A Simplified Numerical Decision Making Toolbox for Physical Asset Management Decisions

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Declaration

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Abstract

The management of physical assets has become a popular field of study over recent years and is being acknowledged in multiple disciplines world wide. In this project, research on Physical Asset Management (PAM), maintenance and decision making are presented. PAM is a complex subject and requires the participation of multiple disciplines in order to successfully manage physical assets. Moreover, the management of maintenance makes a big contribution in achieving successful PAM. Decision making is a core element to manage maintenance efficiently, both on strategic and operational level. Various methods and techniques can be used to aid the decision making process such as, using past experience, fixed decision making techniques and techniques involving numerical calculations, to mention only a few. However, using numerical calculations to make decisions are not very popular. This is due to various reasons, for example the inherent complexity of the mathematics and the time required to execute such calculations are disliked. People tend to avoid complex numerical calculations and rather rely on past experience and discussion of circulating opinions to make decisions. This is not ideal and can lead to inconsistent and inaccurate decisions. In this project, the importance of numerical decision making is researched, especially in maintenance related decisions. The focus is placed on the simplification of numerical decision making techniques with the aim to make it easy and quick to use to support operational PAM decisions.

Different decisions regarding PAM, especially decisions with regards to managing maintenance in order to achieve PAM, are discussed by means of a literature study. This is done to clarify the applicability of using numerical decision making techniques to support this type of decisions. A few different available numerical techniques are highlighted that can be used to support the decision making process. The decisions together with numerical decision making techniques are evaluated in order to combine the most appropriate techniques in a simplified manner. The purpose of this is that it can be used by anyone with the necessary knowledge of a specific system or operation.

As a result a simplified numerical decision making toolbox is developed that can support maintenance related decision. This toolbox is applied to a real life situation by means of a case study, made possible by Anglo American Platinum Limited (Amplats). An evaluation and validation of the toolbox is done through the case study to conclude wether it has value in practice or not.

Opsomming

Die bestuur van fisiese bates het die afgelope paar jaar 'n gewilde studieveld geword en word erken in verskeie dissiplines reg oor die wêreld. In hierdie projek word navorsing gedoen oor Fisiese Bate Bestuur (FBB), instandhouding en besluitneming. FBB is 'n komplekse onderwerp en vereis die deelname van verskeie dissiplines om sukses te behaal. Die bestuur van instandhouding maak 'n groot bydrae tot suksesvolle FBB. 'n Kern element van doeltreffende instandhouding is besluitneming, beide op strategiese en operasionele vlak. Verskillende metodes en tegnieke kan gebruik word om die besluitnemingsproses te ondersteun soos byvoorbeeld om gebruik te maak van ondervinding en vorige gebeurtenisse, vaste besluitnemingstegnieke, tegnieke wat numeriese berekeninge gebruik en nog meer. Die gebruik van numeriese metodes om besluite te neem is nie baie gewild nie. Dit is as gevolg van verskeie redes soos byvoorbeeld die inherente kompleksiteit en ingewikkeldheid van die wiskunde en ook die tyd wat benodig word om sulke berekeninge uit te voer. Mense is geneig om ingewikkelde numeriese berekeninge te vermy en eerder staat te maak op vorige ervaring en die bespreking van menings om besluite te neem. Dit is nie ideaal nie en kan lei tot onkonsekwente besluite, of selfs verkeerde besluite. In hierdie projek is die belangrikheid van numeriese besluitneming nagevors, veral in die onderhoudsverwante besluite. Die fokus word geplaas op die vereenvoudiging van die numeriese besluitnemings tegnieke. Die doel is om dit op so 'n manier te vereenvoudig dat dit maklik en vinnig is om te gebruik vir operasionele FBB besluite.

Verskillende besluite oor FBB, veral besluite met betrekking tot instandhouding om suksesvolle FBB te bereik, word bespreek deur middel van 'n literatuurstudie. Die literatuurstudie ondersoek die toepaslikheid van die gebruik van numeriese besluitnemingstegnieke vir hierdie soort besluite. 'n Paar verskillende beskikbare numeriese tegnieke wat gebruik kan word om die besluitnemingsproses te ondersteun word uitgelig. Die besluite, saam met numeriese besluitnemingtegnieke, word geëvalueer om die mees gepaste tegnieke te kombineer in 'n vereenvoudigde manier. Uiteindelik moet dit deur enige iemand met die nodige kennis van 'n spesifieke stelsel of proses gebruik kan word.

As resultaat is 'n vereenvoudigde numeriese besluitnemingstegniekkombinasie ontwikkel wat besluite verwant aan instandhouding kan ondersteun. Hierdie tegniek-kombinasie word toegepas in 'n werklike situasie deur middel van 'n gevallestudie, wat moontlik gemaak is deur Anglo American Platinum Limited. 'n Evaluering en validering van die tegniek-kombinasie word gedoen in die gevallestudie om te bepaal of dit wel waarde het in die praktyk of nie.

Acknowledgements

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The Author
December, 2012

Dedication

This thesis is dedicated to my parents,
Hennie and Amanda.
Their continuous understanding, trust
and love have sustained me throughout my life.

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Abreviations

IAM	Institute of Asset Management
Amplats	Anglo American Platinum Limited
ACP	Asset Care Plan
ACRG	Asset Care Research Group
AHP	Analytical Hierarchy Process
ALCM	Asset Life Cycle Management
AM	Asset Management
AMS	Asset Management System
BAO	Bad-As-Old
BOWN	Better-than-Old-Worse-than-New
BSI	British Standards Institution
CBM	Condition-Based Maintenance
CR	Consistency Ratio
CM	Condition Monitoring
DOM	Design-out Maintenance
EAM	Engineering Asset Management

