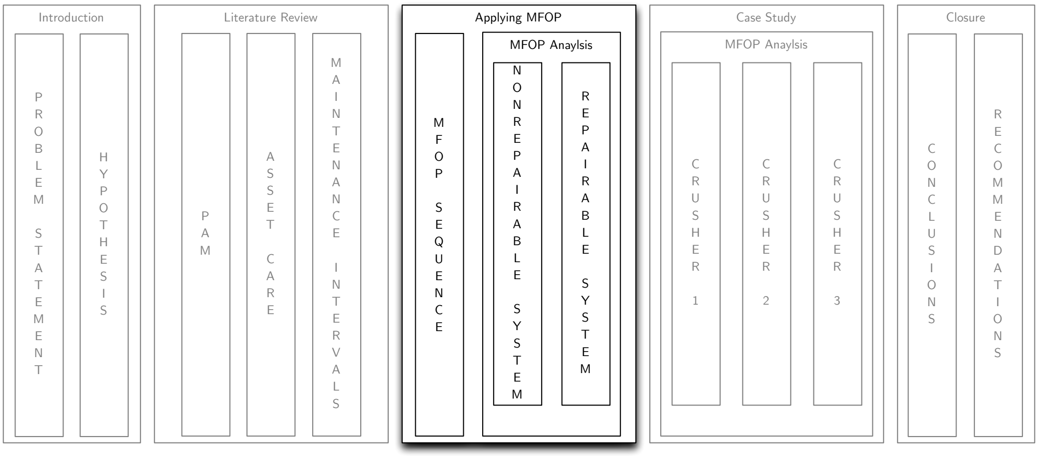


Figure 2.24: Research flow highlighting Chapter 2.

Figure 2.24, how Chapter 2 fits into the overall research flow. The Chapter contextualised the problem and from this a proposed solution was presented. The following Chapter, Applying the Maintenance Free Operating Period Paradigm, explains the application of the MFOP on a failure data set, worked examples are also provided.

Chapter 3

Applying the Maintenance Free Operating Period Paradigm



Chapter Aims:

This chapter aims to develop and explain the implementation methodology of the MFOP principle. Set forth are the theoretical calculations of both MTBF and MFOP and how they would be applied to a system's or equipment's life data set, and the use of failure statistics for both repairable and non-repairable system.

Chapter Outcomes:

⇒ Understanding the application methodology implemented in the case study.
⇒ Employment failure statistics for both repairable and non-repairable systems.
⇒ Utilising MFOP statistics for both repairable and non-repairable systems.

3.1 Introduction

This chapter introduces the reader to the application methodology or proposed solution that will be further used in this study. A brief explanation of the MFOP sequence is given as additional background knowledge. Once the MFOP analysis is rendered, an overview of the application methodology is given in Figure 3.2 on Page 77 and is split into four distinct phases. Within the application methodology data trends, failure statistics and MFOP theories are illustrated.

3.2 The MFOP Sequence

Due to the fact that MFOP, unlike MTBF, fundamentally does not accept random failures, a specific sequence for maintenance operations is formed. This sequence is formed from the calculation of the MFOP being a certain number of hours long. As illustrated in Figure 3.1, already shown in Section 2.7.2 and reproduced here again for convenience, schematically shows the breakdown of a MFOP. Here it can be seen that, in an ideal case, reliability would drop from 100 % over time, down to a predefined and chosen lower level reliability value that would define the length in hours of the MFOP. Shown here is an ideal case, because reliability of a system would never be 100 %, as no system would ever have perfect reliability.

After the MFOP of a certain calculated length, determined by reliability at a certain pre-chosen value, the system or equipment is taken out of service and the MRP is initiated. MRP, already defined in section 2.7.2, is where all maintenance activities are performed, preventive as well as corrective, for redundant items. All activities performed during the MRP are done in order to bring the system in question back to its original reliability, as it was, at the beginning of the previous MFOP, so that a new MFOP may begin. Preplanned minimal maintenance, such as the replacement of consumables and oil changes, are allowed during the course of an MFOP.

The FFOP shown in Figure 3.1, describes the time the system or equipment has gone without failure. This failure is defined as a failure that causes the complete stop of the system, thereby not allowing the system to complete its assigned mission. Faults in redundant components are still permissible.

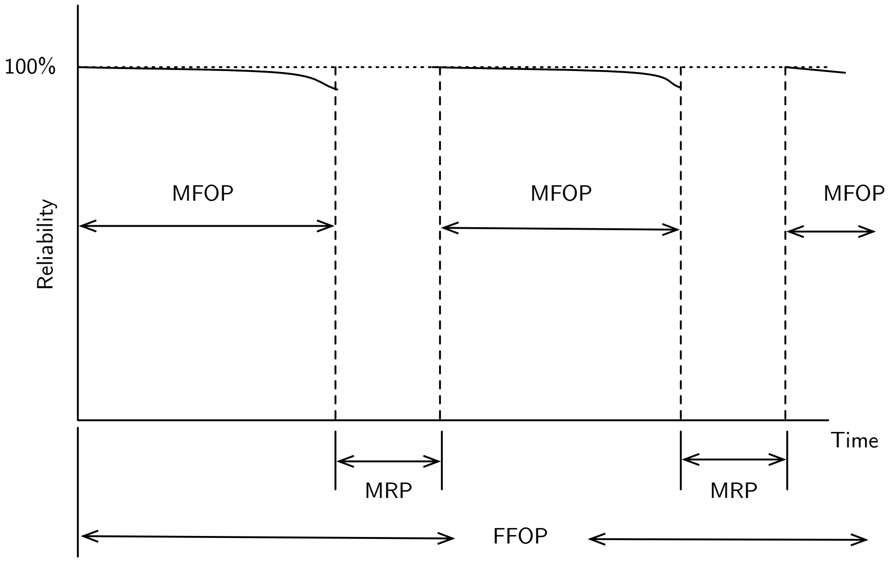


Figure 3.1: Breakdown of MFOP over time, including FFOP.

Adapted from Brown and Hockly (2001)

3.3 MFOP Analysis

In order to get started with an MFOP analysis, a system or piece of equipment should be identified. A substantial amount of historical maintenance/failure data should be available, unless the system in question has been designed from its conception with MFOP in mind. Data that are already in electronic form are of course preferred, this saves time as opposed to transferring manual records to electronic form. The more data that are available, the better, ini order to improve the prediction of the MFOP of the chosen system. The complete methodological overview is given in Figure 3.2.

3.3.1 Identification of System

In order to identify which equipment the MFOP methodology should be applied too, a basic question is asked. Which equipment or sub-systems of equipment are critical to be kept in a running condition, with minimal unplanned maintenance interruptions? This decision should be made on the basis of minimising output loss from the system, through a reduction or eradication of unplanned maintenance activities, a criticality analysis can provide this. It is of course ultimately desired that all equipment found necessary, runs on an MFOP maintenance program. An overview of the overall methodology is shown in Figure 3.2, here phase 1 is specifically highlighted, which is discussed in this section and the next section.

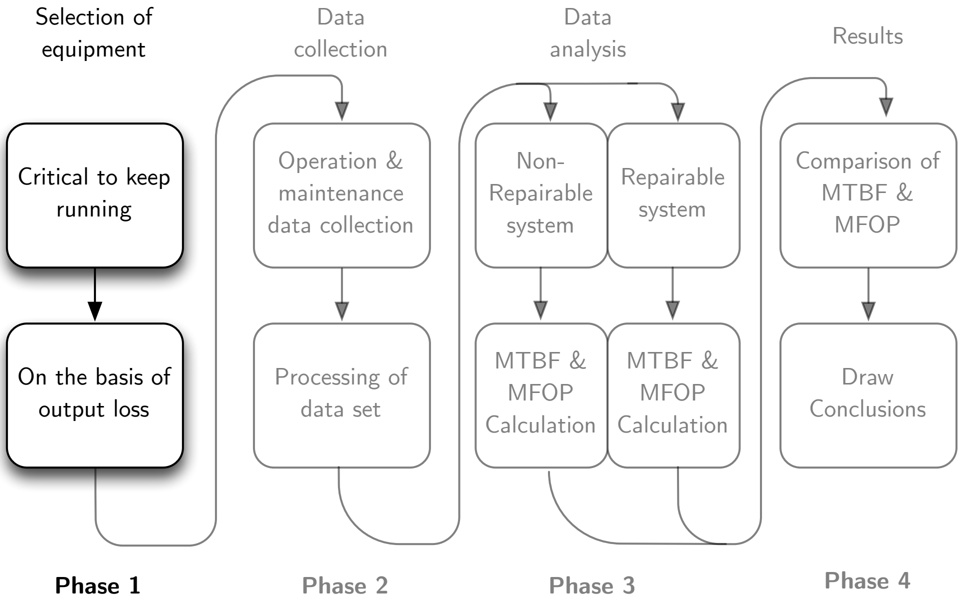


Figure 3.2: Main steps in the applied methodology, with emphasis on phase 1

3.3.2 Setting System Boundaries

The setting of system boundaries is dependent on a number of factors. The level of detail in the failure data that is available, if detailed maintenance data is available on a single component level, then the system can be analysed on that level of detail. However, if the data only display failures on an entire system level, then the system boundary on the vertical scale must be set to analysing the system as a whole or in its entirety. Figure 3.2 shows how this section is placed into the overall analysis methodology, making up phase 1.

On the horizontal scale, the system boundaries set will depended on the complexity of the system and its surroundings. The complexity of the study will be directly proportional to the complexity of the system chosen. It is therefore advantageous to study smaller pieces of the greater system and to only subsequently place parts together.

Helpful in setting system boundaries would be to use the systems manufacturer's manuals and guides, in order to gain an understanding of the parts and their interrelations to each other within the system. Once boundaries are set, failures falling outside these boundaries will not be taken into account for the scope of the study.

3.3.3 Identification of Correct Failure Data

Failure data should firstly only be relevant to the system that has been chosen for analysis. It is therefore important that the system boundaries are not only correctly set but also understood. If for example only one part of a system is analysed, then failure data only relevant to that part should be taken into account. If, however, the entire system is analysed, then failure data up to the chosen boundary should be taken into account.

If summaries of failures for the system are readily available, then these should be used. However, if no condensed version is accessible, then individual job cards for the equipment chosen must be obtained and captured, for the chosen study period, in order to gain a failure data set.

Two types of events are obtainable: (1) a failure, here the equipment failed completely and operation had to be stopped; (2) a suspension or a suspended data point where scheduled maintenance was carried out on the equipment and the operation was suspended. Figure 3.3 places this and the following sections in context with the overall analysis, making up phase 2 of the analysis process.

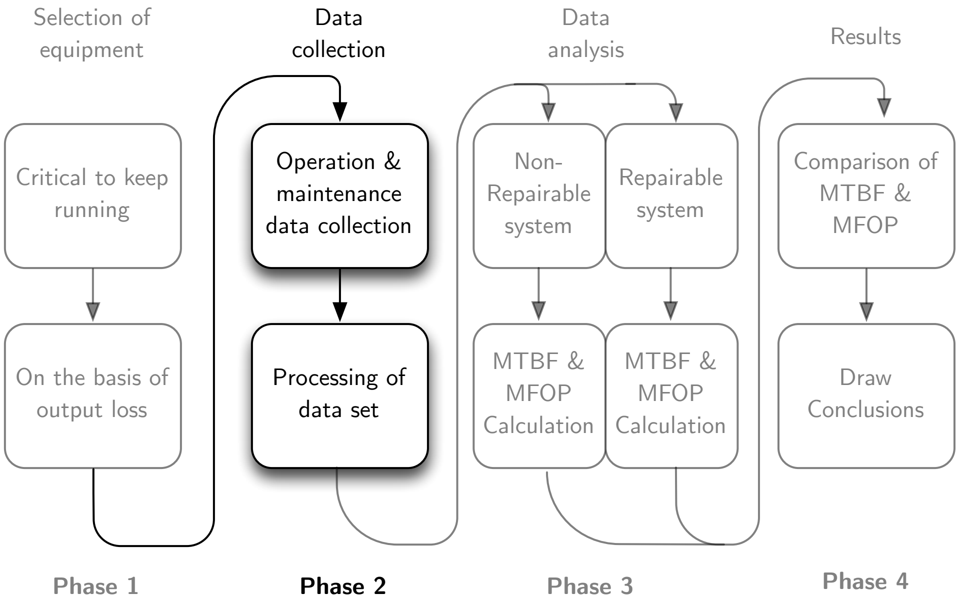


Figure 3.3: Main steps in the applied methodology, with emphasis on phase 2

3.3.4 Data Collection and Management

Once the system to be analysed has been chosen, data collection for that particular system may begin. Data collection will depend largely on the sophistication of the database employed at the facility where the system is situated.

If electronic systems are used in the form of the commonly installed Historian or PI system, large volumes of time data from vast numbers of sensors on machines or equipment in the facility can be captured. The data captured is stored for future reference or can be viewed live. The information seized by the historian program can then be pulled from the system at a later stage, either through proprietary software bundled with the complete package system or newer software packages which often include Microsoft Excel add-on programs that enable the user to pull data values from a user set time start and end points, including the time resolution or interval amount. The PI systems usually record a number of values including failure reasons, downtime and other information that is relevant to the study.

If a less sophisticated data capturing system is used, such as a manual system or a basic Systems, Applications, and Products in Data Processing (SAP) software, then maintenance records need to be manually examined for failure data of the equipment in question and then transposed into electronic format in order to start the analysis.

A data base should be created and prepared in order to receive the raw data from the source, a standard program used for this purpose is Microsoft Excel. This database can then be edited in order to suit the study that is being conducted, here data that is not required or data points that have become corrupted can be corrected, thereby clarifying the raw data. A schematic of the complete data analysis process is shown in Figure 3.4, an overall view is provided in Figure 3.3

In order to more effectively manage and understand the failure data collected, a simple but effective Pareto analysis can be performed on the failure causes. Madu (2000) states that is important to classify failure problems based on their degree of importance. The author therefore recommends a Pareto analysis based on the 80-20 % rule, meaning that approximately 80 % of the failures stem from 20 % of the equipment's components. O'Connor and Kleyner (2011) also recommend the Pareto principle of "significant few and insignificant many" as a first step in reliability data analysis. It is often found that a large proportion of failures in a system are due to a small number of

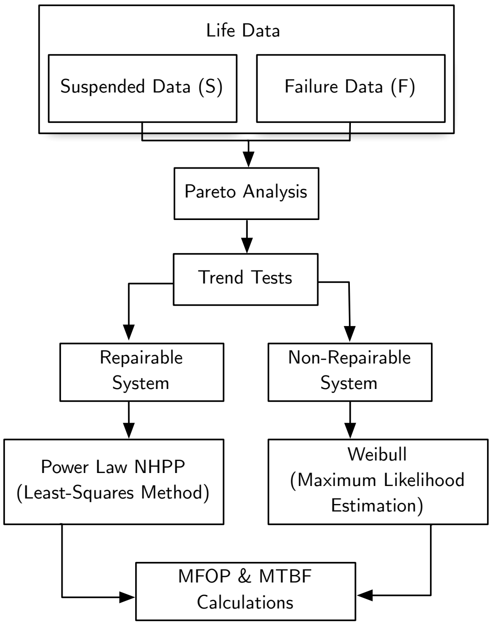


Figure 3.4: Main steps within the data analysis.

causes. Therefore a number of failure causes can be eliminated from further analysis by performing a Pareto analysis of the failure data. A Pareto analysis helps the organisation to focus and zoom in on the most critical failure problems.

3.3.5 Determination of Data Set Trends

As described in the previous section, once data is correctly collected and managed with a database, such as a Microsoft Excel file, the first step in the analysis of the data may begin, this, as shown in Figure 3.5, makes up part of phase 3 of the overall analysis. In order to ascertain what type of method should be applied to the data collected on the equipment being studied, that being if the data are Homogenous Poisson Process (HPP) or Non-homogenous Poisson Process (NHPP). A HPP can be described as a process were the frequency of the number of failures in an interval of fixed length does not vary no matter when the interval is sampled. A NHPP can be described as a process where the frequency of the number of failures in an interval of fixed length varies, at either an increasing or decreasing rate.

It is necessary to test for a trend in the chronologically ordered data set, looking for increases or decreases in the inter arrival times of the data set. For this purpose, there are a number of data trend tests available. Vlok (2011)

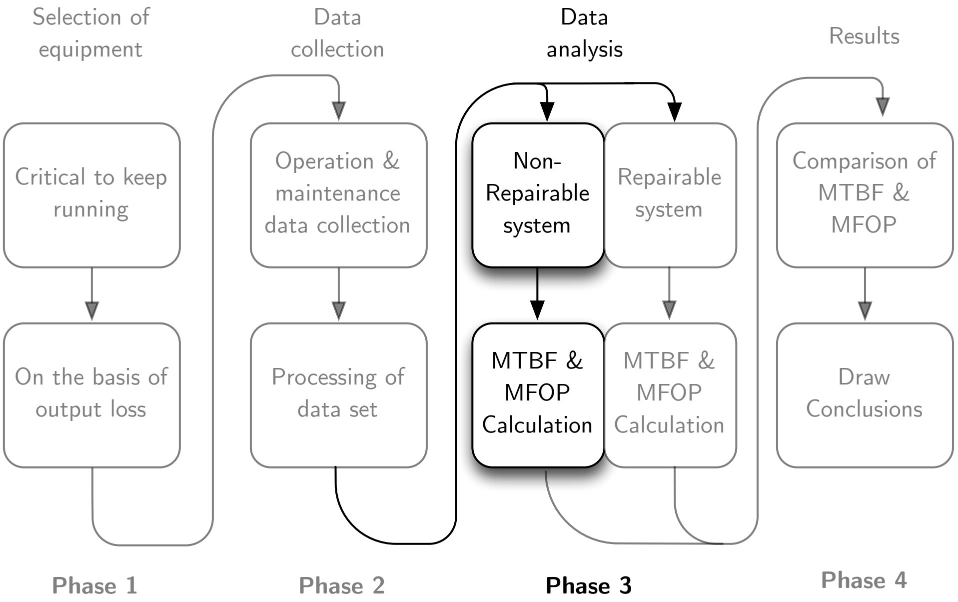


Figure 3.5: Main steps in the applied methodology, with emphasis on phase 3

and O'Connor *et al.* (1995) state that the *centroid test* or the *Laplace test* is a suitable place to start. The test compares the centroid of the observed arrival values with the midpoint of the period of observation.

The Laplace test tests the following hypothesis:

H_0 : HPP

H_a : NHPP

Bartholomew (1955) makes use of the fact that under H_0, the assumption is that the first $n-1$ arrival times, $T_1, T_2, ..., T_{n-1}$, are uniformly distributed on $(0, T_n)$. The test statistic is defined in Equation 3.1 as the following:

$$U_L = \frac{\sum_{i=1}^{n-1} {}^{T_i}\!/_{n-1} - {}^{T_n}\!/_{2}}{T_n\sqrt{1/12(n-1)}} \tag{3.1}$$

where n = number of failures, and $T_i = i^{th}$ failure arrival time.

U_L approximates a standardised normal variate at a 5 % level of significance as soon as $n \geq 4$. The Laplace test yields the following results, also shown graphically in Figure 3.6: If $U_L \geq 2$ then there is strong evidence for reliability degradation, while if $U_L \leq -2$ this indicates a reliability improvement. Between $-1 \leq U_L \leq 1$, there is no evidence of an underlying trend and it is therefore referred to as a noncommittal data set. In the last two cases where $2 > U_L > 1$ or $-1 > U_L > -2$, the Laplace test cannot provide indication with certainty that a trend is present in the data set or not. In such a case alternative trend tests are available, such as the Lewis–Robinson test which is shown in the next section.

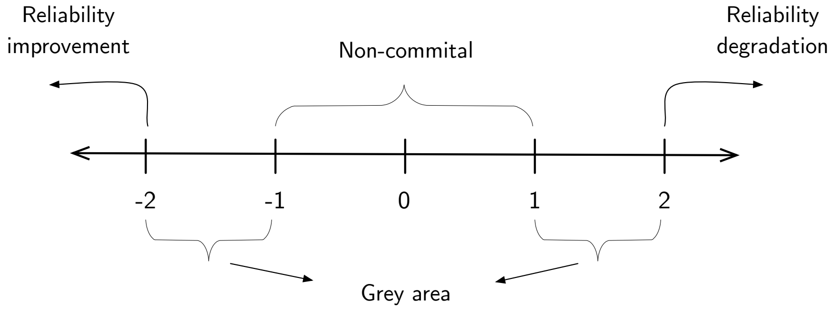


Figure 3.6: The possible outcomes of the Laplace test.

Adapted from Vlok (2011)

As stated, if the outcome of the Laplace test is in the grey area, there is no conclusive evidence for a trend in the data set. One must therefore use a different test, such as the Lewis–Robinson test, as recommended by Wang and Coit (2004). The Lewis–Robinson test is a modification of the original Laplace test and uses the numerical values of inter-arrival times.

The Lewis-Robinson test hypothesis is:

H_0: renewal process

H_a: not a renewal process

U_{LR} the test statistic is formed by dividing the previously defined Laplace test statistic U_L by the coefficient of variation (CV) for the observed inter-arrival times. U_{LR} is defined in Equation 3.2 as follows:

$$U_{LR} = \frac{U_L}{CV}, \tag{3.2}$$

here CV^1 is the estimated coefficient of variation of the inter-arrival times. The result of the Lewis–Robinson test can be interpreted in the same way as the Laplace test as shown in Figure 3.6.

If the result of the Laplace test, as discussed above, falls within the interval U_L of $1 \geq U_L \geq -1$ there is no dependence of the data. It then follows, as shown in Figure 3.7, that non-repairable systems theory may be applied to the data set, this will be discussed in the next section.

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[1] Coefficient of variation defined by: $CV[X] = \frac{\sqrt{V\hat{a}r[X]}}{\bar{X}}$

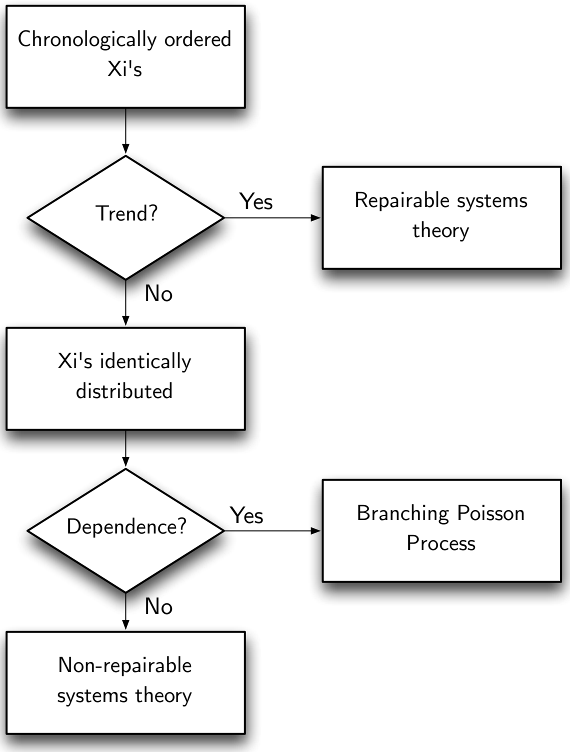


Figure 3.7: Decision tree for the statistical failure analysis of successive inter arrival times for a single system.

Adapted from Ascher and Feingold (1984)

It can thus be determined that if a trend exists in the data, different distributions can be fitted to the data set, depending on the outcome of the trend tests, this is outlined in the sections that follow. First, however, an example calculation of the Laplace trend test is shown below.

Example

To better illustrate the use of the Laplace trend test, a simple worked example is show in this section. An example data set, consisting of 11 events of inter–arrival times and arrival times is shown in Table 3.1.

Equation 3.1 can be used in the example data shown in Table 3.1, to determine if a trend exists in the data set. To do this, the arrival times, T_i, are calculated from the inter-arrivals times, X_i, found in the original maintenance data. This also includes the event classification, failure or suspension, which is indicated in C_i as either a 1 for failure or 0 for suspension. The example is worked are follows:

Table 3.1: Data for worked example.

Obs. #	X_i **(hours)**	T_i **(hours)**	C_i
1	28	28	1
2	27	55	1
3	55	110	1
4	90	200	1
5	30	230	0
6	92	322	1
7	72	394	1
8	88	482	0
9	49	531	1
10	95	626	0
11	55	681	1

$$\begin{aligned}
\sum_{i=1}^{n-1} T_i &= 2978 \\
n-1 &= 10 \\
\frac{\sum_{i=1}^{n-1} T_i}{n-1} &= 297.8 \\
T_n/2 &= 313 \\
U_L &= \frac{297.8-313}{681\sqrt{1/(12\times 10)}} \\
&= -0.6869
\end{aligned}$$

From the result given above, it can be seen that there is no trend in the data, (refer to Figure 3.6), and non-repairable systems theory is applicable.

3.4 Non-Repairable System Analysis

With the ultimate goal of calculating the MFOP length, and the probability of the achievement in mind, the first step is to fit a distribution to the data set and find estimates of the distributions parameters. Referring to Figure 3.5, this section still forms part of phase 3 of the application methodology.

If after the Laplace trend test has been applied (as discussed in the previous section), the inter-arrival times of the data yield no trend, thereby landing in the noncommittal interval, the data set should be analysed using non-repairable systems theory. O'Connor *et al.* (1995), Vlok (2011) and Montgomery and Runger (2010) recommend the use of the Weibull distribution in reliability modelling, due to its flexibility. The Probability Density Function (pdf) shown in Equation 3.3 provides the probability of system failure at the exact instant, x.

$$f(x) = \frac{\beta}{\eta}\left(\frac{x}{\eta}\right)^{\beta-1} \cdot \exp\left(-\left({}^{x}\!/_{\eta}\right)^{\beta}\right), \tag{3.3}$$

here β is the shape parameter and η is the scale parameter of the Weibull distribution, with $\beta > 0$ and $\eta > 0$. These parameters are required in order to later calculate the MFOP of the system selected.

In order to numerically calculate the Weibull parameters β and η, maximising the likelihood should be applied, this is given in equation 3.4:

$$\ln L(X_i, \theta) = \sum_{i=1}^{m}\left[\ln\frac{\beta}{\eta} + (\beta-1)\ln\frac{X_i}{\eta}\right] - \sum_{j=1}^{r}\left(\frac{X_j}{\eta}\right)^{\beta} \tag{3.4}$$

Equation 3.4 returns the fitting values for β and η. It is important to discern between observed failure times and observed suspensions.

The cumulative probability function can be derived from Equation 3.3, this is shown in Equation 3.5.

$$F(x) = 1 - \exp(-(x/\eta)^{\beta}) \tag{3.5}$$

The reliability function for the Weibull distribution given in Equation 3.3 is shown in Equation 3.6.

$$R(x) = \exp(-(x/\eta)^{\beta}) \tag{3.6}$$

The equations detailed above, pertaining to non-repairable systems, and the relevant calculations applied to the obtained data set, can all be calculated in Microsoft Excel. Here Microsoft Excel can be used for both the database for the obtained field data and the calculations explained in this section, specifically, for example: Equation 3.4 which is used in order to find the parameters β and η, which can be maximised by using Excel's solver function.

Now that a distribution that represents the data set and the Weibull parameters β and η are known, the MFOP of the system can be calculated, this is shown in Section 3.4. The MTBF of the non-repairable system can be calculated for comparative reasons, this is shown in Section 3.4.1.

In order to give more context to the above shown equations, a short worked example is shown in the next section.

Example

Using the same data as provided in the example shown in Section 3.3.5, and continuing with the example, the data set can now be modelled using the Weibull distribution. Equation 3.3 will be fitted to the data by using the maximum likelihood method shown in Equation 3.4, finding the Weibull parameters β and η, shown in Table 3.2, by using Microsoft Excel's solver function. The Weibull parameters found can then be substituted into Equation 3.3, the equation below shows the pdf found for this data set.

Table 3.2: Weibull parameters found for example data set.

Parameter	**Value**
β	2.49
η	78.52

$$f(x) = \frac{2.49}{78.52}\left(\frac{x}{78.52}\right)^{2.49-1} \cdot \exp\left(-(x/78.52)^{2.49}\right)$$

Now that the pdf for the data set is known, Equation 3.4 can be plotted, this is shown in Figure 3.8.

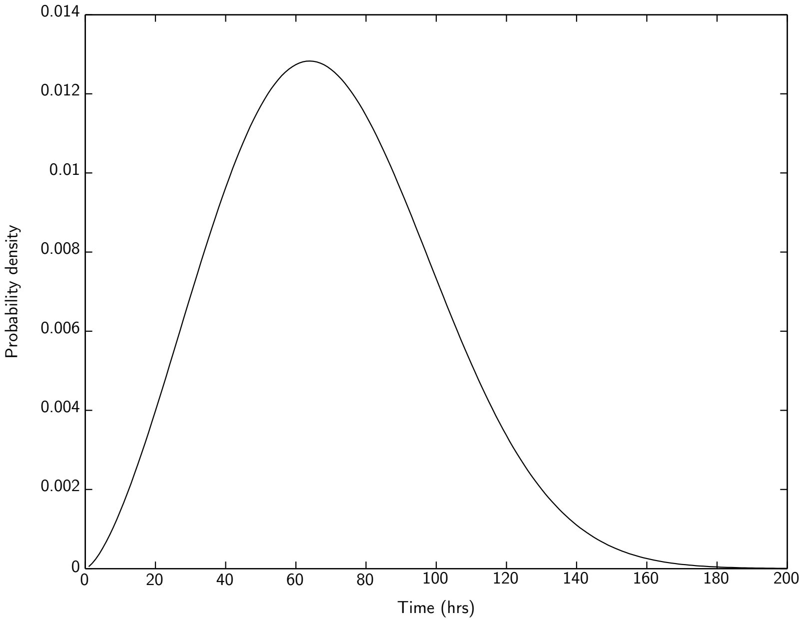


Figure 3.8: Weibull pdf for the worked example.

3.4.1 Calculation of MTBF

In order to compare analysis results between the proposed MFOP method, a comparison should be made with the traditionally used MTBF. For a non-repairable system, the historic MTBF can be calculated by Equation 3.7:

$$\mathrm{MTBF} = \frac{\sum X_i}{m} \tag{3.7}$$

where X_i is the inter-arrival times of failures, and m is the total number of observed failures. The future or predicted MTBF can also be found, Vlok (2011), and is shown in Equation 3.8.

$$\mathrm{E}\left[X_{r+1}\right] = \frac{\int_0^\infty x \cdot f(x)\mathrm{d}t}{\int_0^\infty f(x)\mathrm{d}x} \tag{3.8}$$

In order to calculate the future as described in Equation 3.8, it is best to use numerical integration in Microsoft Excel.

Example

Using the example data presented in the previous section as an on going example, the MTBF, both historic and future, can be calculated using the equation set out in this section. Using equation 3.7, the historic MTBF can be determined.

$$\begin{aligned}\text{MTBF} &= \frac{468}{8} \\ &= 58.5\end{aligned}$$

The future MTBF can be determined by using Equation 3.8, here the integral of $f(x)$ will converge to 1 and the integral of $x \cdot f(x)$ will converge to the future MTBF of the system, this is best calculated in Microsoft Excel using numerical integration, once the pdf for the data has been found. The future MTBF for the example given was found to be 69.9 hours.

3.4.2 Calculation of MFOP

Continuing from Section 3.4 where the data set found was analysed using the Weibull distribution, including finding the Weibull shape and scale parameters, MFOP calculations can now be performed.

In order to calculate the MFOP length for a certain system, another term needs to be introduced in addition to MFOP previously defined in Chapter 2 Section 2.7.2. Since it is almost impossible to provide a 100 % guaranteed MFOP, we introduce the term Maintenance Free Operating Period Survivability (MFOPS), which is defined by Dinesh Kumar *et al.* (1999), Kumar (1999), Long *et al.* (2009) and Chew (2010) as:

> *The probability that the part, subsystem, or system will survive for the duration of the MFOP, given that it was in a state of functioning at the start of the period.*

Kumar (1999) describes the probability of surviving t_{mf} units, given that the system has already survived t units, provided that the system is modelled with the Weibull distribution, in Equation 3.9.

$$\text{MFOPS}(t_{mf}) = \exp\left(\frac{t^{\beta} - (t + t_{mf})^{\beta}}{\eta^{\beta}}\right), \tag{3.9}$$

where η is the scale parameter and β is the shape parameter of the Weibull distribution, which are calculated in Section 3.4 of this Chapter. Equation 3.9

can be seen as a version of Equation 3.6, the reliability function of the Weibull distribution. The MFOP length for a given confidence (MFOPS), is found by rearranging the previous equation and is shown in equation 3.10 below:

$$t_{mf} = [t^{\beta} - \eta^{\beta}\ln(\mathrm{MFOPS}(t_{mf}))]^{1/\beta} - t \tag{3.10}$$

The maximum length of a MFOP for a chosen confidence, MFOPS, can be calculated and constitutes the design life of that system. This symbolises the age of an item, up to which the reliability of the system is greater than or equal to the design reliability value. Equation 3.11 donates the maximum achievable MFOP at a given MFOPS, this equation will be used most often when calculating MFOP.

$$\mathrm{MFOP} = \eta \times \left\{\ln\left(\frac{1}{\mathrm{MFOPS}}\right)\right\}^{1/\beta} \tag{3.11}$$

An example, MFOP calculation is shown in the next section, in order to better clarify the concept.

Example

For the sake of continuity and simplicity, the same data set as shown in Section 3.4 is used in this example to calculate the MFOP of the system at a certain MFOPS. This is done, of course, using the Weibull distribution parameters found in the example in Section 3.4.2. Equation 3.11 is used and Weibull parameters found, β and η, found in the previous example are substituted.

$$\mathrm{MFOP} = 78.5 \times \left\{\ln\left(\frac{1}{\mathrm{MFOPS}}\right)\right\}^{1/2.49}$$

Here, Microsoft Excel can be used to create a graph showing the maximum attainable MFOP length at a confidence MFOPS, such a graph is shown in Figure 3.9 below.

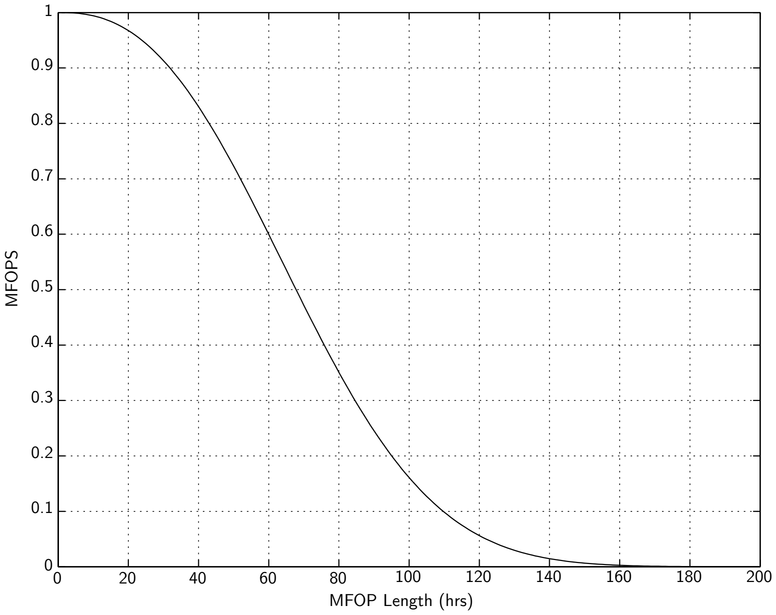


Figure 3.9: Probability of achieving MFOP length for example data.

3.5 Repairable Systems Analysis

Now that non-repairable systems have been dealt with, the other case possible in the analysis is discussed, the repairable system. The repairable system case, referring to Figure 3.10, is still placed within phase 3 of the analysis methodology.

Two outcomes of the Laplace test are possible to indicate that there is a trend in the data set, therefore initiating the use of repairable systems theory. If $U_L \geq 2$ or $U_L \leq -2$ (see Figure 3.6) both indicate that there is a trend in the data set, the one a reliability degradation and the other a reliability improvement respectively.

An NHPP describes a process were the rate at which events occur is not constant. The rate at which events occur is called mean intensity or the ROCOF. The power law NHPP is used here to model the repairable system, given in Equation 3.12:

$$\rho_1 = \lambda \delta t^{\delta - 1}, \tag{3.12}$$

here $\delta > 0$ for repairable systems. The parameters, δ and λ for a specific system, are required not only for Equation 3.12 but also later in the analysis, in order to determine the MFOP and future MTBF.