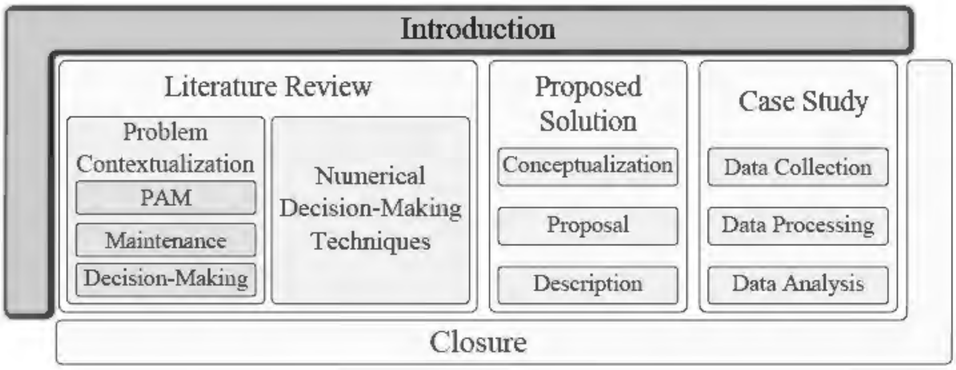
FCF	Failure Consequence Factor
FFOP	Failure Free Operating Period
FMEA	Failure Modes and Effect Analysis
FOM	Force of Mortality
FPF	Failure Probability Factor
FTA	Fault Tree Analysis
GAN	Good-As-New
HPP	Homogeneous Poisson Process
ISO	International Organization for Standardization
KPA	Key Performance Areas
LCC	Life Cycle Costing
LCM	Life Cycle Management
MCDM	Multi-Criteria Decision Making
MAUT	Multi-Attribute Utility Theory
MFOP	Maintenance Free Operating Period
MFOPS	Maintenance Free Operating Period Survivability
MRP	Maintenance Recovery Period
MTBF	Mean Time Between Failure
MTTR	Mean Time To Repair
NHPP	Non-Homogeneous Poisson Process
OE	Operational Excellence
PAM	Physical Asset Management

PAS 55	Publicly Available Specification 55
PDF	Probability Density Function
PdM	Predictive Maintenance
PGM	Platinum Group Metals
PM	Preventive Maintenance
PV	Present Value
QTS	Quick Tactic Selection
RCA	Root Cause Analysis
RCM	Reliability Centered Maintenance
RI	Random Consistency Index
RPN	Risk Priority Number
RTF	Run-To-Failure
SMART	Simple Multi-Attribute Rating Technique
TAHPP	Tactical Analytical Hierarchy Process for Prioritization
TBM	Time-Based Maintenance
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
TPM	Total Productive Maintenance
TQM	Total Quality Management
TTF	Time To Failure
TTR	Time To Repair
UBM	Use-Based Maintenance
WO	Worse-than-Old

Chapter 1

Introduction

This chapter serves as an introduction to the study conducted, as shown in the figure below. It introduces the fundamental topics discussed in this thesis and provides an overview of the study conducted together with a specific problem statement. The methodology that will be followed in an attempt to solve the identified problem area is also included in this chapter.



The aim of the chapter is to develop an understanding of the thesis domain together with the specific problem that is addressed. Also, to understand the methodology that will be followed, in an attempt to find a solution for the problem.

1.1 Physical Asset Management Introduction

A physical asset is defined by Amadi-Echendu (2004) as follows:

> *"An entity that is capable of creating, sustaining or destroying value at any stage in its life-cycle."*

An asset can be any item that is owned for continued use, long-term and short term, in earning economic benefit for an organization. It can be either intangible or tangible. In the past, activities related to the management of assets in organizations were not considered as important and thus have been neglected for many years. According to Hastings (2010) the perception of managing assets, seeing it as a professional activity, has only become acknowledged in recent times. Tywoniak *et al.* (2008) state that Asset Management (AM) is a process recognized in many fields, including engineering, information technology and information management systems, financial services and human resources. In addition to this, the AM can have different meanings in different industries. Various definitions of AM are provided by Mitchell (2007), Schneider *et al.* (2006), Hastings (2010) and many more. Even though all of these definitions are similar in a way, Tywoniak *et al.* (2008) provides the following definition as a broad consensus to describe AM:

> *"Asset Management is the process or cycle in which assets are "put through" in order to create a product or provide a service at optimum level."*

Mitchell (2007) mentions that the management of assets has been adopted by manufacturing, process, operation and production industries. In this context, and according to Hastings (2010), typical assets can include any physical items such as plant, machinery, buildings, vehicles, pipes and wires, and associated information and technical control and software systems that are used to serve a business or organizational function. Leading from this and looking from an engineering perspective, AM concentrates on the operational performance of physical assets.

According to Frolov *et al.* (2010) the concept of PAM has recently become acknowledged in multiple industries and is rapidly growing worldwide. One of the reasons for this is that organizations have realized that physical assets need to be managed effectively and efficiently to achieve successful operations. Mitchell (2002) points out that it is necessary to both maintain and increase revenue, effectiveness and customer satisfaction while reducing operating, support and capital costs. These necessities need to be balanced and are crucial to achieve effective AM. This is considered as the largest challenge in operation and production enterprizes. This thesis primarily focuses on the management of tangible and physical assets.

Many industries commonly see PAM as an equivalent of maintenance, as supported by Myburg (2007). However, PAM encompasses a broader set of activities than only maintenance, Amadi-Echendu (2004) discusses PAM as a paradigm shift from maintenance. Maintenance is primarily concerned with keeping existing equipment in operating condition and Mobley (2002) mentions that effective maintenance is one of the most important driving forces behind efficient and reliable operations. Even though many industries are armed with this knowledge, ineffective maintenance practices are still performed. This emphasizes the need to optimize maintenance practices in order to obtain the maximum benefits from assets. Therefore, optimized maintenance activities in the PAM environment is of great value.

A standard for managing physical assets was introduced by the Institute of Asset Management (IAM), who serves as a professional body for those involved in acquisition, operation and care of physical assets. This was done in collaboration with the British Standards Institution (BSI) and various other organizations. This standard, Publicly Available Specification 55 (PAS 55), provides a holistic view on what needs to be done to manage physical assets for business objectives at any point in its life cycle.

The next section provides a brief background of PAS 55 and also describing PAM according to the published standard.

1.2 Publicly Available Specification 55

The BSI together with the IAM and other collaborating organizations introduced PAS 55 in 2004 as the standard specification for optimized management of physical assets and infrastructure.

PAS 55 divides into two different sections. The first, PAS 55-1, is the *Specification for the optimized management of physical assets*. The second, PAS 55-2, is the *Guidelines for the application of PAS 55-1*. The scope of PAS 55 considers the most important features in an organization with the aim of improving PAM. It also focusses on the interdependency of different asset categories by aligning an organization's strategic plan with its asset management goals. Figure 1.1 presents five broad asset categories which are included.