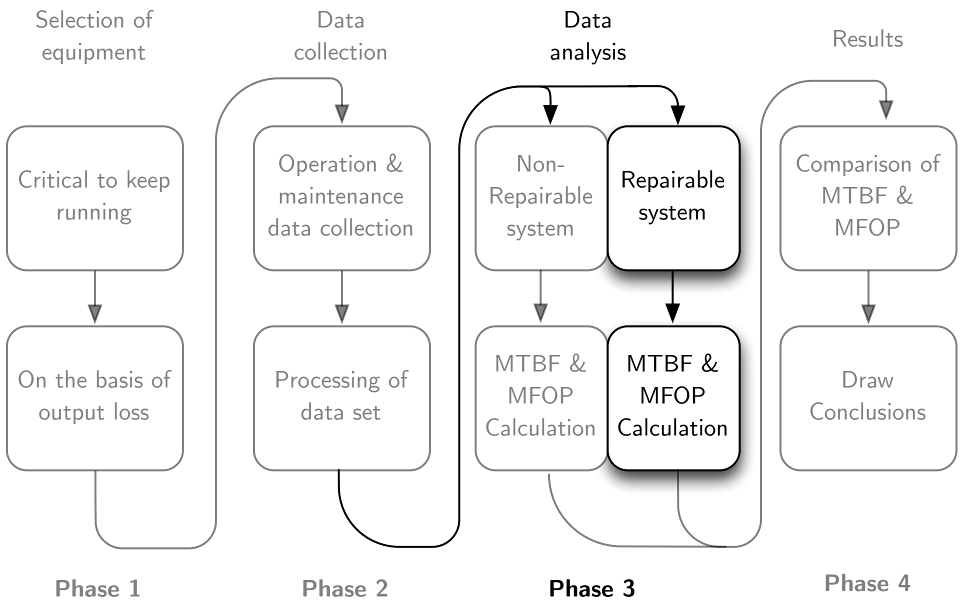


Figure 3.10: Main steps in the applied methodology, with emphasis on phase 3.

Equation 3.13 gives the expected number of failures, N, between any two points in time, t_1 and t_2.

$$E\left[N\left(t_1 \rightarrow t_2\right)\right] = \lambda(t^{\delta}{}_2 - t_1^{\delta}) \tag{3.13}$$

Vlok (2011) recommends that the parameters for the power law NHPP be estimated using the least-squares method, this being the difference between the observed number of failures and the number of failures expected by $\rho_1(t)$, which should be minimised. As stated previously, there are two types of events possible in the analysis, one a failure or two a suspension. For a failure event, Equation 3.14 is applicable.

$$\min\left(\hat{\lambda},\hat{\delta}\right) : \sum_{i=1}^{r}\left[E\left[N\left(0 \rightarrow T_i\right)\right] - N\left(0 \rightarrow T_i\right)\right]^2, \tag{3.14}$$

For a suspended event type, Equation 3.15 is applicable.

$$\min\left(\hat{\lambda},\hat{\delta}\right) : \sum_{i=1}^{r-1}\left[E\left[N\left(0 \rightarrow T_i\right)\right] - N\left(0 \rightarrow T_i\right)\right]^2. \tag{3.15}$$

Now that the parameter, δ and λ, can be estimated, the reliability of the system can be determined from t_1 to t_2 by using the Equation in 3.16:

$$R\left(t_1 \rightarrow t_2\right) = e^{-\lambda(t_2^{\delta} - t_1^{\delta})} \tag{3.16}$$

The method described above is put into context with a simple worked example in the following section.

Example

As done in the non-repairable methodology section, a simple example is provided to better illustrate the analysis procedure. As the data set, used continuously in previous examples, describes a non-repairable system, a new example data set is required to explain the approach. The new example data set is provided in Table 3.3.

Table 3.3: Data for repairable system worked example.

Obs. #	t_i **(hours)**	T_i **(hours)**
1	357	357
2	162	519
3	175	694
4	154	848
5	107	955
6	81	1036
7	43	1079
8	74	1153
9	54	1207
10	51	1258
11	45	1303
12	35	1338
13	41	1379
14	37	1416

In order to ascertain if a trend is present in the data, the Laplace trend test should be applied to the given data set. By way of an inspection, it can already be noted that the data shown in Table 3.3 displays a trend, however, in the interest of completeness, the Laplace trend test is shown below.

$$\begin{aligned}
\sum_{i=1}^{n-1} T_i &= 13126 \\
n-1 &= 13 \\
\frac{\sum_{i=1}^{n-1} T_i}{n-1} &= 1009.7 \\
T_n/2 &= 708 \\
U_L &= \frac{1009.7 - 708}{1416\sqrt{1/(12 \times 13)}} \\
&= 2.6611
\end{aligned}$$

The outcome of the Laplace test shows that there is a trend present in the data and that there is a reliability degradation, this can also be seen by inspecting the inter-arrival times in the data. This result allows for the use of the power law NHPP to model the data set and can now be applied.

In order fit Equation 3.12 in to the data, the least squares method is used, Equation 3.14, it is assumed in this example that all events are failures. Applying this produces parameters, δ or λ, shown in Table 3.4, with specific $\rho_2(t)$ for the data shown below.

Table 3.4: Parameters found for the power law NHPP example data set.

Parameter	**Value**
λ	3.74×10^{-7}
δ	2.398

$$\left(3.74 \times 10^{-7}\right) \cdot 2.398 t^{1.398}$$

Now that the example system can be modelled and the power law NHPP parameters are known, MFOP calculations can be performed, as well as, past and future MTBF calculations, these are detailed in the sections that follow.

3.5.1 Calculation of MTBF

As already mentioned in Section 3.4.1, the MTBF of the system is calculated in order to compare it to the MFOP of the system and draw conclusions. For a non-repairable system, the historic MTBF can be calculated by using Equation

3.17, this section still makes up phase 3 of the methodology layout shown in Figure 3.10.

$$\mathrm{MTBF}_{\rho_1}(t_1 \rightarrow t_2) = \frac{(t_2 - t_1)}{\lambda\left(t_2^{\delta} - t_1^{\delta}\right)} \tag{3.17}$$

Providing a better representation of the current state of the system is the future MTBF. If the system is put back in operation after the last recorded failure, then the next failure of the system can be predicted, $(r+1)^{\mathrm{th}}$. With Equation 3.18, the residual life of the system is calculated from the last recorded event.

$$\mathrm{E}\left(T_{r+1}\left|t = T_r\right.\right) = \left(\frac{1 + \lambda T_r^{\delta}}{\lambda}\right)^{1/\delta} \tag{3.18}$$

Example

Continuing with the example introduced in Section 3.5, using the same data set, the past and future MTBF can be determined. Using Equation 3.17, the historic MTBF can be found over the already observed event period.

$$\begin{aligned}\mathrm{MTBF}(0 \rightarrow 1416) &= \frac{(1416 - 0)}{(3.74 \times 10^{-7})(1416^{2.398} - 0^{2.398})}\\ &= 105.2\,\text{hours}\end{aligned}$$

Here, it can be seen that the historic MTBF is approximately 105 hours, however, as previously stated, the data set displays a trend with an indication of reliability degradation which therefore makes the historic MTBF no longer appropriate. A future MTBF can therefore be predicted, using Equation 3.18 with the last recorded event.

$$\begin{aligned}\mathrm{E}\left(T_{15}\left|T_{14} = 1416\right.\right) &= \left(\frac{1 + (3.74 \times 10^{-7}) \cdot 1416^{2.398}}{3.74 \times 10^{-7}}\right)^{1/2.398}\\ &= 1458.95\,\text{hours}\end{aligned}$$

This yields the next expected failure, T_{15}, in order to attain the future MTBF, the last recorded event time needs to be subtracted.

$$\begin{aligned}\mathrm{MTBF} &= 1459 - 1416\\ &= 43\,\text{hours}\end{aligned}$$

From the above calculation it can be seen that the predicted MTBF, for the reasons stated, is far lower than the historic MTBF.

3.5.2 Calculation of MFOP

As seen with the calculation for the MFOP of a non-repairable system, it is attainable by using, in the non-repairable case, the probability of system survival up to a certain instant, t. The same principle can be applied to a repairable system, by using Equation 3.16, to derive an equation for the MFOP of a repairable system. The probability of surviving (MFOPS) t_{mf} units of time is given in Equation 3.19:

$$\text{MFOPS}(t_{mf}) = e^{-\lambda((t_{mf}+T_r)^{\delta}-(T_r)^{\delta})} \tag{3.19}$$

here, T_r is the global time unit of the last known failure event and the parameters, λ and δ, have been previously found through the least squares method shown in Section 3.5.

Example

In the example calculations in Section 3.5, the sample data was modelled using the power law NHPP and the parameters, λ and δ, found. These parameters can now be used to calculate the maximum attainable MFOP length at a certain confidence, MFOPS.

$$\text{MFOPS}(t_{mf}) = e^{-(3.74\times10^{-7})((t_{mf}+1416)^{2.398}-(1416)^{2.398})}$$

In putting a number of values for t_{mf}, in this example from 1 to 200, yields a graph depicting the MFOP performance over that time period, this is shown in Figure 3.11

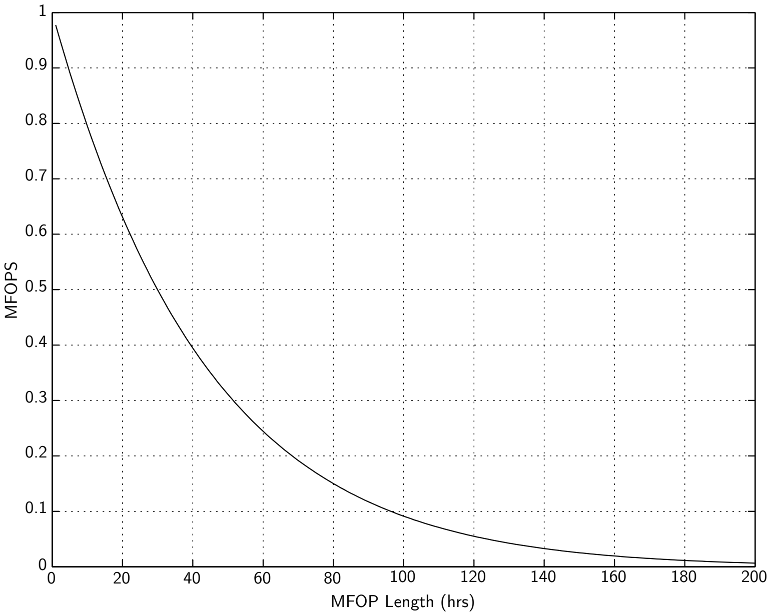


Figure 3.11: Probability of achieving MFOP length for repairable system example data.

3.5.3 MFOP–Renewal Theory

A mathematical model was developed by Dinesh Kumar *et al.* (1999) to predict MFOPS and makes use of renewal theory to model a repairable system. A certain number of MFOP cycles will be reached and there will be a MRP, states Knowles (1995) and Nowakowski and Werbińka (2009). MRP was defined earlier in Chapter 2, it is basically the downtime during which all major preventative maintenance activities are carried out.

A system that has a required MFOPS of t_{mf} life units, to find the MFOPS during a stated period T including the MRP was considered. The following assumptions are made with regard to the repairable item:

1. The time to failure distribution of the item follows an arbitrary distribution with density function represented by $f(t)$.
2. The maintenance recovery time of the item follows some arbitrary distribution with density function represented by $g(f)$.
3. The item in question can have two given states $\{1,0\}$, here “1” is the up state and “0” is the down state.

Define $\mathrm{P}_1(T)$ as the probability that the item will have t_{mf} hours of MFOP throughout the mission T. Maintenance will be carried out as soon as the item fails. Equation 3.20 show the expression for $\mathrm{P}_1(T)$:

$$P_1(T) = R\left(t_{mf}\right) + \int_0^T f\left(\mu|t_{mf}\right) P_0\left(T-\mu\right) d\mu, \tag{3.20}$$

where $f(u\,|t_{mf})$ is the probability that the system fails at time u, given that it has survived up to time t_{mf}. In order to calculate P_0 within equation 3.20, equation 3.21 is defined:

$$P_0(T) = \int_0^T g(v)P_1(T-v)dv, \tag{3.21}$$

The recursive function in the integrals in equations 3.20 and 3.21 can be solved by numerical approximation (e.g. Newton–Raphson method), for any given time to failure distribution. For the purpose of this thesis, renewal theory is not applied, but for the sake of completeness it is shown here.

3.6 Summary

This chapter, on the whole, provides the reader with the tools to perform a MFOP analysis. Here, the application of the proposed solution is put forward, as shown in Figure 3.12, the MFOP principle is introduced in the literature review and contrasted to the traditionally used MTBF, and the numerous disadvantages attributed to it. The MFOP proposition follows a set sequence of, maintenance free operation, followed by a period where all planned maintenance activities are performed, recovering the system so it can start the next MFOP.

From this chapter, it could be seen that in order to calculate the MFOP of a specific system failure statistics need to be applied first. This stems from the fact that the proposed MFOP length is a remodelled form of the reliability function. The data set therefore first needs to be modelled as either a repairable or non-repairable system before MFOP calculations can be made, examples are provided in this chapter.

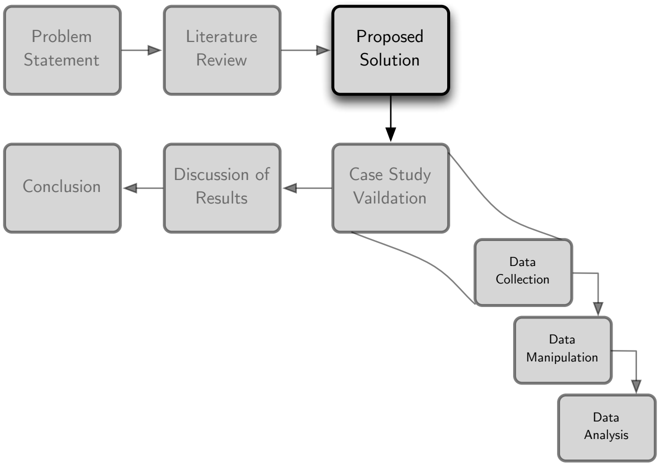


Figure 3.12: Research flow placing Chapter 3 in context

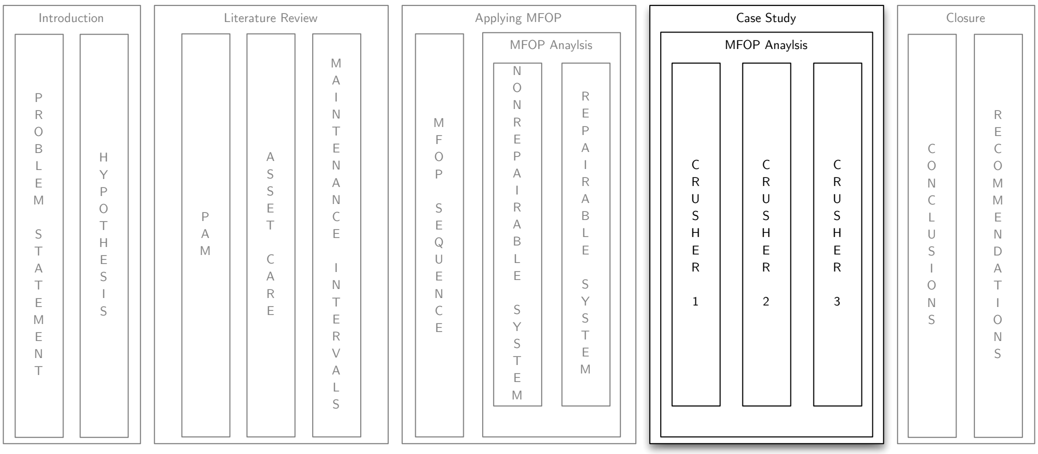
From Chapter 2 it was seen how maintenance has moved form the “necessary evil” to a “profit contributor” and “partnership”. Maintenance has come to be an integral part of any organisation, this view has been formalised with the AM standard PAS 55. The most common reliability measure in maintenance is MTBF, which by its very definition provides for the *acceptability of failures* by counting the number of failures per some time unit. The high costs of the consequences of system unreliability has provided motivation for the search for a new way to describe reliability, originating from the field of aircraft maintenance, the result has been the definition of MFOP.

The application of the MFOP mindset can provide a vital step towards focused reliability improvement, not only in the aviation sector. The mining sector, just like the aviation sector, is massively asset intensive. Big capital investments are made into machinery in order to create revenue, these machines must be maintained in order to achieve a high reliability. MFOP provides more certainty to the question of reliability and thereby reduces risk, MTBF only caters to the one number syndrome. It is therefore of interest to apply the fundamental shift in definition, MFOP, to a mining environment in order to ascertain if, as set out in the hypothesis, MFOP is a better way to assess the performance of physical assets.

Chapter 4, Case Study and Validation (see Figure 3.12), attempts to apply the method set out in this chapter to real data collected in the field and assess if the MFOP concept can be applied effectively outside of the context of aviation and change the rudimentary mind set that there is no such thing an *acceptable* amount of failures.

Chapter 4

Case Study



Chapter Aims:

The case study conducted in this chapter aims to validate the proposed solution in Chapter 3. The chapter aims to show if the MFOP philosophy can be applied in a real world example and to what effect the outcomes can be seen. The chapter provides the reader first with an overview of the specific case study conducted and then presents results of the analysis of a real world system using MFOPs.

Chapter Outcomes:

⇒ Understanding the case study environment.
⇒ Understanding the system analysed.
⇒ Gaining a complete overview of the results.

4.1 Overview of Anglo American

The case study used here for validation purposes, was conducted in conjunction with Anglo Platinum Limited. Anglo Platinum Limited is a subsidiary of Anglo American PLC, which holds the major share in the company, even though Anglo Platinum is still listed as a separate company on the JSE securities exchange, London's FTSE stock exchange and Brussels' Euronext stock exchange.

Anglo Platinum was formed when the Johannesburg Consolidated Investments company unravelled and its platinum interests became Amplats and was later renamed Anglo Platinum Limited. Anglo Platinum is the world's largest primary producer of Platinum group metals, accounting for 40 % of the world's annual production. Six metals make up the group of platinum metals, these are: ruthenium, rhodium, palladium, osmium, iridium and platinum. These metals have similar physical and chemical properties and tend to occur in the same mineral deposits. As of the end of 2011 the entire Anglo American group held US $ 40.5 billion in assets, Anglo American (2011), of that, Anglo Platinum has R44,5 billion in assets, Anglo Platinum (2011).

The case study was specifically conducted at one of Anglo Platinum's bushveld complex mines, in South Africa. There are two distinct and separate concentrators which form part of this mine, these being the newer North concentrator and the older South concentrator. The newer North concentrator was chosen to conduct the study.

4.2 Chapter Overview

In the sections that follow the study is performed on data collected from Anglo Platinum. A brief outline of the specific problem is given first, thereafter more is said about the case study and the system analysed is formally introduced. Practicalities of data gathering is then discussed, with data requirements, collection and classification playing a prominent role.

Now that the case study has been defined the analysis can be conducted. Three identical systems were analysed, general and coherent analysis steps were followed throughout, these are shown in Table 4.1.

Table 4.1: Analysis steps followed for each system.

No.	Step
1	Analysis of failure data set
2	MTBF calculations for actual system
3	MFOP calculations for actual system
4	MFOP calculations for hypothetical system
5	Summary of results

4.3 The Problem

The global problem, as stated previously, is that current reliability metrics, Mean Time Between Failure (MTBF) that is widely used, do not provide a unambiguous and untainted view of the performance and operation of the equipment analysed. MTBF remains a simple mean and has created a widely accepted view that random failures are completely unavoidable.

In this specific study it is to be researched if there is an application within mining for the proposed solution to the shortcomings of MTBF, Maintenance Free Operating Period (MFOP) originating from the aviation industry. Having found a research partner, Anglo Platinum, a system or equipment needed to be found so that the hypothesis could be tested. After a visit on-site to one of Anglo Platinum's mines and discussions with various key players from the plant, a system was established. The equipment that was chosen to be studied was a grouping of cone crushers used in secondary crushing operations. The group of crushers consisted of three individual and identical cone crushers. These crushers were vital to the overall process. Due to smaller sized stockpiles downstream in the process, a failure at this station in the process would have had far reaching consequences in proceeding stations. Another factor that was taken into consideration was that this grouping of crushers had seen some unreliability in the past, a better picture of the crushers was therefore desired.

4.4 Aims of Case Study

The aim of this Case Study is to investigate the idea of using the aviation derived concept of MFOP within a mining environment. Here a specific item of the total mining concentrator system is chosen and its failures are modelled and the MFOP concept then applied to the chosen item, in this case a grouping of cone crushers.

The failure distribution of the crusher in question is found and thereafter the relevant MFOP statistical formulas are applied on the distribution, in order to find the maintenance free time of operation, specific for that item. It can then be seen if this period of time is feasible and could be applied to the item. The modelling of the crusher failure distributions is an additional sub-aim of the study additionally.

Ultimately, a better understanding of applying the MFOP concept should be gained, thereby testing the school of thought of MFOP against that of the traditionally used reliability metric MTBF.

4.5 Field of Study

The concept of MFOP falls within the field of reliability metrics and maintenance. However, with an ever increasing interest and research from both industry and academia, in the field of maintenance, and the creation of the British Standard on AM, PAS 55, this study also falls under the greater umbrella of PAS 55.

The acceptance of random failures, and therefore unscheduled maintenance activities that are then performed during operating hours, this leads to production losses and increased maintenance costs are, according to Relf (1999), a direct result of the use of the reliability metric MTBF, as MTBF conveys the impression that there is an allowable level of failure.

Here, MFOP could provide better maintenance planning capability, by guaranteeing, to a certain confidence level, a period which is maintenance free. This philosophy should also decrease maintenance costs, as unplanned maintenance activities are transferred to planned activities, usually cheaper than unplanned ones. It is therefore required to test the MFOP concept in practice, in this case study a mining environment, an industry associated with an intense use of physical assets was used.

4.6 Study Design

The general study design and methodology used is discussed in Chapter 3, where statistical methods applied are discussed and expanded upon in this

Chapter. Study specifics are elaborated below.

After detailed discussions with the concentrator plant manager on the system and its subcomponents, a decision was made on which equipment to use for the analysis. This decision was based on the plant manager's in-depth knowledge of the complete system and the complexities thereof. Also taken into account, were conditions such as equipment criticality to continuous uninterrupted operations, based on non-operational output loss.

The chosen equipment was an arrangement of three cone crushers. These crushers were pivotal to the smooth operation of the complete system and the equipment downstream from them. They were, however, to different degrees, susceptible to breakdowns and therefore unplanned maintenance activities had to be conducted, thereby hampering the continuous operation of the system. Due to their susceptibility and varying reliability, this system was chosen for the study. Figure 4.1 shows the methodology that was already put forward in Chapter 3.

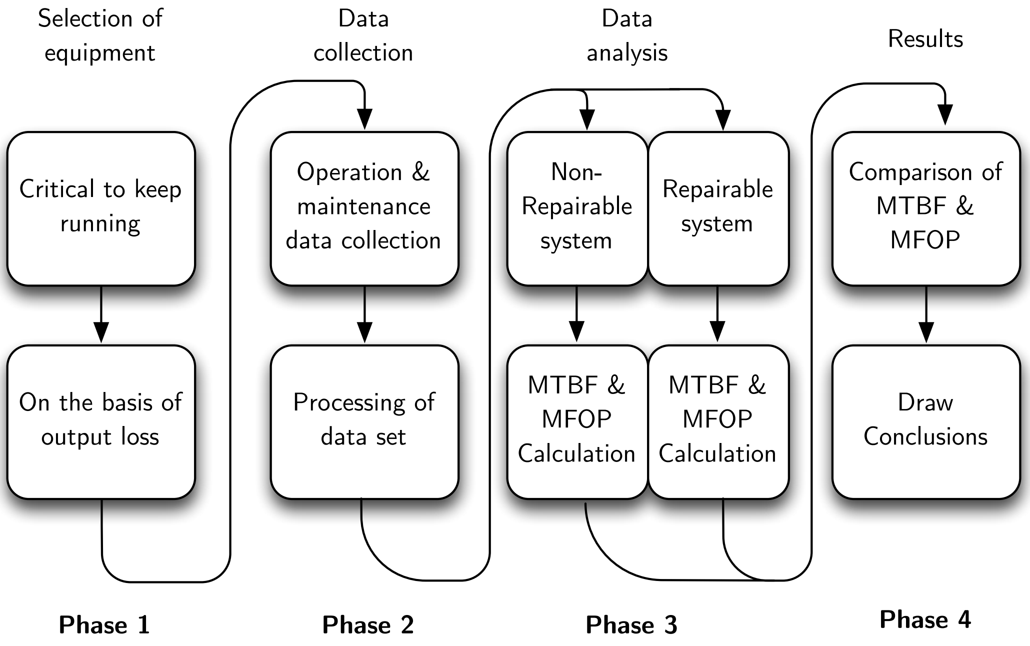


Figure 4.1: Application methodology from Chapter 3, employed in Case Study.

4.7 System Boundaries

As stated in the previous section, the system chosen for the study was a grouping of three cone crushers that are used in secondary crushing operations in the concentrator of the mine. The secondary crushers are part of the larger dry circuit of the concentrator, they receive product from the primary stockpile after it has gone through the Grizzly vibrating sorting machine. Once the product has gone past the grizzly, ore that is too large, is sent to the secondary crusher feeders, here product is fed to one of the three secondary crushers for crushing. After being crushed, it is then sent on to the secondary screen feed and thereafter to the High Pressure Grinding Roller (HPGR) silo. Figure 4.2 gives an extract of the process and the relative position of the secondary crushers.

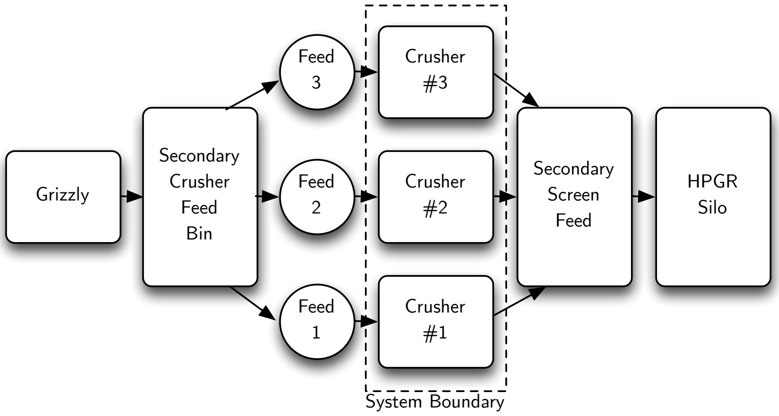


Figure 4.2: Relative position of the secondary crushers.

The system boundary was taken around the grouping of secondary crushers, with each crusher being analysed individually. Any failure which pertained to one of the secondary crushers was included in the compiled data set for each crusher. Failures of conveyors, feeders, grizzly or of the HPGR do not pertain to any of the secondary crushers and was therefore not taken into account for the analysis. A cross sectional drawing of the crushers analysed is shown in Figure 4.3.

1	Spider Cap
2	Spider bushing
3	Head nut
4	Mantle
5	Concave ring
6	Mainshaft with headcentre
7	Eccentric wearing plate
8	Bottomshell bushing
9	Eccentric
10	Eccentric bushing
11	Step bearing
12	Hydroset piston
13	Pinionshaft housing
14	Pinionshaft
15	Dust collar
16	Locating bar
17	Dust seal ring
18	Bottomshell
19	Topshell

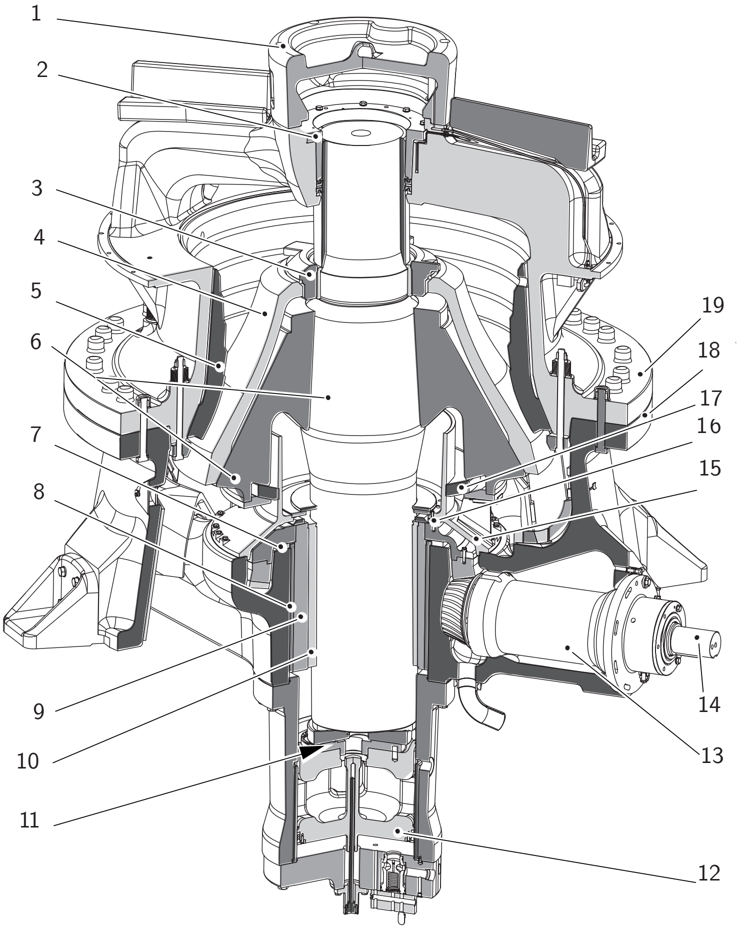


Figure 4.3: Cross sectional drawing of Sandvik CH880 cone crusher.

4.8 Practicalities of Data Gathering

Described in this section are the practicalities of data gathering during the conducted case study.

4.8.1 Data Requirements

In terms of data requirements needed, failure data is required for the crushers that were analysed. Within this maintenance or failure data, there should be two types of events present: (i) failure or unscheduled stoppages; and (ii) suspensions or scheduled stoppages, i.e. planned maintenance. Additional data types, such as the power readings for the crusher, can also be sampled for the same time period, in order to cross reference the maintenance data sampled.

4.8.2 Data Collection

The purpose of collecting data in order to solve empirical problems, according to Ghosh (1990), has a dual function to both understanding and formulating action. Ishikawa (1982) states two important questions that should be asked when collecting data: (i) will the data determine the facts? (ii) is the data collected, analysed and compared in such a way as to reveal the facts?

The data that was used in this study were failure and maintenance data of the system of crushers. This data come from secondary sources, this being from Anglo Platinum's electronic data capturing system, which records vast amounts of data and variables. From this system maintenance data on the crushers were pulled and stored in Microsoft Excel. Data was obtained from 2010 to 2011, at a resolution or in increments of 10 minutes over the entire period, a higher resolution would have become impractical within the Microsoft Excel environment, due to the large amounts of data points. Data could not be obtained earlier than the 1st of October 2010, due to no data on failures being available before that point. Table 4.2 shows the number of events found for each crusher from the stated period.

Table 4.2: Number of Events Found in Data.

Crusher	Number of Events
Crusher 1	110
Crusher 2	102
Crusher 3	90

The data set obtained from Anglo consisted of a number of data elements, as previously stated, each element had a resolution of 10 minutes. Elements that were taken from the PI data capturing system were: Status, downtime reason, downtime reason commented, motor power and motor running time. These data elements were used to build a picture of when the crusher's were down and for what reason.

4.8.3 Data Classification

In terms of data classification, the first step is to identify if the data point found can be classified as a failure or suspension. This is important as it influences future calculations that take into account whether a data point is a failure or a suspended data point. The data set obtained was manually sorted through and it was ascertained whether an observation was a failure or suspension. Due to the fact that the acquired data set was at times haphazardly completed, in terms of its accuracy the assumption was made that only events that state in their description "planned maintenance" or "maintenance" would be taken as suspended data points.

Once a data set has be complied for a specific crusher, a Pareto analysis can be conducted in order to identify the most frequent causes of failure, this is especially useful due to the large quantity of data obtained. For the Pareto analysis, only failure data points were taken into account, suspended data points were of course not included. The Pareto analysis and the ancillary Pareto chart, provided a far better global view of the system and its current failure modes, from here the failure analysis could continue. Table 4.3 shows an extract of the failure data that was extracted from the raw data obtained for the crushers.

Table 4.3: Extract of found failure data for all three crushers.

Crusher 1			**Crusher 2**			**Crusher 3**		
Obs. #	X_i	C_i	Obs. #	X_i	C_i	Obs. #	X_i	C_i
1	12.2	1	1	9.8	1	1	39.6	1
2	38.0	1	2	4.1	1	2	3.8	1
3	4.6	1	3	34.8	1	3	52.7	1
4	28.2	1	4	11.5	1	4	26.8	1
5	25.5	1	5	41.4	1	5	0.4	1
6	7.4	1	6	1.6	1	6	79.2	1
7	12.1	1	7	89.7	1	7	146.1	0
8	24.7	1	8	22.9	1	8	38.0	1
9	4.0	1	9	6.7	1	9	26.4	0
10	67.4	0	10	7.4	1	10	74.6	1
11	41.2	1	11	29.1	1	11	47.2	1
12	36.8	1	12	0.8	1	12	3.5	1
13	26.0	0	13	6.0	1	13	12.7	1
14	87.0	1	14.0	18,2	1	14	1.0	1
15	41.7	1	15	70.4	1	15	116.1	1
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.
100	181.8	1	92	0.4	1	80	15.9	1
101	6.9	1	93	116.7	1	81	6.3	1
102	225.2	1	94	15.5	1	82	50.3	1
103	35.1	0	95	116.4	1	83	63.8	1
104	123.2	0	96	22.3	1	84	129.2	1
105	206.1	0	97	45.9	0	85	104.0	1
106	85.5	0	98	851	0	86	4.1	0
107	91.0	1	99	90.7	1	87	7.6	1
108	21.5	1	100	20.2	1	88	8.3	1
109	271.1	1	101	59.8	1	89	7.6	1
110	37.0	0	102	237.0	0	90	7.2	0

4.9 Analysis of Crusher 1

In this section the results of the analysis for the first of the three crushers in the system are shown. The time period used from the data set was from the 1^{st} of October 2010 to the 31^{st} of July 2011. Specific assumptions were made in addition to the general assumptions, stated in Section 4.7, regarding crusher 1, as stated in Appendix A.

4.9.1 Analysis of the Failure Data Set for Crusher 1

The maintenance and failure data for crusher 1 was sorted through from the original data, in order to gain a data set that purely applied to the events that needed to be categorised. These were unscheduled maintenance, failure or scheduled maintenance and suspensions. Once the data had been sorted, the 110 events found during the previously stated analysis period were imported into Microsoft Excel. Here data such as event number (Obs. #), actual time (X_i), event type (C_i) and global time (T_i) were categorised and calculations were performed.

A Pareto analysis was, performed in order to gain a better or more complete overview and understanding of the types of failures and their frequency of occurrence. The Pareto chart for crusher 1 is shown in Figure 4.4. Different failures were grouped into a number of categories namely: lube system, feedback fault, other/unplanned maintenance, speed monitor/speed switch, mechanical and liner. Two other categories, electrical and spider, were found to be less than 5 % and are therefore not shown in Figure 4.4.