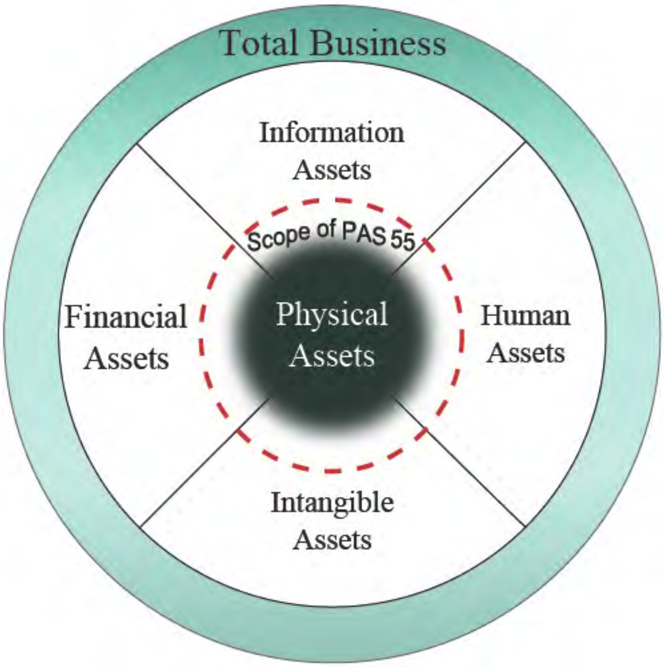


Figure 1.1: Asset Type Categories
Adapted from PAS (2008)

Furthermore, it is clearly indicated that the scope of the PAS 55 primarily focusses on how to achieve successful PAM. It highlights the fact that effective implementation of PAM enables an organization to maximize value and achieve its strategic objectives. PAS (2008) defines PAM as follows:

> *"Physical asset management is the systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and asset systems, their associated performances, risks and expenditures over their life cycles for purpose of achieving its organizational strategic plan."*

PAM is defined by various authors such as Smith (2005), Hastings (2003), Davis (2007) and more. However, this definition of PAS 55 is much more exhaustive than any other definition found in literature. For the execution of PAM a strategy is developed to ensure that appropriate arrangements, functional policies, standards, processes, procedures, asset management enablers and resources are made available for efficient and cost effective implementation of the asset management system. PAS 55 also defines an Asset Management System (AMS) as follows:

> *"An Asset Management System is an organization's physical asset management policy, physical asset management strategy, physical asset management objectives, physical asset management plan(s) and the activities, processes and organizational structures necessary for their development, implementation and continual improvement."*

The purpose of such a system is to provide a clear "line of sight" by supporting the organizational strategic plan, which is the starting point of the asset management strategy, policy and objectives development. An AMS, according to PAS 55, is vital for organizations dependent on the products or services delivered by its physical assets. The essentiality of an AMS for the coordination and optimization of the complexity and diversity of assets in line with the organizational objectives, risks and priorities is also pointed out. This is illustrated by BSI in Figure 1.2 in which the influence of maintenance is noted.

According to BSI, PAS 55 has proven to be very successful in various sizes and types of organizations worldwide. The applicability of PAS 55 is stated in its scope as follows:

> *"PAS is applicable to all sizes of business, from small to medium enterprises through to multinationals, and to any organization that wishes to:*

- *Establish an asset management system to optimally and sustainably manage its physical assets over their life cycles or over a defined long-term period;*
- *Implement, maintain and improve an asset management system;*
- *Assure itself of its compliance with its stated asset management policy and strategy;*
- *Demonstrate such compliance to others;*
- *See certification/registration of its asset management system by an external organization;*
- *Make self-determination and self-declaration of compliance with this PAS."*

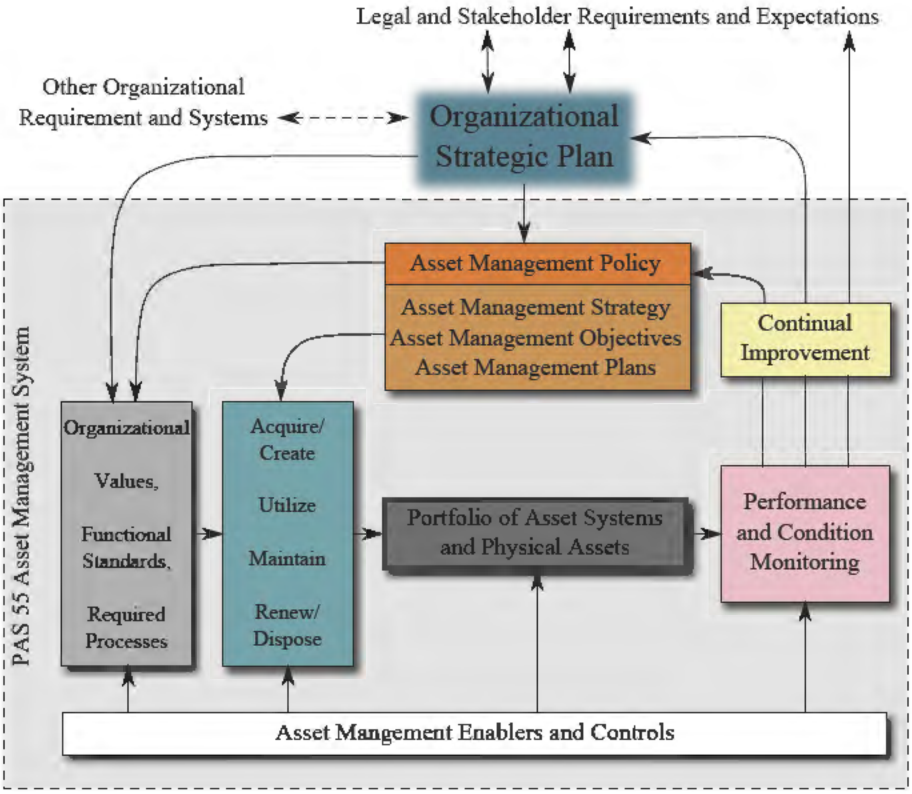


Figure 1.2: Asset Management System
Adapted from PAS (2008)

The application of PAM is discussed in PAS 55-1 Clause 0.5 where it is also associated with maintenance:

> *"This PAS is applicable to any asset intensive business, where significant expenditure, resources, performance dependency and/or risks are associated with the acquisition, utilization, maintenance or renewal/disposal of assets."*

Evidently, maintenance plays a key role in managing assets to ensure the system continues to operate appropriately.