The first calculation performed on the data was the Laplace trend test, discussed in Section 3.3.5 and shown in Equation 3.1. The result of the Laplace test for the found data was $U_{L_{CR1}} = -3.989$, this was clearly in the reliability improvement area of the test and therefore displayed a trend, see Figure 3.6, therefore making the Lewis–Robinson trend test superfluous. The results are outlined in Table 4.4

The Power Law NHPP was used in this analysis, this method is discussed in Section 3.5. Referring to Figure 3.7, the data set for crusher 1 can be analysed using repairable systems theory. Here a power law NHPP was used to model the system in order to find expected failure times. The power law's parameters, λ and δ, were found through the least-squares method, the parameters were found by using the solver function in Microsoft Excel. Parameters are shown

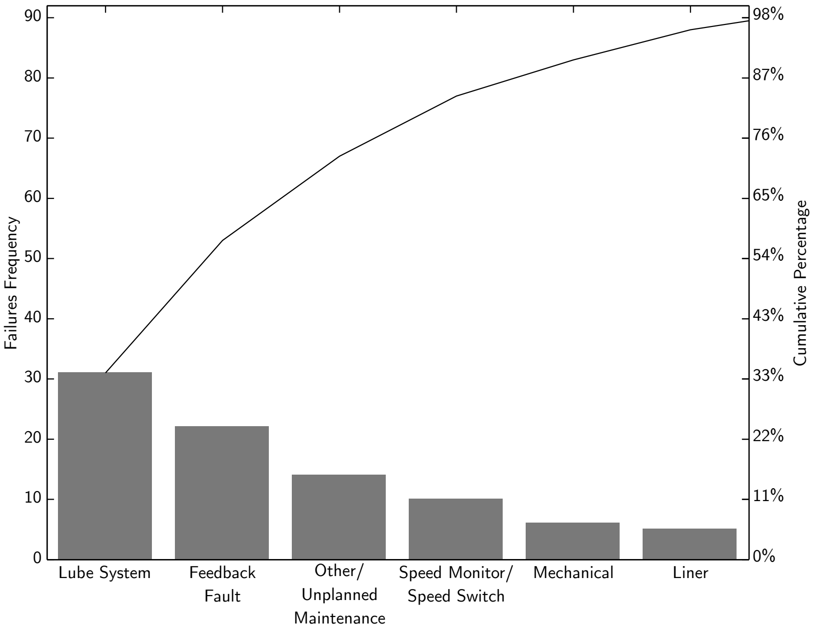
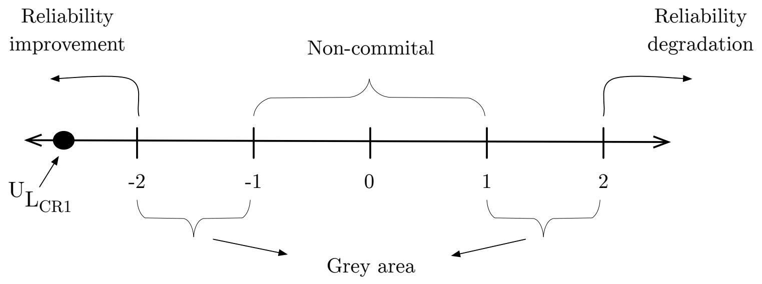


Figure 4.4: Pareto Chart for Crusher 1

Table 4.4: Results of Trend Tests applied to Crusher 1 data.

Trend Test	**Result**
Laplace Test	$U_{L_{CR1}} = -3.989$
Lewis-Robinson Test	N/A



in Table 4.5. Using the found parameters, the formula of the distribution that was found to follow the actual failure events is shown in Equation 4.1.

Table 4.5: Power law parameters found for Crusher 1.

Parameter	**Value**
λ	0.3357
δ	0.6767

$$\rho_{CR1} = (0.3358) \cdot 0.6767t^{0.6767-1} \tag{4.1}$$

The outcome of using the Power Law NHPP, in order to model the failure data is shown in Figure 4.5. Figure 4.5 plots the actual found failure events, together with the predicted or modelled failure events, found through the use of the Power Law NHPP.

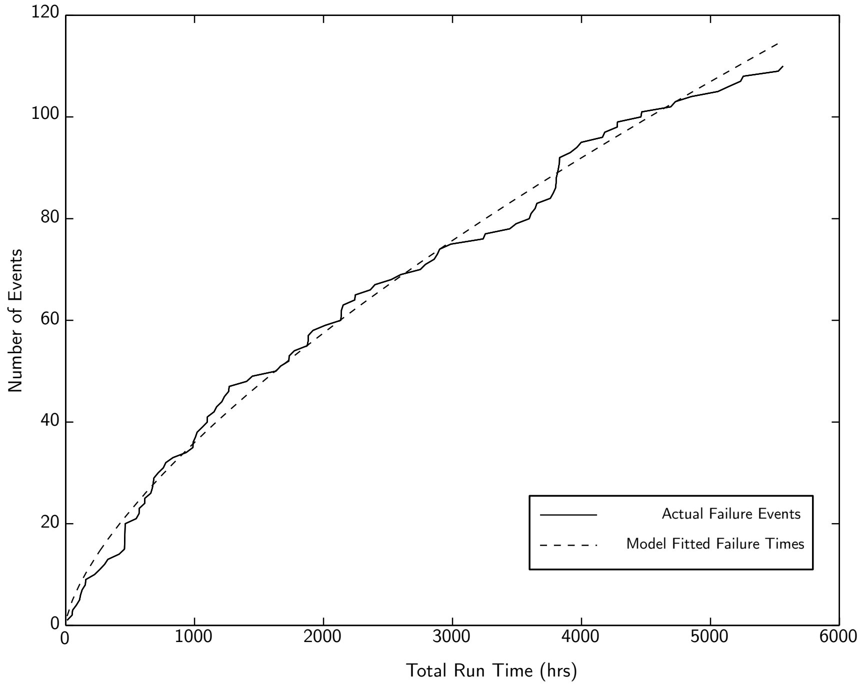


Figure 4.5: Modelled failure times using the Power Law NHPP.

4.9.2 MTBF Calculation for Crusher 1

The historical and future MTBF of crusher 1 is determined for comparative purposes and in order to have a reference in the analysis that was used. The calculation of the MTBF for the repairable Crusher 1 system, is detailed in Chapter 3, Section 3.5.1. An extract of crusher 1's data set is shown in Table 4.3.

The historic MTBF for Crusher 1 was found to be 49.06 hours, using Equation 3.17 in Chapter 3. The future MTBF was calculated by using Equation 3.18, and was found to be 71.65 hours, results are summarised in Table 4.6.

Table 4.6: Summary of both historic and future MTBF found for Crusher 1.

MTBF type	Hours
Histortic MTBF	49.06
Future MTBF	71.65

4.9.3 MFOP Calculations for Crusher 1

MFOP calculations specific to crusher 1 are shown in this section. It was established that crusher 1 followed a repairable system and was modelled accordingly, using the power law NHPP. The distribution that Crusher 1 followed is shown in Equation 4.1, with parameters λ and δ found, these parameters will be needed in order to perform MFOP calculations.

In order to determine the MFOP and MFOPS of Crusher 1, a system that is modelled on a NHPP was used, details of which can be found in Section 3.5.2.

$$\text{MFOPS}(t_{mf}) = e^{-\lambda((t_{mf}+T_r)^{\delta}-(T_r)^{\delta})} \tag{4.2}$$

Using Equation 4.2, and the previously determined power law NHPP parameters, the MFOP of Crusher 1 could be determined, this is shown graphically in Figure 4.6.

From Figure 4.6 it can be seen that Crusher 1 did not yield particularly high MFOPS probabilities for long MFOP. The comparison of the historic MTBF, refer to Section 4.9.2, to the equivalent MFOP of the same length gave the following results that were found through the application of failure statistics and are not just a mean. At Crusher 1's MTBF of approximately 49 hours, the probability of achieving this, or the MFOPS, was about 50 %, without requiring any corrective maintenance actions.

A further MFOP length that could be taken, as it is easy to comprehend, is the length of a full day or 24 hours. Inspecting Figure 4.6, it is found that Crusher 1 had a MFOPS of 71 % at an MFOP of 24 hours.

4.9.4 MFOP Calculations for Hypothetical Crusher 1

In order to better perceive the MFOP principle, a hypothetical Crusher 1 was modelled. This crusher used the same data set found for Crusher 1 but removed the top two failures, found in the Pareto chart (Figure 4.4), from the data set. Even though this is a hypothetical system, it does not seem unrealistic in the

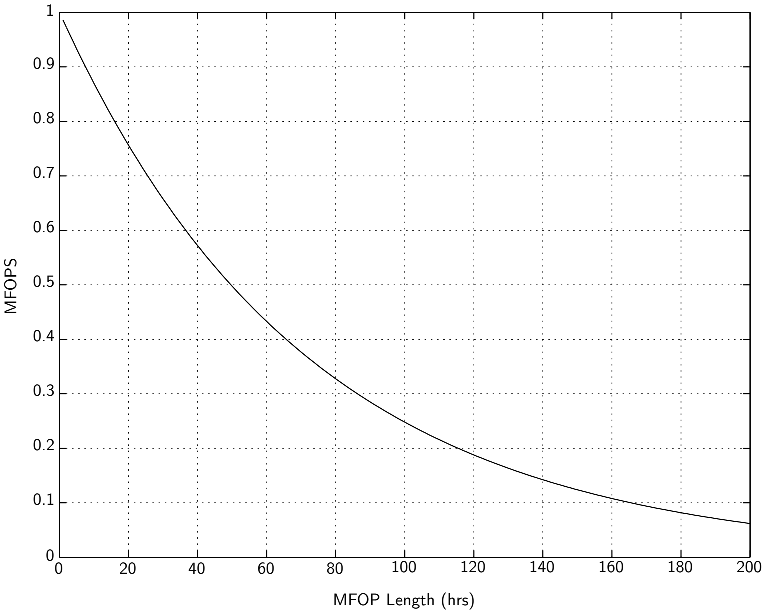


Figure 4.6: Probability of achieving MFOP length for Crusher 1.

targets it achieves. In the case of Crusher 1, the top two failures that were removed were the categories of the lube system and feedback faults, these made up approximately 70 % of the failures of Crusher 1. Now that a new data set was formed, the analysis began again with the application of trend tests to the failure data set. Using the Laplace trend test it was established that the hypothetical Crusher 1 lay in the grey area of the test. Therefore, no conclusive statement can be made as to whether their is a trend present or not. The Lewis–Robinson trend test was then applied to the data set, here, again no conclusive result was found, the data was still in the grey area. At this point an assumption needs to be made, plotting the data, it can be seen that the system looks like a repairable system with a distinct reliability improvement, it was therefore decided to model the system accordingly.

The power law NHPP was therefore used to model the new data set, with the power law parameters, λ and δ, being found numerically, using the least squares method. The results for the parameters are shown in Table 4.7.

After the parameters for the power law NHPP were known, the MFOP analysis could begin. Plotted in Figure 4.8, is a comparative plot of the MFOP length and equivalent MFOPS for both the current Crusher 1 and the hypothetical Crusher 1 system.

Table 4.7: Power law parameters found for the hypothetical Crusher 1.

Parameter	Value
λ	0.0863
δ	0.7551

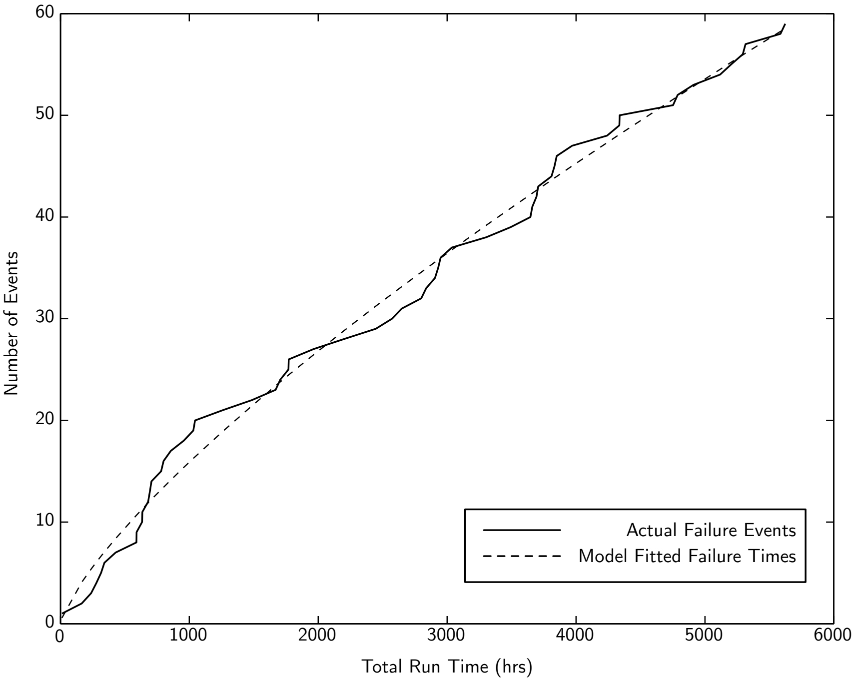


Figure 4.7: Modelled failure times using the Power Law NHPP.

4.9.5 Summary of Results of Crusher 1

Crusher 1 is the only crusher of the three that could be modelled as a repairable system, due to the results of the Laplace trend test. The greatest cause of failure for Crusher 1 was the lube system, accounting for nearly 40 % of all failure. MFOP calculations performed on the crusher found that the crusher at an MFOP length equal to that of its MTBF (49 hours), the MFOPS is approximately 50 %. In essence, giving Crusher 1 was given a 50 % chance of completing its found MTBF, without requiring unscheduled maintenance.

A different outlook of Crusher 1 was given in the hypothetical case that was modelled, here the top two failures were removed from the data and a new failure data set was defined.

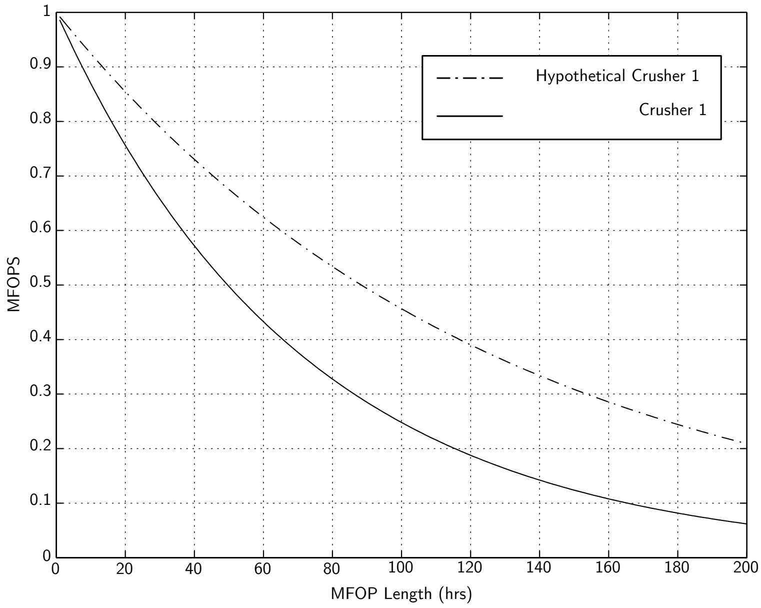


Figure 4.8: Probability of achieving MFOP length for both hypothetical and current Crusher 1.

4.10 Analysis of Crusher 2

In this section the results of the analysis for the second of the three crushers in the system is shown. The data set was within the time period of 2010 to 2011. Specific assumptions made in addition to the general assumptions, stated in Section 4.7, regarding Crusher 2 are stated in Appendix A.

4.10.1 Analysis of the Failure Data Set for Crusher 2

The maintenance and failure data for Crusher 2 was sorted through from the original data in order to gain a data set that purely applied to the events that should be categorised. These again, as with Crusher 1, should be unscheduled maintenance, failure, or scheduled maintenance and suspensions. Times between failures or suspensions were taken, these failures being system failures. Once the data had been sorted the, 102 events found during the stated analysis period were imported into Microsoft Excel. Here data such as event number (Obs. #), actual time (x_i), event type (C_i) and global time (T_i) were categorised and calculations were performed.

A Pareto analysis was performed on the data set for Crusher 2, in order to ascertain what the predominant causes of failure were, also providing a better overview of the system. The Pareto chart is shown in Figure 4.9. Different failures were grouped into a number of categories namely: lube system, feedback fault, speed monitor/speed switch, spider, electrical, mechanical, mantle and other. Mechanical and mantle faults were found to be less that 5 % and are therefore not shown in Figure 4.9.

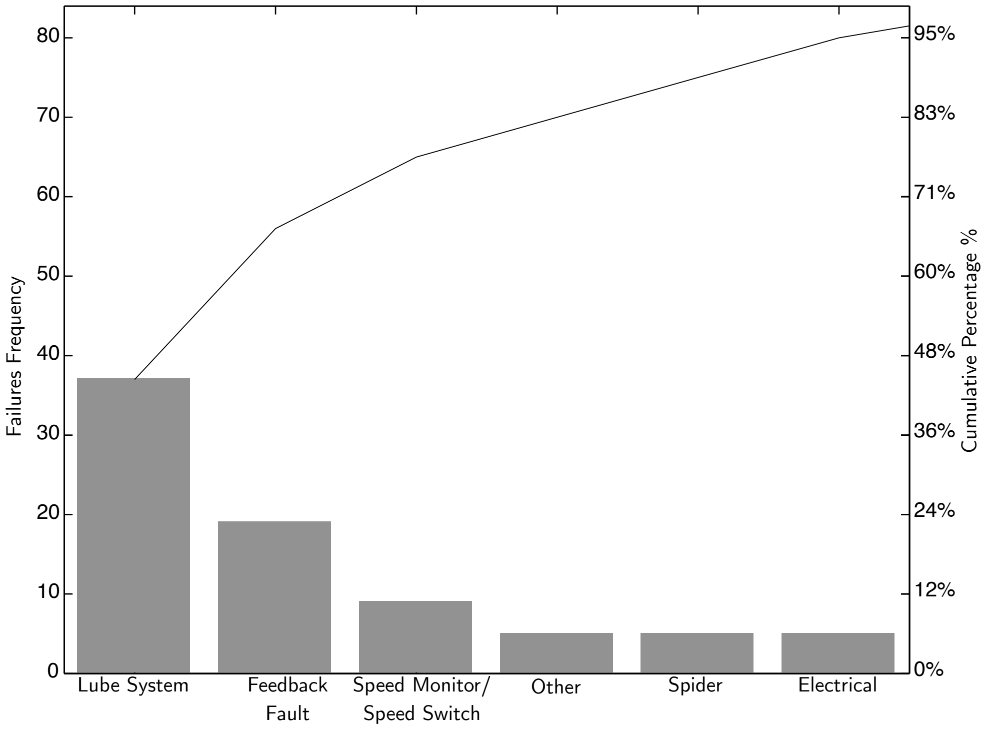


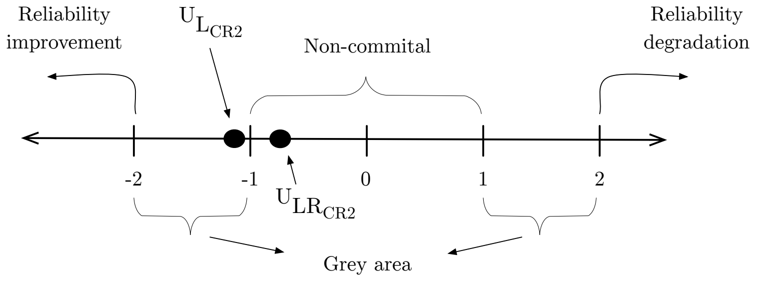
Figure 4.9: Pareto Chart for Crusher 2

The first calculation performed on the failure data for Crusher 2 was the Laplace trend test, discussed in Section 3.3.5 and shown in Equation 3.1. The result of the Laplace test for the found data was $U_{L_{CR2}} = -1.169$. This puts Crusher 2 into the grey area of the Laplace trend test and the test could therefore not provide a definitive answer as to whether there was a trend or not. The Lewis–Robinson trend test was then applied to the data, this test was described in Chapter 3 Section 3.3.5. The outcome of the Lewis–Robinson test was found to be $U_{LR_{CR2}} = -0.818$. This took Crusher 2 back into the noncommittal or no trend area of the Laplace trend test. The results are outlined in Table 4.12.