PAS 55 has also been accepted by the International Organization for Standardization (ISO) as the basis for the development of the new ISO 55000 series of international standards. The ISO 55000 series accommodates three standards:

- ISO 55000 which provides an overview of PAM together with the standard terms and necessary definitions.
- ISO 55001 which is the requirements specification for an integrated and effective PAM system.
- ISO 55002 provides guidance for the implementation of such a system.

PAS 55 ensures consistency with other related organizational standards such as ISO 9001 and 14001. ISO 9001 specifies the requirements for a quality management system, whereas ISO 14001 addresses various aspects of environmental management. Chapter 2 further elaborates on PAM and PAS 55.
The next section provides a brief introduction to maintenance.

1.3 Maintenance

Maintenance has been around forever due to the necessity to keep equipment operable. Historically maintenance was only done on equipment when a failure occurred and it was no longer possible to run the equipment. This is also known as a breakdown. In present times, according to Ben-Daya *et al.* (2009) this type of maintenance is seen as reactive or corrective maintenance. However, over the past century maintenance has become an acknowledged aspect in any organization and different maintenance strategies and sub-strategies or tactics has developed over the years. Murthy *et al.* (2002) supports this statement in briefly discussing the evolution of maintenance, stating that the approach has changed dramatically over the last century. It is also mentioned that maintenance was never incorporated into the design of a system, nor was the impact of maintenance duly recognized. Nowadays maintenance is one of the main concerns in designing and operating systems or items.

Gulati (2008) states that in order to use an asset to its full capacity it should be kept in good working condition at all times. Thus, assets are maintained to ensure availability when needed. A wide range of varying definitions of maintenance are found in literature: Defined by Gulati (2008):

> *"Keep in 'designed' or an acceptable condition; Keep from losing partial or full functional capabilities; Preserve, protect."*

Defined by the BSI glossary:

> *"The combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function"*

Defined by Pintelon & Gelders (1992):

> *"All activities necessary to restore equipment to, or keep it in, a specified operating condition."*

Pintelon & Gelders (1992) also point out that one of the objectives of maintenance is to maximize the availability of equipments' operational condition to utilize it at its' full capability. Following this, maintenance is understood as the care or upkeep of assets to ensure that it is in an operational condition to carry out required functionality. Furthermore, it aims to restore deteriorated assets to a condition that is acceptable to accomplish required performance. In brief, maintenance can be summarized as the act that enables equipment to continue through repair.

In managing maintenance activities it is important to identify how maintenance should be executed. Various different maintenance tactics exist and can be categorized into three maintenance strategy categories: *Life Improvement Maintenance*, *Proactive Maintenance* and *Reactive Maintenance*. These different maintenance categories together with related tactics and types are illustrated in Figure 1.3 by means of a hierarchy.

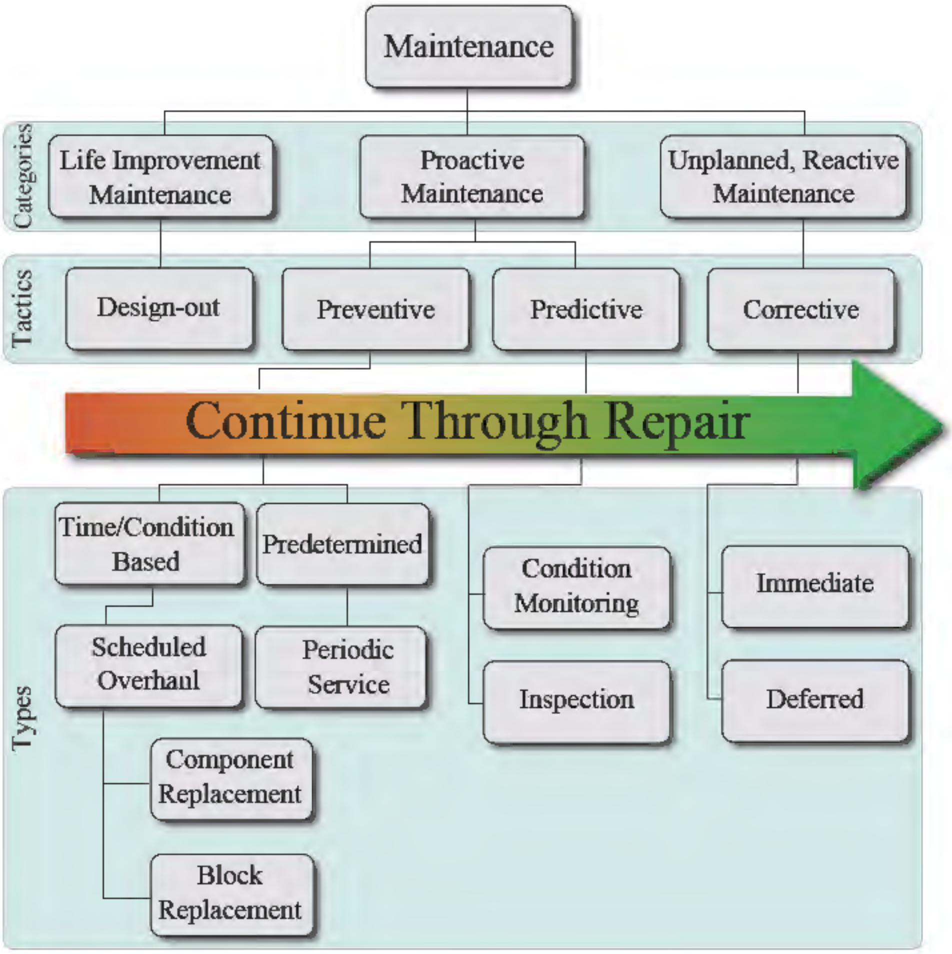


Figure 1.3: Maintenance Hierarchy

Life Improvement Maintenance is a maintenance strategy that involves the redesign of a system or part in an attempt to eliminate reoccurring failures. A *Proactive Maintenance* strategy can either be of predictive or preventive manner. The sub-strategy or tactic Preventive Maintenance (PM) usually involves the condition of an asset or the time operated. It is done in order to prevent failure occurrences. For example, the condition based type focusses on the possibility of failure occurrences, as the condition of a system or part deteriorate the possibility of failure increases and thus requires maintenance to prevent a failure. Whereas the time based type also focusses on the possibility of failure but is related to the failure rate which increases as time progresses. This PM type can either be done on an indication of system/item age, and is scheduled accordingly, or periodically which is predetermined. Predictive Maintenance (PdM) involves the detection of condition by means of Condition Monitoring (CM) or regular inspection. CM continuously monitors the condition and performance of a system or item and is used to estimate when a failure might occur. Maintenance is executed in accordance with the prediction.

Reactive Maintenance, is the initial maintenance approach as mentioned earlier. Maintenance is executed once a failure has occurred, as a corrective action, and a response to such failure can either be immediate or deferred. Usually this tactic is only applicable when none of the other tactics is economically viable or if the failure occurrences are totally random and hidden.

Chapter 2 elaborates on maintenance in general and the different tactics. The availability and reliability of equipment are influenced differently by each of the tactics and directly affects operational performance and throughput. Consequently, an important decision regarding maintenance is to identify which tactic is most appropriate for which equipment or failure type. Pintelon & Gelders (1992) point out that maintenance also affects an organization's environmental impact and employee safety by ensuring that equipment is safe and operable.

The importance of maintenance in the execution of PAM is brought to light in the presented sections. In addition to this, the IAM states that PAM plays a key role in determining the operational performance and profitability of industries that operate assets as part of their core business. IAM also mentions that the PAM process includes activities such as the selection of assets, the maintenance thereof, conducting inspections and identifying renewal times. These are all important decisions that should be made in the execution of PAM. Leading from this, accurate decision making is a crucial aspect involved in achieving effective maintenance and ultimately successful PAM. Taking all of the above mentioned into account, decision making can be considered as a key element and is therefore briefly introduced in the next section.

1.4 Importance of Decision Making

Decision making is a primary function of management, and the importance thereof should not be underestimated. As supported by Al-Tarawneh (2012), many important theorists and practitioners consider decision making to be the core managerial function. Effective decision making is a vital task that enables an organization to function properly. It also helps to utilize all available resources in order to achieve organizational objectives. Harris (1998) states the following about decision making:

> *"Decision making is the study of identifying and choosing alternatives based on the values and preferences of the decision-maker. Making a decision implies that there are alternative choices to be considered, and in such a case we want to choose the one that best fits with our goals, objectives, desires, values, and so on."*

Rue & Bayrs (1986) state that in reality, managers must make decisions while performing managerial functions. Such functions include planning, organizing, staffing, leading, and controlling. Moreover, a manager must first be a good decision-maker to be a good planner, organizer, staffer, leader and controller. Even though experienced decision-makers expect high quality outcomes they can be misled by their confidence and sometimes quick judgement. High quality decision making is done within a confidence interval and thus the possibility of disappointment is always there. In order to prevent disappointment or increase the confidence of a decision, available decision making methods can be utilized.

The importance of decision making in PAM and maintenance was briefly mentioned in the previous sections. In both of these environments decisions are made constantly, both on an operational and strategical level. Examples of related decisions are:

- What is the optimum preventive replacement time to maximize availability at the lowest cost possible?
- What is the optimal maintenance tactic to use?
- When can the next failure be expected?
- What is the optimal PdM frequency in order to maximize profit and availability?
- How to blend asset health/condition monitoring and age replacement?
- What is the probability of failure?
- How often should maintenance be done?
- What assets need to be maintained?
- Should an asset be repaired or replaced?

The decisions mentioned above are only a few examples. Numerous decisions need to be made daily to achieve success in PAM and maintenance. Al-Tarawneh (2012) mentions that decisions can be made either formally or informally. Formal decisions are non-routine decisions that are normally rather complex and are usually not repetitive. Creativity plays a big role with regards to formal decision making because fixed procedures, policies, methods and criteria are not in place to assist formal decision types. Informal decisions are repetitive decisions that are done routinely. Fixed procedures, policies, criteria and methods often exist to assist such decisions. The decisions focussed on in this thesis are informal of nature and therefore it is necessary to study possible decision making techniques that can be used to support such decisions. Typical numerical techniques that are available in literature for analyzing informal PAM decisions include:

- *Criticality analyzes* which are used to identify and prioritize critical areas or items in a system by means of linear ranking.
- *Failure mode analyzes* which are used to analyze and prioritize different failure modes of an item. This also uses linear ranking or decision tree analyzes.

- *Reliability analyzes* which investigate the reliability and performance of a system or item to indicate the chance of a failure occurrence and is accomplished by the use of statistical analyzes.
- *Failure statistics* which investigate the failure behaviour of a system or item to determine the possibility of failure or estimate the residual life, through analysis of historical failure data.
- *Priority rating analyzes* which are used to prioritize items by use or a rating system related to criteria. This calculates importance in accordance with assigned criteria weights.
- *Decision tree analyzes* which map the logical flow of events graphically in order to find alternatives to support the decision making process, taking into account occurrence probabilities.
- *Alternative comparison methods* which compare possible solutions relative to given criteria that are related to a given problem. This also includes a type of ranking method and calculates importance according to assigned weights.
- *Pareto analysis* (the 80/20 rule) which identifies 80% of the problems, indicating the most of the times 80% of the problems are due to only 20% of the causes.

Apart for the techniques above, many more decision making techniques exist. Different decision making techniques will be discussed in detail in Chapter 3.

In literature, there are various publications discussing different decision making techniques, both qualitative and quantitative. However, little or no evidence of applying and implementing these techniques to solve informal PAM related decisions, on an operational level, were found. Due to this lack of evidence in literature, shortcomings with the use of numerical decision making techniques were identified by means of dialogue with various practitioners. In practice, operational PAM decisions are made with the use of discussions in meetings, reaching an agreement on circulating opinions. One downside of this is that often in meetings, considering different opinions, one participant can easily dominate another.

A result of this is that the opinions of soft-spoken practitioners are withheld and not taken into account. Various complaints were noted with regards to the inconsistency and inaccuracy of operational PAM decision making, mostly in the maintenance environment. This can have major consequences such as making inefficient decisions which can lead to major losses in production as well as financial losses. In clause 4.3 of PAS 55-2 various adverse effects of inefficient decision making are mentioned such as: extensive downtime for maintenance, increased safety health and environmental risk to personnel; additional cost or lost income due to poor timing of planned activities. In practice the need for such techniques is realized more and more.