Due to the fact that the Lewis–Robinson test showed that Crusher 2 had no apparent trend within the data, Crusher 2 was analysed using non-repairable

Table 4.8: Results of Trend Tests applied to Crusher 2 data.

Trend Test	Result
Laplace Test	$U_{L_{CR2}} = -1.169$
Lewis-Robinson Test	$U_{LR_{CR2}} = -0.818$



systems theory. This required a Weibull analysis as described in Chapter 3 in Section 3.4. The shape parameter, β, and the scale parameter, η, were numerically found by the Maximise the Likelihood Method, also shown in Section 3.4, results are given in Table 4.9.

Table 4.9: Weibull parameters found for Crusher 2.

Parameter	Value
β	0.875
η	56.092

This creates the specific distribution for Crusher 2 given in Equation 4.3 below:

$$f(x) = \frac{0.875}{56.092}\left(\frac{x}{56.092}\right)^{-0.125} \cdot \exp\left(-(x/56.092)^{0.875}\right) \tag{4.3}$$

Equation 4.3 provides the probability of system failure at instant x and is plotted in Figure 4.10.

In Equation 4.3, as shown theoretically in Equation 3.5, the probability of system failure before a certain instant, x, is yielded, this is shown graphically in Figure 4.11.

Analysing the found shape parameter, β, of Crusher 2, which is also know as the Weibull slope, as the value of β, is equal to the slope of the probability density function shown in Figure 4.10. Even though Crusher 2 is not a non-repairable system, it behaves like one, with the current $\beta < 1$, Crusher 2 displayed a probability of failure that decreases with time. Analysis determined

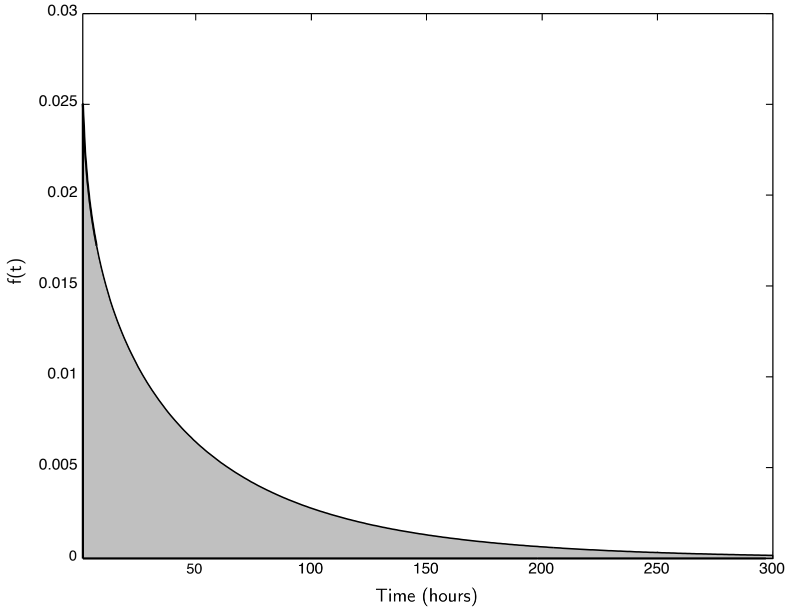


Figure 4.10: Weibull pdf for Crusher 2.

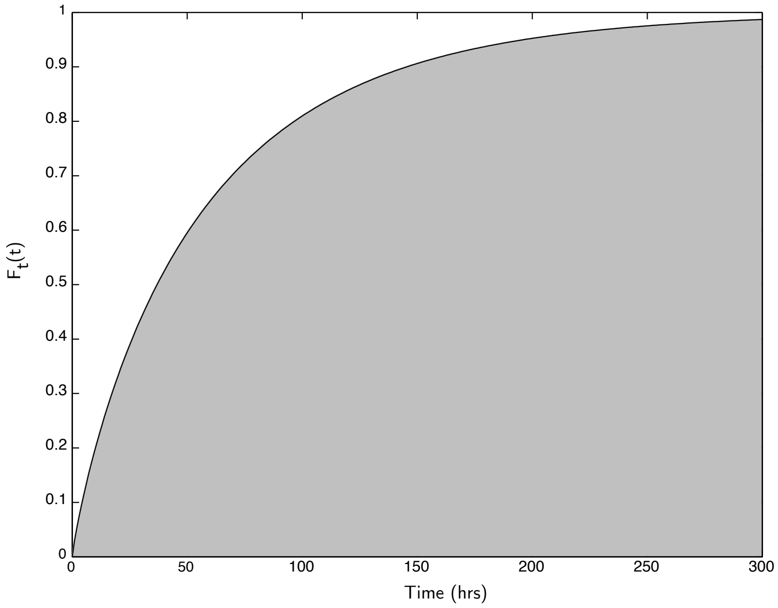


Figure 4.11: Weibull cdf for Crusher 2.

the scale parameter, η, which has the effect of stretching out the probability density function, or the same effect as a change in the abscissa scale. The peak value of the probability density function curve could decrease, as the area under the probability density function remained a constant one. An increase in η, while keeping β constant, stretches the curve out towards the right and its height decreases. A decrease in η, while keeping β constant, pushes the distribution to the left and its height increases.

Now that parameter estimators are known and systems reliability is modelled, including graphically, the MFOP calculation can begin.

4.10.2 MTBF Calculation for Crusher 2

The historic and future MTBF of Crusher 2 is determined simply for comparative reasons and in order to have a currently used reference in this analysis. For the non-repairable system of Crusher 2 the calculation of the MTBF is clearly the average of the failure times found in the collected failure data, a short extract of this data is shown in Table 4.3.

From the data, shown in Table 4.3, the average X_i was calculated and then divided by the total number of observations, in this case 102. The historic MTBF of crusher 2 was then found to be 50.34 hours and the future MTBF, found by applying Equation 3.8, was determined as 60.01 hours, results are summarised in Table 4.10.

Table 4.10: Summary of both historic and future MTBF found for Crusher 2.

MTBF type	Hours
Histortic MTBF	50.34
Future MTBF	60

4.10.3 MFOP Calculations for Crusher 2

MFOP calculations are shown in this section, these calculations are specific for Crusher 2. Crusher 2 has been found to act like a non-repairable system previously, thereby necessitating a Weibull analysis of the system, which was done in the previous section. The shape and scale parameters for the Weibull distribution of Crusher 2 were found, these are needed for further analysis.

In order to determine the MFOP and MFOPS of Crusher 2, a system that can be Weibull modelled on Equation 4.4 is used, MFOP calculations have been discussed in Section 3.4.2.

$$\mathrm{MFOPS}(t_{mf}) = \exp\left(\frac{t^{\beta} - (t + t_{mf})^{\beta}}{\eta^{\beta}}\right) \tag{4.4}$$

Using Equation 4.4 and the previously determined Weibull shape and scale parameters, the MFOP of crusher 2 was calculated, and is shown graphically in Figure 4.12.

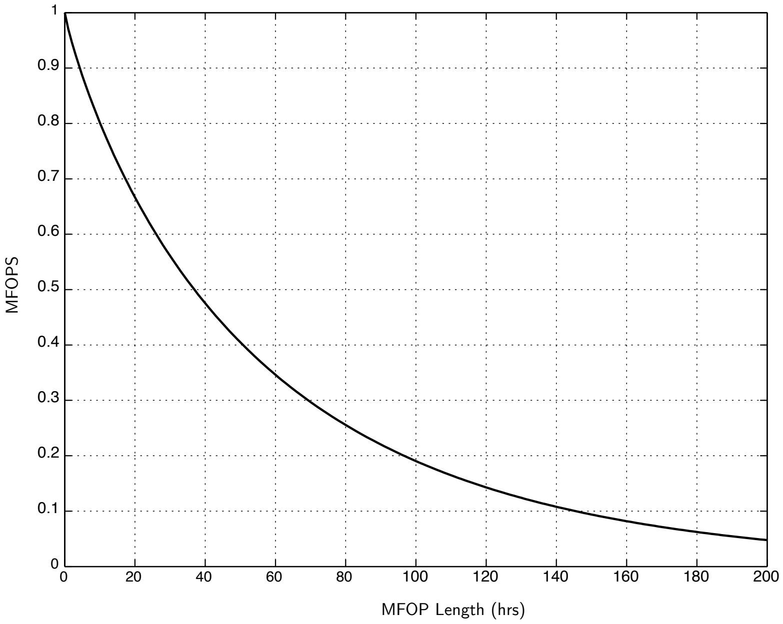


Figure 4.12: Probability of achieving MFOP length for Crusher 2

It is immediately obvious that Crusher 2, in its current state, does not provide a particularly high MFOP at a high probability of achievement at that MFOP length. In comparison to the MTBF found in Section 4.10.2, which was approximately 50 hours of operation, MFOP yields additional information calculated through formal failure statistics and is not just a Mean as in MTBF. Figure 4.12 presents us with the fact that if Crusher 2 was given a MFOP length equal to that of the MTBF (50 hours), Crusher 2 would only have an approximately 40 % probability of completing that period without requiring any corrective maintenance actions.

Another MFOP length of interest, which is easy to comprehend, is the length of 24 hours or a full day. Again, by examining Figure 4.12, finding 24 hours on the x-axis of the plot and then reading off the equivalent probability, it is found that Crusher 2 has an approximately 62 % probability of achieving an MFOP of 24 hours.

4.10.4 MFOP Calculations for Hypothetical Crusher 2

For the purpose of better illustrating the MFOP principle, a hypothetical crusher 2 system was modelled. With reference to the Pareto analysis shown in Section 4.10.1, Figure 4.9, the hypothetical case removed the top two failures from the data set, the lube system and feedback faults, these failures constituted approximately 70 % of the failures in Crusher 2. Once again the first step in the analysis of the data set was a trend test, the Laplace trend test yielded a result that indicates no underlying trend in the data. This therefore again required a Weibull analysis to be performed, thereby finding the Weibull parameters β and η for the hypothetical system. Results for the Weibull parameters are shown in Table 4.11.

Table 4.11: Weibull parameters found for hypothetical Crusher 2.

Parameter	Value
β	0.759
η	201.054

The Weibull pdf for both the current crusher and the hypothetical system is shown in Figure 4.13. Here a vast difference can be seen, the probability of failure is seen to rapidly decrease when compared to the current system, stabilising faster.

Now that the Weibull parameters, β and η, are known, an MFOP calculation could be made, again using Equation 4.4 as before. The plot of the results of the MFOP of the hypothetical system, together with the current system as a comparison, is shown in Figure 4.14.

Comparing the current MFOP of Crusher 2 and the hypothetical one in Figure 4.14, it is immediately noticeable that the hypothetical system provided a substantially improved MFOP, at a far higher probability of success. Studying the 50 hour MTBF value that was established previously, it now becomes apparent that the new system has a far higher chance of achieving this period, up from 40 % to 70 %.

4.10.5 Summary of Results of Crusher 2

Crusher 1 and 2 have very similar MTBF values, 49 hours and 50 hours respectively, but behave very differently and need therefore to be modelled in a

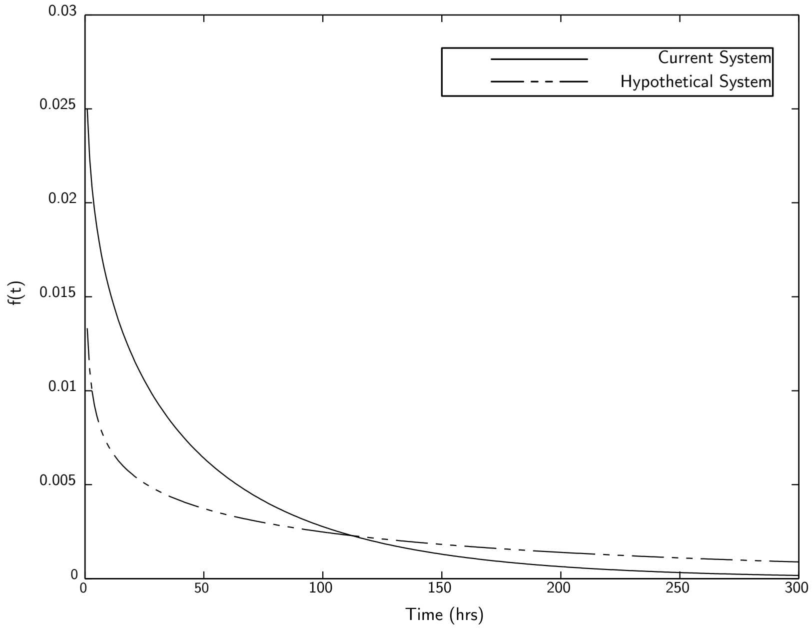


Figure 4.13: Combined plot of the Weibull pdf of the current and hypothetical Crusher 2.

different way. The greatest cause of failure for Crusher 2, as for all crushers, is the lube system, accounting for nearly 50 % of the total failures within the analysis period. Owing to the results of the Laplace and Lewis-Robinson trend tests, the crusher was modelled using the Weibull distribution with parameters found, as seen in Table 4.9. The MFOP calculations performed on crusher two found that the crusher at an MFOP length equal to that of its found MTBF, had a MFOPS of approximately 40 %. Therefore giving the crusher a 40 % chance of achieving its found MTBF.

In order to show another perspective of the Crusher 2 system, a realistic hypothetical case was constructed. The top two failures found in the Pareto analysis were removed from the data set and a new failure data set was compiled. The conceived system displayed a significant improvement in its attainable MFOP and MFOPS, gains of an MFOP of 50 hours from a previous MFOPS of 40 % to one of 70 % are seen in Figure 4.14.

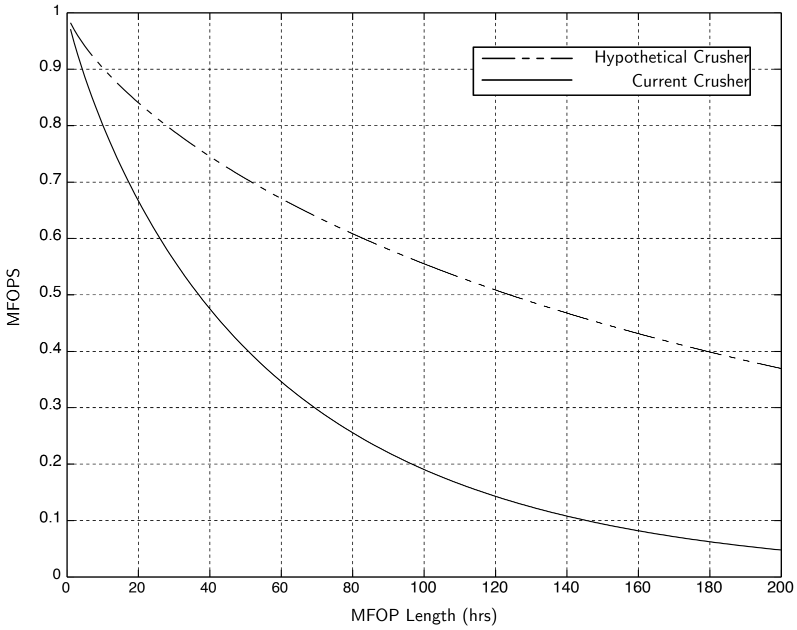


Figure 4.14: Probability of achieving MFOP length for both hypothetical and current Crusher 2

4.11 Analysis of Crusher 3

In this section the results of the analysis for the third of the three crushers in the system is shown. Here again the same period was analysed as before, within the time period of 2010 to 2011. Specific assumptions made in addition to the general assumptions, stated in Section 4.7, regarding crusher 3 are stated in Appendix A.

4.11.1 Analysis of the Failure Data Set for Crusher 3

For Crusher 3 the same procedure used before was applied to the data set. The maintenance and failure data, specific to Crusher 3 was sorted through from the original sampled data, this was done in order to gain a data set that purely applied to the events that should be categorised. The events are either failures or unscheduled failures or suspensions or scheduled maintenance. The data set consisted of times between failures or suspensions, these failures being system failures. Once the data was compiled, Crusher 3 presented 90 events for the analysed period. These 90 events were then further analysed in Microsoft Excel.

A Pareto analysis was performed on the data set for Crusher 3 in order to gain a better understanding of the predominant causes of failure, providing a better overview of the system. The Pareto chart is shown in Figure 4.15. Different failures were grouped into a number of categories namely: lube system, other/unplanned maintenance, feedback fault, speed switch/speed monitor and electrical. Two other categories, mechanical and spider, constituted less than 5% and are therefore not shown in Figure 4.15.

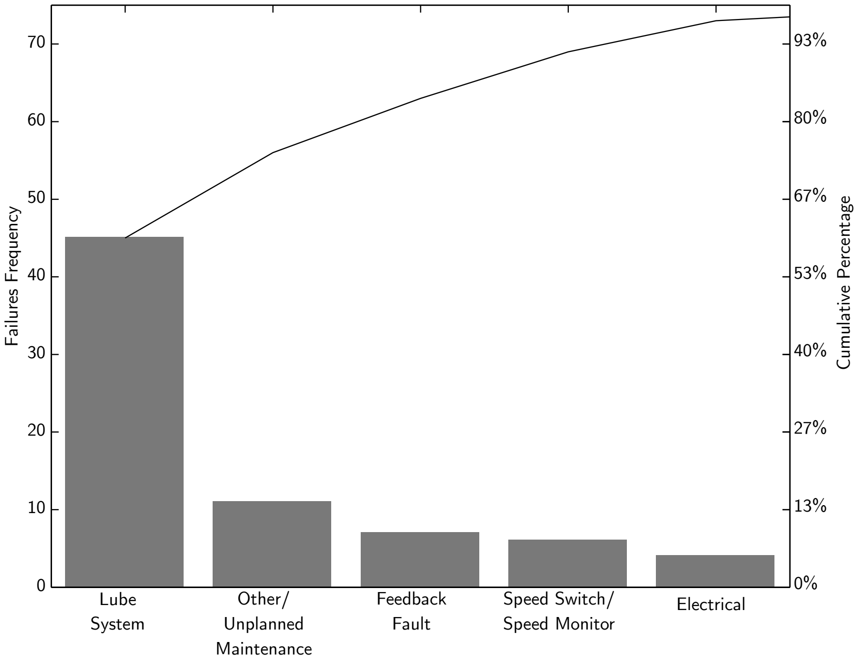
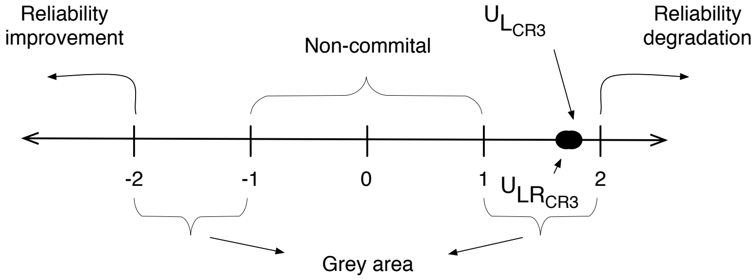


Figure 4.15: Pareto Chart for Crusher 3.