Numerical techniques can be used to carry out complex calculations, provide a valuable outputs and can be used to weigh the objectives in order to find an optimal solution based on the data used. However, the decision-maker is still responsible for the final decision and thus the outcomes of such techniques are used only to support the decision-maker's judgement. It provides the decision-maker with the ability to combine quantitative outcomes with human judgement. Consequently, quantitative and qualitative factors are taken into account and a best possible solution to a problem can be found.

Although quantitative techniques provide support with an optimal solution based on the data used, most current techniques are designed to optimize a single criterion, for example: minimizing total maintenance costs, minimizing risk or maximize equipment availability. The problem with this is that when the total maintenance costs are minimized the risk is likely to increase and/or the equipment availability is likely to decrease. Or, if the availability is maximized the cost and risk might increase. This is illustrated with the use of a theoretical pulley system, shown in Figure 1.4.

PAM related decisions tend to have more than one objective. For this reason, most of the time one of the other criteria is influenced negatively. For this reason experienced decision-makers tend to rather use discussion and judgement than mathematical techniques to make decisions. This approach can lead to inaccurate solutions and only satisfying a single objective and influencing the other

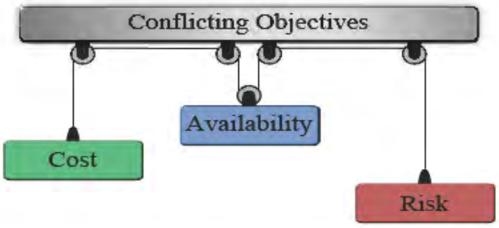


Figure 1.4: Balancing Conflicting Objectives

objectives negatively. By optimizing a single objective, decision-makers tend to be content with the outcomes. However, unknowingly more adverse effects are obtained. It is also stated by Al-Tarawneh (2012) that decision making is a process of thought and deliberation that leads to a solution. Therefore the use of mathematical decision making techniques are neglected due to the fact that it takes time to implement and use such techniques and also because of the complexity. As a result, decision making can become an inconsistent process. Even with years of experience making decisions through guesswork can be inaccurate.

Allaire (2009) mentions that numerical models that support decision making are often complex and involve many disciplines, long computational times as well as multiple factors. Because of such great complexity the application of numerical models have great opportunity for human errors and misunderstanding, therefore these influences lead to increase uncertainty and inaccuracy in the results. To avoid the possibility of error and difficulty of understanding it will be beneficial to look into techniques that are easier understandable but can deliver almost the same results achieved with complex techniques.

Literature about this topic is surprisingly limited, however the problem with the complexity of decision making techniques has been confirmed in practice. Although numerous literature sources have been researched for the application of decision making tools on operational decisions, very limited literature on decision making techniques being applied on operational decisions was found. These decisions are made mostly from experience of by use or discussion. By having various dialogues with people involved with practical decision making the topic of decision making techniques being too complex to use for operational decisions can be considered as a fact.

1.5 Problem Statement

PAS (2008) provides a holistic view of PAM and the implementation thereof. It is an interdisciplinary approach with great complexity. In the previous sections a background and brief overview of PAM and maintenance were given and the importance of decision making was discussed briefly. Having a brief overview of PAM, maintenance and decision making this section will discuss a problem area that was identified.

As mentioned previously, there are various mathematical decision making techniques available to assist the decision making process. Nevertheless, these techniques are not popular due to time being a limited resource and the dislike of the inherent complexity. In most cases, managerial decisions are based on human judgement, discussion and previous experiences which are not ideal.

Even though numerical models aid in the addressing and solving of problems, they cannot be expected to make final judgements. For this reason, the process of decision making in PAM can never be fully automated but mathematical techniques can be used to do quick and complex calculations to support a PAM decision making process. However, current decision making techniques, that are relevant to PAM decisions, are mostly designed to focus only on the optimization of one criterion and neglect others. Therefore there is a need for decision making techniques that supports multiple criteria in order to execute PAM related decisions effectively. No company wants to over or under maintain their facilities. Both of these cases will result in an increased production/service cost, thus it is important to find an appropriate balance.

It is necessary to study methods and procedures where concerns about multiple conflicting criteria can be formally incorporated into the management planning process. This is required on an operational level where people can use numerical decision making techniques without effort and taking up too much time. Hence, the simplification of numerical decision making techniques is emphasized. The aim is to implement simplified techniques for PAM related decisions on an operational level.

In addition, the study presents endeavors to assess the combining of numerical decision making techniques which can be both simple and understandable and applied on an operational level. Leading from this a key research question can be formulated:

> *Is it possible to combine different numerical decision making techniques to support complex PAM decisions-making and be presented in a simple and understandable manner?*

Following from this the null hypothesis is stated as follows:

H_0:	*Different numerical decision making techniques cannot be combined to support PAM related decisions on operational level in a simple, understandable and effective manner.*

1.6 Research Objectives

The study conducted in this thesis aspires to combine numerical decision making techniques that can be used to support decisions associated with PAM. The key research question is broken down into sub-goals resulting in a series of research objectives. In order to test the null hypothesis the following objectives should be fulfilled:

1. Establish whether numerical decision making techniques can be combined and used in simplified and easily understandable manner in order to support PAM related decisions on an operational level.

2. Systematically develop a way to combine the most appropriate numerical decision making techniques in order to fulfill the need for a simplified and easy useable decision making tool.

3. Demonstrate the application of the combined tool on a real world situation in order to verify the practical applicability of such a tool.

A project roadmap is developed and presented in the next section. The aim of this is to provide a guideline for meeting the research objectives.

1.7 Research Methodology and Project Roadmap

Leading from the problem statement and research objectives presented, it is clear that both qualitative and quantitative studies should be included. Therefore, a mixed method research methodology is applied, attempting to achieve the desired objectives through the following steps.

1. Master the field of study through relevant literature to gain comprehensive understanding of the areas: PAM, maintenance and decision making.
2. Conduct a comprehensive study on numerical decision making techniques, to master the mathematical understanding of the techniques.
3. Evaluate the applicability of such techniques to PAM decision making.
4. Evaluate the different numerical decision making techniques to ultimately select the most appropriate techniques for assisting PAM decision making.
5. Attempt to combine the appropriate techniques to create a valuable decision making tool, proposing a possible solution to the research question.
6. Attempt to simplify the technique combination with the aim to camouflage the complexity of the techniques.
7. Evaluate the practicality of the combined PAM decision making tool attempt.

In Figure 1.5 these steps are transformed into a project roadmap for the intended research.