As the same procedure is followed as for Crusher 1 and 2, the first calculation performed in the failure data set for Crusher 3 was the Laplace trend test. Details of the Laplace trend test are shown in Section 3.3.5. The result of the Laplace trend test in the data set was found to be $U_{L_{CR3}} = 1.60$. This put Crusher 3, as with Crusher 2, in the grey area of the Laplace trend test, the test thus provided an inconclusive result and did not deliver an answer as to whether there is a trend present within the data set. The Lewis-Robinson trend test, a modification of the Laplace trend test, was then applied to that data set. The test uses the same test scale as the Laplace test, the result of the Lewis-Robinson test was found to be $U_{LR_{CR3}} = 1.59$. This did not show a significant change and was still within the grey are of the test metric, revealing

Table 4.12: Results of Trend Tests applied to Crusher 3 data.

Trend Test	**Result**
Laplace Test	$U_{L_{CR2}} = 1.608$
Lewis-Robinson Test	$U_{LR_{CR2}} = 1.591$



no further details on whether the data set has an underlying trend or not. This information was needed in order to ascertain whether the crusher should be modelled as an repairable or non-repairable system.

As both trend tests did not divulge a definitive answer, the data was looked over again and from looking at the event times it was assumed that no trend was present. Crusher 3 was therefore modelled with a Weibull distribution and as a non-repairable system, providing a satisfying result.

Crusher 3 as with Crusher 2 required a Weibull analysis to be performed, as described in Chapter 3 in Section 3.4. This analysis would yield the two Weibull parameters, β and η, needed for further analysis and found numerically by Maximising the Likelihood Method. The results of this are given in Table 4.13.

Table 4.13: Weibull parameters found for Crusher 3.

Parameter	**Value**
β	0.9239
η	78.114

Substituting the found shape and scale parameters into Equation 3.3, the specific equation for Crusher 3 shown below in Equation 4.5.

$$f(x) = \frac{0.924}{78.1}\left(\frac{x}{78.1}\right)^{-0.076} \cdot \exp\left(-(x/78.1)^{0.924}\right) \tag{4.5}$$

Analysing the found Weibull shape parameter, β, of Crusher 3 it was found that it is close to a value of 1. If the β was equal to 1 then the effect would be a constant failure rate, or one which is consistent with the exponential distributions. Even though β was still less than 1 for Crusher 3 the Crusher does display a very slightly decreasing failure rate, but close to a constant one. The Weibull pdf is shown in Figure 4.16 and the failure probability function is shown in Figure 4.17.

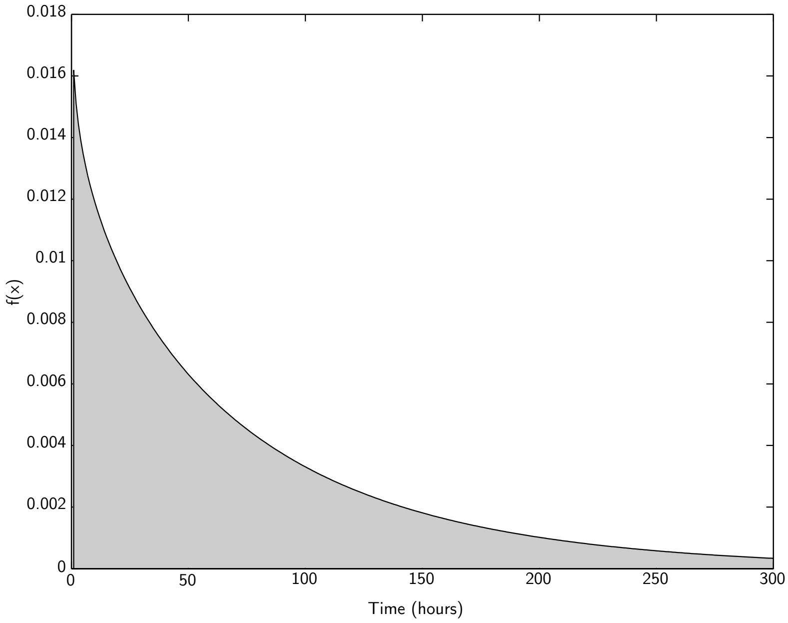


Figure 4.16: Weibull pdf for Crusher 3.

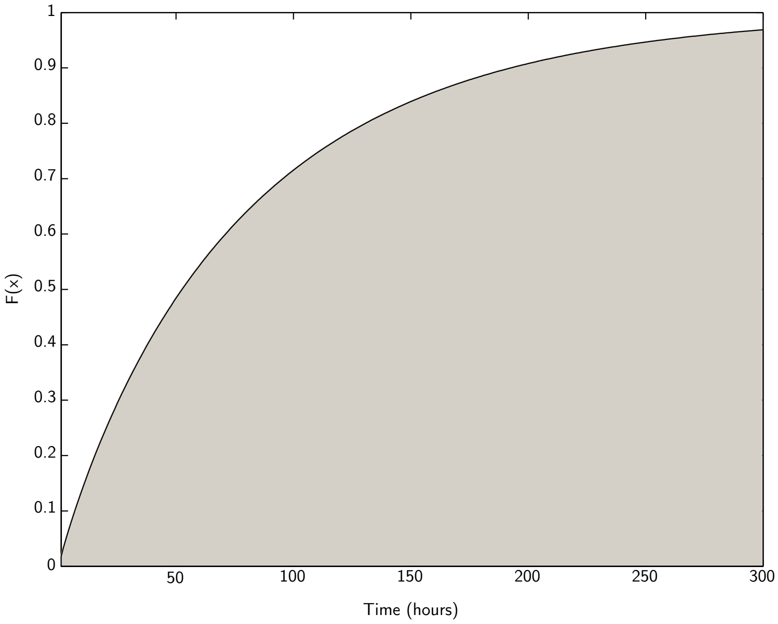


Figure 4.17: Weibull cdf for Crusher 3.

4.11.2 MTBF Calculation for Crusher 3

The historic and future MTBF of Crusher 3 is again calculated for comparative reasons and in order to have reference in the analysis of Crusher 3. As Crusher 3 was modelled as a non-repairable system, the calculation of the MTBF was the average of the failure times found in the failure data, a short extract of this data is shown in Table 4.3.

From the data, shown in Table 4.3, the average X_i was calculated, thereby yielding the historic MTBF of Crusher 3. The historic MTBF of Crusher 3 was found to be 64.5 hours and the future MTBF was determined as 81 hours, results are summarised in Table 4.14.

Table 4.14: Summary of both historic and future MTBF found for Crusher 3.

MTBF type	**Hours**
Histortic MTBF	64.5
Future MTBF	81

4.11.3 MFOP Calculation for Crusher 3

MFOP results, specific for Crusher 3 are shown in this section. As discussed in previous sections (Section 4.11.1) Crusher 3 was found to act like a non-repairable system, which therefore necessitated a Weibull analysis of the system. The shape and scale parameters, β and η respectfully, were found and are shown in Section 4.11.1. These two parameters were needed in order to perform MFOP calculations.

In order to determine the MFOP and MFOPS of Crusher 3, Equation 4.4, as with Crusher 2 was used. The shape and scale parameters are substituted into the equation to calculate the MFOP, and are shown graphically in Figure 4.18.

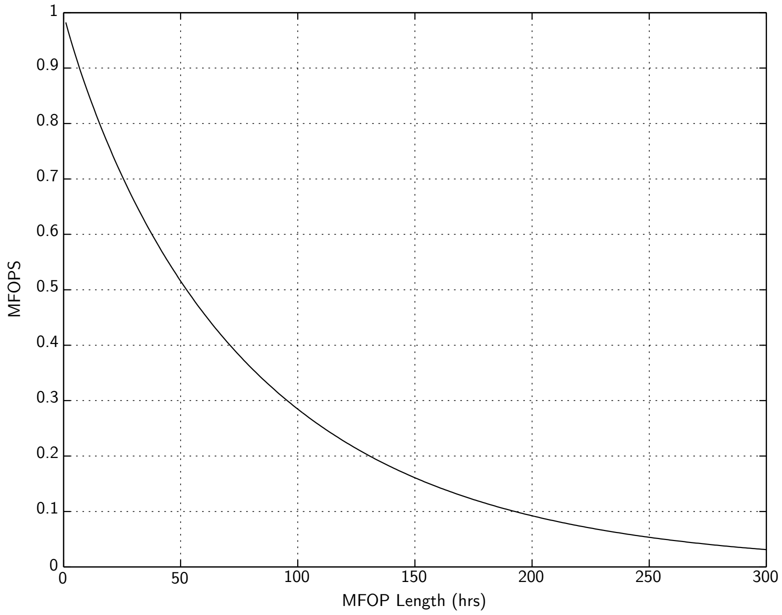


Figure 4.18: Probability of achieving MFOP length for Crusher 3.

As with Crusher 2, Crusher 3 does not provide a particularly high MFOP at a high probability of achievement. However, immediately noticeable, is that Crusher 3 is more reliable than Crusher 2. Comparing Crusher 3's previous MTBF, 65 hours, with the found MFOP it was seen that Crusher 3 actually only had an approximately 44 % chance of completing this period without requiring any corrective maintenance actions.

Table 4.15: Weibull parameters found for hypothetical Crusher 3.

Parameter	Value
β	0.9249
η	357.023

As with Crusher 2, looking at a 24 hour period, is relatively easy to comprehend, Figure 4.18 shows that the Crusher had a 71 % chance of completing a full day without requiring corrective maintenance actions.

4.11.4 MFOP Calculation for Hypothetical Crusher 3

A hypothetical Crusher 3 was modelled, again, in order to better demonstrate the MFOP concept. Even though this system was hypothetical it was not unrealistic. With reference to the Pareto chart shown in Figure 4.15, the hypothetical case removed the top two failure cases from the data set. In the case of Crusher 3, these were the categories of lube system failures and other/unplanned maintenance. The latter failure was classified by failures such as sequence stops or data points that are simply named "unplanned maintenance". These two failure categories made up over 70% of failures for Crusher 3. Once a new data set had been formed, the analysis started again with a trend test. The Laplace trend test established that there was no underlying trend present in the new data set and therefore the hypothetical Crusher could again be modelled using the Weibull analysis. Weibull parameters were then found by using the Maximising the Likelihood Method, parameters β and η, shown in Table 4.15.

The Weibull pdf for both the current Crusher 3 and the hypothetical system is shown in Figure 4.19. Here the vast difference can be seen, by rectifying the two failure modes, a substantial difference to the reliability of Crusher 3 can be made.

As the Weibull parameters, β and η, of the hypothetical system are now known, an MFOP calculation could be performed. The results were plotted together with the current MFOP performance, shown in Figure 4.20.

By comparing the two systems, a vast difference can be seen in the probability of achievement of MFOP length. The supposed system was immensely more reliable than the current system. Taking the previously established current systems MTBF of 65 hours, Crusher 3 had a 44 % chance of completing

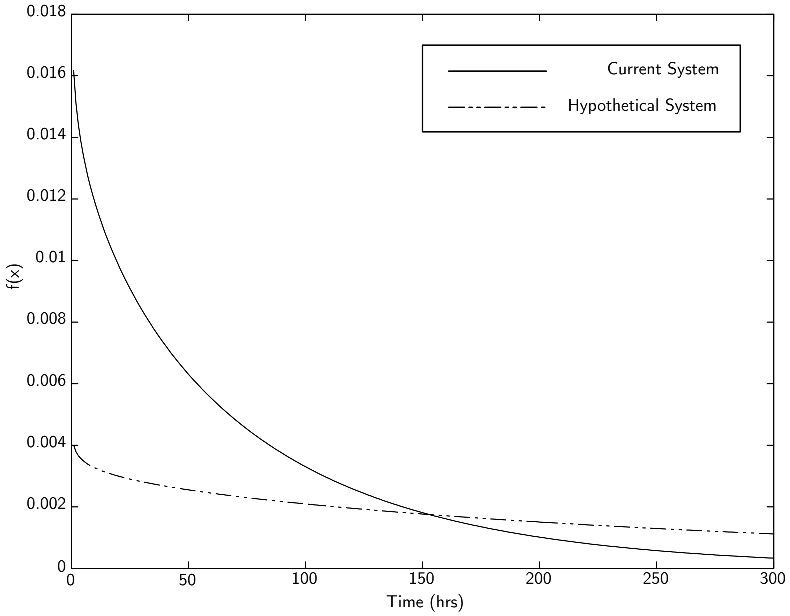


Figure 4.19: Combined plot of the pdf of the current and hypothetical Crusher 3.

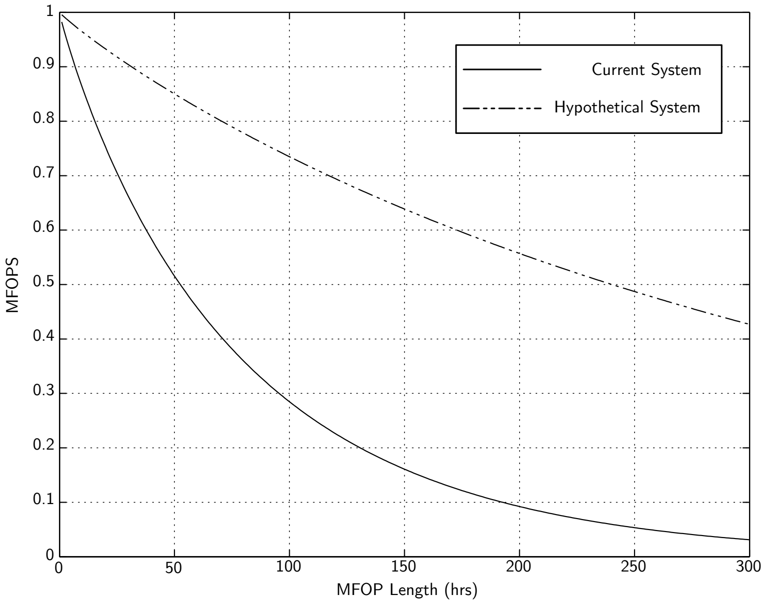


Figure 4.20: Probability of achieving MFOP length for both hypothetical and current Crusher 3.

this period. The proposed system would now have a 82% chance of making the same period, a sizeable improvement.

4.11.5 Summary of Results of Crusher 3

It can be ascertained that Crusher 3 is the most reliable Crusher of the three cone crushers analysed. Of the 90 events that were found during the analysis period, the Pareto analysis established that the lube system was by far the greatest cause of failure, accounting for over 60 % of failures. The data set was analysed and it was found that it could be characterised with a Weibull distribution. Weibull parameters were found with results provided in Table 4.13, Crusher 3 displayed a probability of failure that decreased with time. The MFOP of Crusher 3 was calculated and found to be 44 % at the crusher's MTBF of 65 hours. Here the operator of the equipment immediately had more information at hand about the current performance of the system.

A hypothetical or proposed Crusher 3 was then modelled, with the top two causes of failure removed from the data set, and a new failure data set found. A considerable and realistic improvement was found in both the MFOP and MFOPS, seen in Figure 4.20, with the crusher achieving an MFOP of over 100 hours at an MFOPS of more than 70 %.

4.12 Final Remarks

Now that the MFOP analysis for all crushers has been performed, a final comparison can be conducted. Starting with the familiar MTBF values found for each crusher, shown in Table 4.16. the most striking element is the fact that Crusher 1 and Crusher 2 have an MTBF that is virtually the same, Crusher 3 displays a MTBF that is approximately 14 hours behind the other two crushers.

Table 4.16: Historic and future MTBF values for all crushers in their current state.

Crusher	**Historic MTBF (hrs)**	**Future MTBF(hrs)**
Crusher 1	49	72
Crusher 2	50	60
Crusher 3	64.5	81

Even though Crusher 1 and Crusher 2 have more or less the same MTBF, there reliability characteristics are vastly different. Looking at an MFOP length equal to that of the shared MTBF of both crushers, it can be seen that

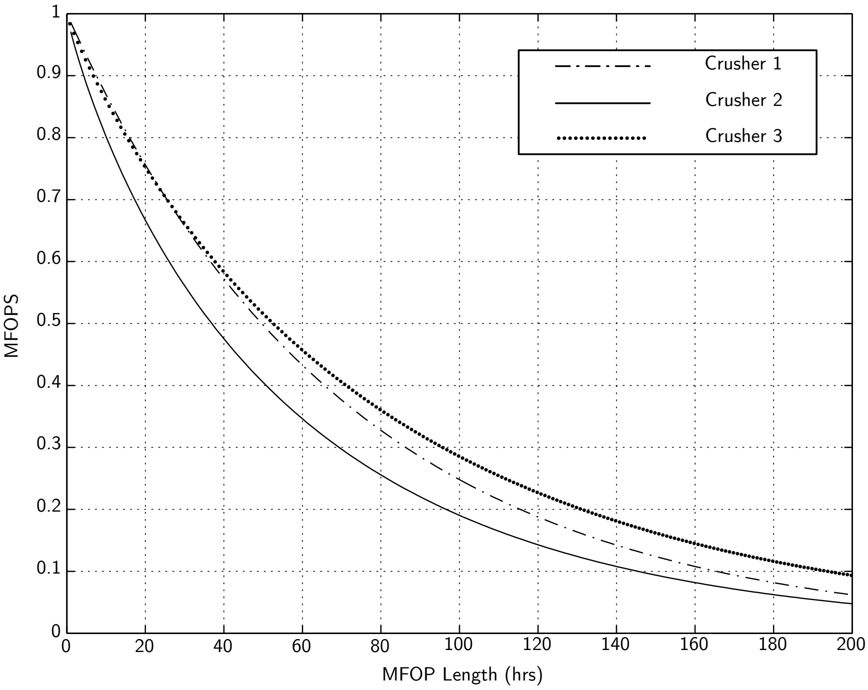


Figure 4.21: Comparison of all three crushers current MFOP performance.

at the exactly the same MFOP of 50 hours, (refer to Figure 4.21), Crusher 1 has an MFOPS of 50 %, whereas Crusher 2 has a MFOPS of only 40 %. This illustrates the vastly different reality of the crushers, performances and provides a more “complete” picture.

Also interesting to note is the performance of Crusher 1, when compared to Crusher 3, these crushers have MTBFs that are close but still different (15 hours difference). However, looking again at Figure 4.21, it is clearly seen that for the first 60 hours of operation, the crushers have the same reliability performance, yielding the same MFOPS for the equivalent MFOPS length.

In order for results to be meaningful, they need to be scrutinised by experienced individuals, the following section presents the validation of the results presented previously and attempts to find validity in the results.

A proposed three day MFOP sequence was calculated and shown in Figure 4.22, this furnished the crusher with an MFOP length of 72 hours at an MFOPS of 80 %. Due to the advocated Crusher 3’s excellent MFOP performance, Figure 4.22 was plotted, shown here is a potential MFOP sequence. The chosen MFOP length is 72 hours or 3 days, this yields a probability of achievement of 80 % at the completion of the 3 day MFOP. After which maintenance

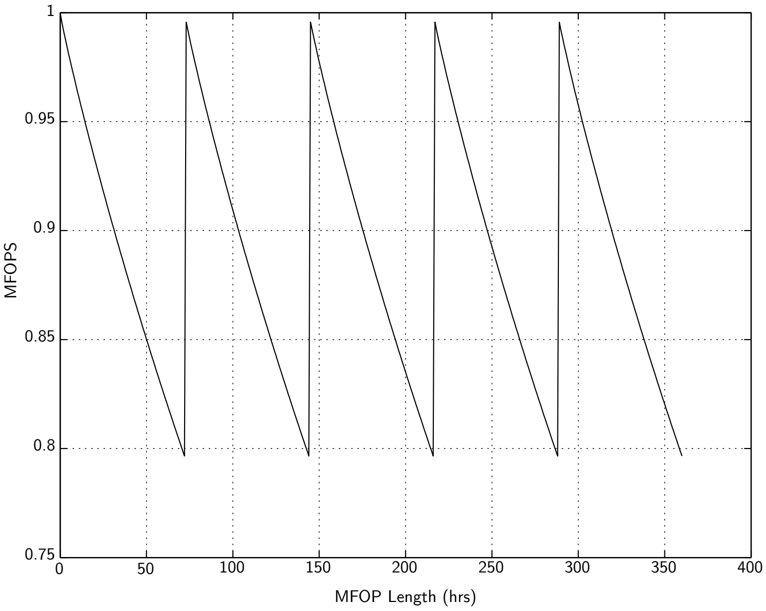


Figure 4.22: Three day (72 hour) MFOP sequence for hypothetical Crusher 3.

would be performed on the crusher and it is assumed that the system would be rejuvenated to its original state to begin the next 3 day MFOP.

4.13 Validation of Practical Value in Industry

The research conducted above has been successfully applied to the data obtained from Anglo Platinum, however, in order to ascertain the practical value of the research, a number of external industry experts were approached.

The first validation was done by a senior engineering manager at a large platinum mine who studied the results and approved the validity of the research in writing. Stating that he preferred the metric MFOP over MTBF, finding it more beneficial to describe reliability.

Another validation was conducted, this was done by way of an interview an external person and introducing him to the research and Case Study results. For this purpose, Mr Stefan Swanepoel was interviewed. Mr Swanepoel is a consultant working for Pragma asset management consulting company, he has extensive experience in reliability and maintenance topics in industry and specifically in mining. The full interview can be seen in Appendix B. In summary of Mr Swanepoel's statements, he stated that MTBF is the most widely used reliability metric in mining. In addition, he said that it is very important that it is understood correctly and that no wrong assumptions are made. When asked if in his opinion MFOP better describes the performance of the system than MTBF, Mr Swanepoel agreed, stating that it is simple enough to measure, yet powerful, but remains understandable at the same time. Mr Swanepoel also described the research as valid and of value providing an example of this thoughts.

These statements echo the results found in the analysis, finding that MFOP shows the "real" and "complete" picture of a systems reliability performance of the system analysed, therefore making MTBF antediluvian.

4.14 Conclusion

It came forth from the literature study conducted in Chapter 2 that there is a definite problem with the use of the maintenance interval metric Mean Time Between Failure (MTBF), this problem is not isolated from the mining industry. The aviation sector has defined a new maintenance interval metric to address the intrinsic issues that MTBF presents. The maintenance interval metric that was defined, is called Maintenance Free Operating Period (MFOP), and was introduced in Chapter 2. It was chosen to investigate this aviation derived metric and is used in the mining industry. After an application methodology was introduced, the principle was applied in a Case Study presented in this chapter.

It can be seen that MTBF effectively appeases the *one number syndrome*, thereby yielding an over simplification of the actual problem at hand. This fact of course make it easy to work with and makes it easily understood, however, just as easy as it is understood it can be very much misunderstood. Mobley (2002) states that the use of MTBF results in either unnecessary repairs or catastrophic failure. Ultimately the use of MTBF to describe the reliability of systems, creates a certain intellectual laziness. MTBF by its very fundamental definition, makes the absolute presumption that failure is inevitable, thereby it does not foster a culture of excellence or improvement. Instead, it yields mediocrity, as it assumes failure.

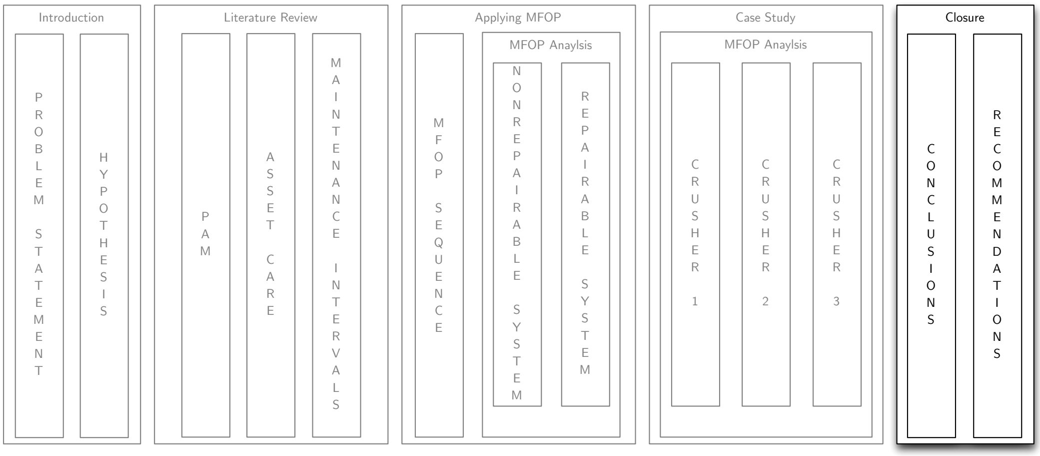
From the analysis, it could be clearly seen that historic MTBFs found for each crusher did not describe the system completely, it did provide indications that the system seems unreliable, but this would have already been known by simply observing the system for a short time physically on-site, no more valuable information is provided. The future MTBF that was found for each crusher also failed to show anymore information, except for showing that Crusher 1 is more reliable that Crusher 3 which is actually not the case.

The proposed maintenance interval metric MFOP makes the assumption that unscheduled maintenance or failures should not be accepted and should be minimised as far as possible. MFOP hereby states, in direct contrast and contradiction with MTBF, that it by definition strives for excellence. Well designed systems are designed from the outset to be reliable. MFOP allows for far better reliability target setting ability, it effectively shows you how long you can trust the system to run without "touching" it. If a certain equipment has an MTBF of 10000 hours then it is not immediately obvious where the equipment is in that time period. With an MFOP of 10000 hours, a given probability of achievement is given (MFOPS), for example 95 %, it is also possible to calculate the MFOPS of the system after already completing a certain amount of hours of the MFOP that is strived for. An example of knowing the MTBF of an aircraft, e.g. 10000 hours, does not say much about the system and if a mission is undertaken now, where in these 10000 hours is the system? However, if the aircraft has a MFOP of 10000 hours and a the MFOPS is given as 98 %, this gives an much more telling characterisation of the system and a assuring description of its performance.

It could be seen from the analysis that the MFOP principle provides a far better and more accurate picture of the analysed systems performance, enabling maintenance engineers to make better informed maintenance decisions on the crushers, the system that was analysed. Applying MFOPs and the philosophy behind its definition also enables maintenance engineers to perform smarter and more focused maintenance, setting reliability targets that can be visually tracked.

Chapter 5

Closure



Chapter Aims:

Chapter 5 aims to merge the research findings and present final conclusions. As a supplement to this the chapter presents limitations of the methodology and study, as well as makes recommendations for future research.

Chapter Outcomes:

⇒ Gain overview of the overall study.
⇒ State the final Conclusions.
⇒ Make recommendations for future research.

5.1 Overview

In today's extremely competitive industrial environment, optimised maintenance decisions and programs are becoming increasingly important to asset centric organisations. Preventive maintenance remains the most popular maintenance strategy, followed by a vast number of organisations, especially in the mining sector. An intrinsic and essential part of maintenance is maintenance interval metrics or reliability metrics, as they yield information of the reliability performance of a certain system or equipment. The most commonly found and used maintenance interval metric is Mean Time Between Failure (MTBF), which is used widely in various industries including the mining sector. A number of inherent problems with the definition and application of MTBF have been found and a proposed solution to these problems has come from the aviation sector. The aviation sector is highly regulated, safety conscious and asset intensive, bearing many similarities to the mining industry. The solution put forward is to define a new maintenance interval metric called Maintenance Free Operating Period (MFOP). This thesis investigated the school of thought of the widely used maintenance interval metric MTBF, against that of MFOP and applied it in the mining sector.

The literature study conducted defined Physical Asset Management (PAM) and where it fits into an organisation. Bringing forth the importance of PAM, is the British Standard, defined for the purpose of effectively managing physical assets. The literature review sought to contrast the current happenings and application of the maintenance interval metric MTBF in the mining industry, with the philosophy and definition of the maintenance interval metric MFOP in the aviation sector. Here, fundamental philosophical differences and their respective interpretations of reliability were shown.

Following the literature study, an application methodology was derived in order to apply the MFOP concept to a system and compare the results to an ordinary MTBF approach. This methodology is based on the use of failure statistics, in order to result in a MFOP for both repairable and non-repairable systems.

The methodology was then applied in the case study, with data being provided from Anglo Platinum. In the case study three cone crushers used for secondary crushing were analysed and both MFOPs and MTBFs were calculated for the crushers.

5.2 Limitations

Part and parcel of any scientific study are limitations, the application of the MFOP methodology exposed several of these limitations, these are expressed in this section.

1. Raw data plays a large part in the application and use of MFOP and the calculation thereof. If no historic data is available for the system then it would be difficult or impossible to model the system.
2. Data quality also becomes a limiting factor in the analysis. The quality of data coming into the analysis is directly proportional to the quality of the output results. If the data has been inputted incorrectly in the first place, the model will reflect these insufficiencies. It is therefore of vital importance not to only collect data, but also to ensure that the collected data is accurate and truly reflects the root cause of the failure that occurred.
3. Some systems, due to their design, will never (without redesign) be able to attain an “acceptable” MFOP length at an equally “acceptable” MFOPS. “Acceptable” here is open to individual interpretation.
4. The calculation, and thereby the application of MFOP, requires a certain amount of background knowledge in failure statistics. If this knowledge is not available, then the MFOP methodology cannot be applied effectively.
5. Another important remark, that ties in with the previous point, is that the application and use of MFOPs, requires a certain “mind shift” by maintenance engineers and operators and thus the setting aside of old, traditionally used ways.

As the limitations have now been stated, final conclusions can be made and are set out in the next section.

5.3 Conclusion

The aim of the research conducted in this thesis was to discern if the application of the maintenance interval metric Maintenance Free Operating Period (MFOP) is more appropriate in physical assets, thereby surpassing the inherent deficiencies of the commonly used metric Mean Time Between Failure (MTBF). The MFOP principle and methodology set out in Chapter 3 was successfully validated in the case study conducted through Anglo Platinum in Chapter 4. Supplementary to this, feedback was gained from industry professionals. It was found that by applying failure statistics and using the MFOP principle of defining reliability in a distinctly contrasting and opposing manner to MTBF, more information could be extracted, providing a more complete and accurate depiction of the system analysed. MFOP can in turn be used to set reliability targets that are better understood and less ambiguous in their definition. Instead of creating an environment conducive to mediocrity, as MTBF does, MFOP contributes to organisational asset optimisation.

The research objectives set out in Chapter 1 were all met. Ultimately the school of thought of MTBF was tested practically in the administered case study against that of MFOP, with the developed methodology. The delineated null hypothesis shown in Table 1.1 of Chapter 1 can therefore be rejected, as it can be shown that using the aviation derived concept of Maintenance Free Operating Period (MFOP) is a far more appropriate reliability metric in the assessment of physical assets.

5.4 Recommendations for Future Research

As stated in the conclusion, the null hypothesis was rejected and the research objectives set out in Chapter 1 were met. However, through experience gained in completing this thesis, there are still areas where future research could improve results, these are stated below. However, a point is also made here regarding data quality.

1. A general comment for future research is that data quality obtained from the South African mining industry remains a problem. There should be a concerted effort to improve data recordings. In the case of this study, failure data was readily available through the modern PI data capturing system, except that the maintenance data inputted was at times am-

biguous or incomplete, specifically as to the root cause of the failure. It would therefore be desirable for future studies to have better data quality, through consistent data capturing, this would further improve the results.

2. The thesis showed that the MFOP concept can be, not only successfully applied in the mining sector, but also add measurable value in terms of optimising maintenance activities. It would now be beneficial to develop an implementation strategy for the physical roll-out of MFOPs on a system, collection of systems or even an entire plant, thereby integrating the concept into the existing maintenance management strategy at the plant of interest.
3. Future research may investigate the incorporation of the MFOP concept, and the MFOPS probability associated therewith, into the criticality analysis. This would be beneficial to a criticality analysis, as commonly, the educated guesses of an employee are simply used to determine which system is critical to the operation. The MFOPS of different systems could be used within the criticality analysis, to better establish which system is most critical to the operation.

The recommendations listed above could provide interesting windows for future research projects conducted in the field of PAM.

Appendices

Appendix A

Analysis Assumptions

A.1 Crusher Assumptions

Due to data and record keeping constrains a number of assumptions had to be made while the data analysis was performed. These assumptions were consistently made through all three data sets of each crusher. The assumptions made are outlined below:

1. When the start of the analysed data set was taken a zero point in terms of run time of each crusher. As the data set was reasonably long with plenty of events over time this assumption can be made.

2. Even though the data obtained was specific to each crusher, the data still indicated when the crusher stopped for other reasons than its own. These reasons would include, conveyor failures, High Pressure Grinding Roller (HPGR) silo full, mill stop, etc. These are of course not failures and do not fall inside the system boundaries defined in Chapter 4, they are therefore not taken are failures pertaining to the crusher.

3. In the obtained data set it was sometimes unclear whether a failure was unplanned or planned. This is of special importance as unplanned failures should be classed as such and planned stoppages should be classed as suspensions. The assumption was made that only events specifically labelled as “Maintenance” or “Planned Maintenance” would be taken as such.

4. In the obtained data set it was also sometimes unclear what the root cause of the failure was, this was sometimes ambiguously inputted. Here

assumptions had to be made as to which part of the system was the actual root cause of the failure, usually obtaining comment from the engineering manager of the plant.

5. The three crushers analysed shared a common lube system, in the analysis of the data sets for each crusher showed individually when a crusher failed due to the lube system, it was therefore assumed for the analysis that each crusher had its own lube system.

6. In the hypothetical case, certain failures were removed from the data set, however it was assumed that the same data set was still used again simply with the failures removed.

Appendix B

Interview

Interview with Mr. Stefan Swanepoel

Interview Details

Name:	Stefan
Surname:	Swanepoel
Occupation:	Consultant
Company:	Pragma
Date:	24-08-2012
Time:	13:00 - 13:40
Place:	Stellenbosch

Author (A) and Mr Swanepoel (S): Welcoming...

A: In your view what is the most used reliability metric used in mining?

Mr. Swanepoel (S): "On a whole it would be Mean Time Between Failure (MTBF)."

A: What is your view on MTBF?

S: "I think its a good measure, however it is very important that one should understand it properly, and not make the wrong assumptions. If one takes the

MTBF of a light bulb for example then you will get a average number but some might fail much earlier than that."

A: Explained Maintenance Free Operating Period (MFOP) concepts to Mr Swanepoel and how they were applied to the research, as well as the details of the Case Study that was conducted...

A: MTBF is just one number and can be said to cater for the one number syndrome, its just one number to describe a complex system, would you agree with this?

S: "I hear what you are saying and agree with that."

A: Further explained the hypothetical case derived in the Case Study to Mr Swanepoel...

A: As a reliability metric and in terms of setting reliability goals, what do you think of MFOP?

S: "No its absolutely excellent, for the reliability side definitely."

A: Does MFOP in this case better describe the actual performance of the system?

S: "Yes it does, I like this way of modelling it, its a simple enough thing to measure, yet powerful, but still remains understandable at the same time."

A: So MFOP is of interest to you?

S: "Looking at this, MFOP is one of the metric's that should definitely be looked at."

A: Explained some other details of MFOP to Mr Swanepoel concerning its actual calculation...

S: "OK I see this now. I think the usefulness here is that now you, as the engineer, can say–look you want to service these things every 50 hours only, but we actually only have a 30 % chance of reaching that target.

Another thing is that MTBF does not directly really show you the amount of effort you are putting in to not fail, where as MFOP can, it shows you how long can I trust this thing to run without touching it."

A: Looking at the research, do you think its valid and has value?

S: "I think its a totally valid way to look at the data and, as I said, its a very good representation of the reliability of the system. I think it would be useful to bring in the consequence of different failures into MFOP.

In terms of value, if you were the engineering manager, I mean those guys don't have much time, if they wanted to look at one metric they would be much more likely to look at MFOP than MTBF."

[The interview ends with formalities; thanking the interviewee for his time and insight.]

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