An extensive qualitative literature review is conducted, attempting to contextualize the problem stated in Section 1.5. Various techniques are then studied and evaluated in order to find a proposed solution. The evaluation and validation of the proposed solution are done in a quantitative manner by means of a real world case study. Further elaboration on the methodology and roadmap are included in the document structure discussion in the following section.

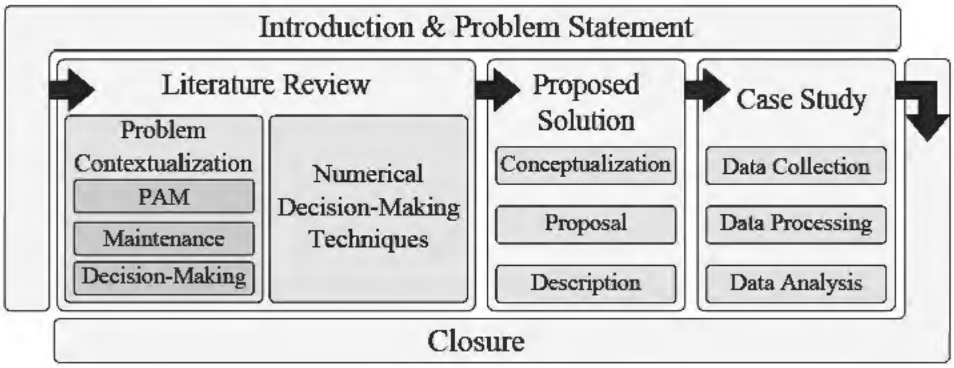


Figure 1.5: Project Roadmap

1.8 Document Structure

In this chapter PAM, maintenance, and the importance of decision making were introduced. The cross-functionality and complexity of these three topics were brought to light. This thesis conducts a study with the attempt to satisfy the research objectives mentioned in Section 1.6 by following the methodology and roadmap presented in the previous section.

This thesis is structured in a logical order, enabling the reader to comprehend the flow of the study in alignment with the objectives. The remainder of the document is constructed as follows:

Chapter 2: Physical Asset Management Landscape

An extensive literature study is presented in Chapter 2. The fundamentals of PAM are included together with a discussion on the different maintenance tactics. Decision making in PAM is discussed in accordance with PAS 55 with the aim to contextualize the problem stated in Chapter 1. Decisions related to maintenance are highlighted from which a roadmap for the development of a decision making toolbox evolves.

Chapter 3: Literature Review of Numerical Decision Making Techniques

Different techniques that may be applicable for the toolbox development are discussed in Chapter 3. A thorough explanation of each technique is provided together with relevant examples. The theory behind reliability and the analysis of failure behaviours by use of statistical analysis are discussed as well. The need for simplicity in the development of the toolbox is also considered.

Chapter 4: PAM Decision Making Toolbox

The concept of the toolbox is proposed in this chapter. The different techniques discussed in Chapter 3 is considered to select the most appropriate techniques for the development of the toolbox. An attempt to combine the selected techniques is presented, proposing a PAM decision making toolbox.

Chapter 5: Case Study

A case study is conducted to apply the proposed toolbox on a real world problem within the mining industry. A full background on the case study is provided together with the application of the toolbox and an interpretation of the results. The aim of this case study is to assess and validate practical value of the proposed toolbox.

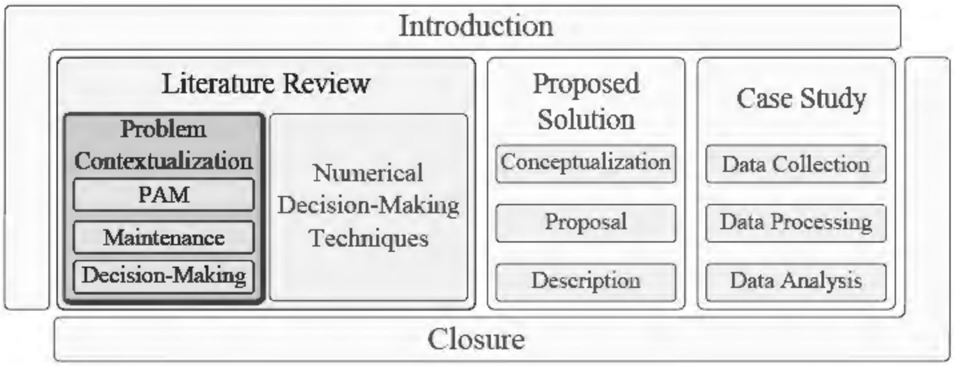
Chapter 6: Conclusion and Recommendations for Future Research

The last chapter sums up the outcomes of the study conducted, including limitations and restrictions within the study. Conclusions of the research are presented, answering the key research question presented in Chapter 1. To conclude, the null hypothesis is accepted or rejected and final recommendations are provided for further research.

Chapter 2

Physical Asset Management Landscape

This chapter presents a literature study, endeavouring to contextualize the problem presented in Chapter 1. A thorough overview of PAM is presented which leads to the specific focus areas of this study. Different maintenance tactics, as presented in the first chapter, are discussed. The necessity of decision making is discussed in accordance with PAS 55 and decision making related to the areas of focus are also discussed. As shown in the figure below the main topics discussed in this chapter are PAM, maintenance and decision making.



The aim of this chapter is to provide a holistic view of PAM and relevant research areas also to justify the necessity of numerical decision making techniques.

2.1 Asset Management

In order to grasp the concept of PAM, the expansive term Asset Management (AM) needs to be understood in general. A general definition of AM, by Tywoniak *et al.* (2008), was provided in Chapter 1. Another definition of AM, is provided by Davis (2007) in the context of engineering:

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

The definition presented in Chapter 1 describes AM as a process to deliver required service at optimum level, whereas Davis (2007) focusses more on the improvement of reliability and availability on systems, equipment and processes. Although this still strives to provide required service by continuously improving processes, the focus is on optimizing the performance of assets within a system in order to improve reliability, availability, etc. of the entire system.

Leading from this, successful AM considers the continuous improvement of conflicting priorities of asset care and utilization, short-term performance opportunities and long-term feasibility. It also includes the consideration between capital investment and subsequent operating costs, risk and performance. Furthermore it can be said that managing assets is the process of using systematic activities to maintain a desired level of service and achieving strategic goals at the lowest possible life cycle cost. New Mexico Science Engineering Research University (2007) identifies five core components of AM which clarifies the meaning of the term, as presented in Figure 2.1.

The first component, *Asset inventory*, enables easy access to information related to the current state of assets. Thus being aware of all assets, the value thereof as well as its' current condition.

The second component, *required service level*, creates awareness in an organization of what performance is expected. In addition to this, to maximize the reliability and availability of assets, proper maintenance is required. The reason

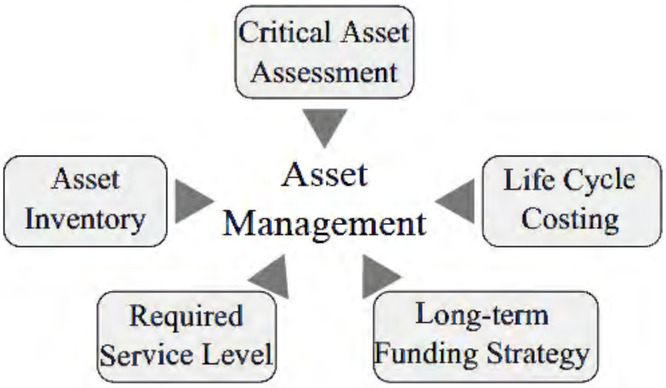


Figure 2.1: Five Core Components of Asset Management

for proper maintenance is to achieve the required service level and striving to obtain maximum return from assets. This also indicates the required performance for achieving organizational goals.

Critical assets assessment is the third component and is a method which identifies assets which are critical for sustainable performance. These are the assets with a high risk and likelihood to fail or have a high consequence due to failures. Assets with a low likelihood of failure and a low consequence due to failures can be seen as assets with a low risk and therefore have a low criticality.

The fourth component, *life cycle cost* of an asset, includes all relevant costs throughout the entire life cycle of an asset. More specifically; initial capital cost, operation costs, maintenance costs, repair costs, rehabilitation costs, disposal costs and also replacement capital costs. The costs are associated with different phases in an asset's life cycle and is monitored throughout its entire life cycle. Lastly, a *long-term funding strategy* determines which approach is the best to properly operate the assets to its' full capacity.

The five components are interrelated and do not necessarily occur in any specific order. These components are important with the execution of AM in general and thus are applicable to all types of assets. The following section discusses AM in the context of engineering.

2.1.1 Engineering Asset Management

Amadi-Echendu *et al.* (2010) contextualizes AM with regards to engineering and present it as a hierarchial pyramid shown in Figure 2.2.

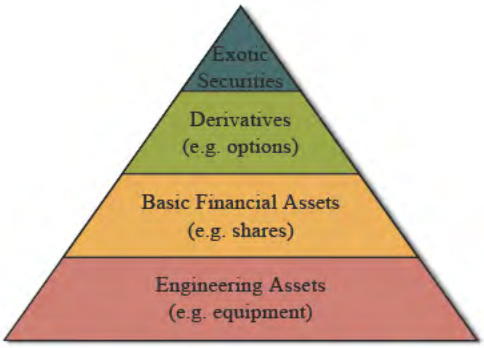


Figure 2.2: Nature of Engineering Assets
Adapted from Amadi-Echendu et al. *(2010)*

This pyramid puts engineering assets in context with other asset types. It is seen that *Engineering Assets* are the base of the pyramid. Such assets include equipment, buildings, inventories, etc. and are managed by engineering assets managers. The other assets in the pyramid are excluded from the definition of an engineering asset and are thus all levels of financial assets. Amadi-Echendu *et al.* (2010) also mention that Engineering Asset Management (EAM) requires an information system to capture data that can be used to support decision making. Three apsects of EAM are highlighted:

- Because skills from virtually any discipline are required, EAM is a multi-disciplinary approach which includes management, economics and information technology.
- EAM decisions cover a wide range, from operational aspects to strategical aspects.
- At its core, EAM requires the use of qualitative analyzes together with quantitative analyzes.

From this it can be reasoned that engineering assets are considered to be physical assets and thus the management of these physical assets are indispensable.

2.1.2 Physical Asset Management

A definition of PAM, with reference to PAS (2008), was presented in Chapter 1 (pg. 4). A similar definition was found in the work of Woodhouse (2001):

> *"A set of disciplines, methods, procedures and tools to optimize the whole life business impact of costs, performance and risk exposures of the company's physical assets."*

From these definitions it is noted that PAM is an aggregation of activities, focussing on the physical assets responsible for the operation flow. It is a mixture of technical and financial aspects together with management's decision making. According to Mitchell (2007) the main objective of PAM is to increase the value and return of physical assets which generate revenue and profitability within production, manufacturing and process industries. In striving to achieve all of this, it is necessary to continuously improve operations. For this reason, the performance of physical assets, also the drivers of the operation, need to be optimized. Mitchell (2007) explains the necessity of a PAM optimization program. Such a program ensures that the physical asset infrastructure has the effectiveness, availability, performance and technical ability needed to meet all the requirements that comply with safety, health and environmental concerns. The following definition for PAM optimization is provided by Mitchell (2007):

> *"A comprehensive, fully integrated strategic program directed to safely gaining and sustaining greatest lifetime value, utilization, productivity, effectiveness, profitability and return on assets from physical manufacturing, production, operating and infrastructure assets.*

In order to achieve PAM optimization, two vital elements are identified:

1. The identification and prioritization of improvement opportunities established from organizational objectives.
2. Transformational plans should be formulated and implemented for improving organizational structure, institutional culture and processes.

The optimization of PAM involves improved performance, effectiveness, utilization and reliability. By optimizing PAM and thus these elements it will result in successful PAM. Furthermore, it can be argued that PAM is an inter-disciplinary field and includes drivers such as performance, compliance and sustainability. The IAM also states that with the management of assets, the fundamental goals of an organization is converted into practical implications for choosing, acquiring, utilizing and maintaining assets to deliver the organization aims. It is clear that there are various decisions involved in managing physical assets. Moreover, the key to successful PAM is effective decision making and finding an adequate balance of these conflicting drivers. In order to achieve this an organizational strategic plan is required. In literature various Key Performance Areas (KPA), to support the execution of PAM, are identified by different authors. Figure 2.3 presents a consensus of 15 KPA that were identified. These KPA's are divided into four categories that corresponds to PAS 55: *Strategy Planning*, *Enablers and Controls*, *Execution* and *Assess and Improve*.

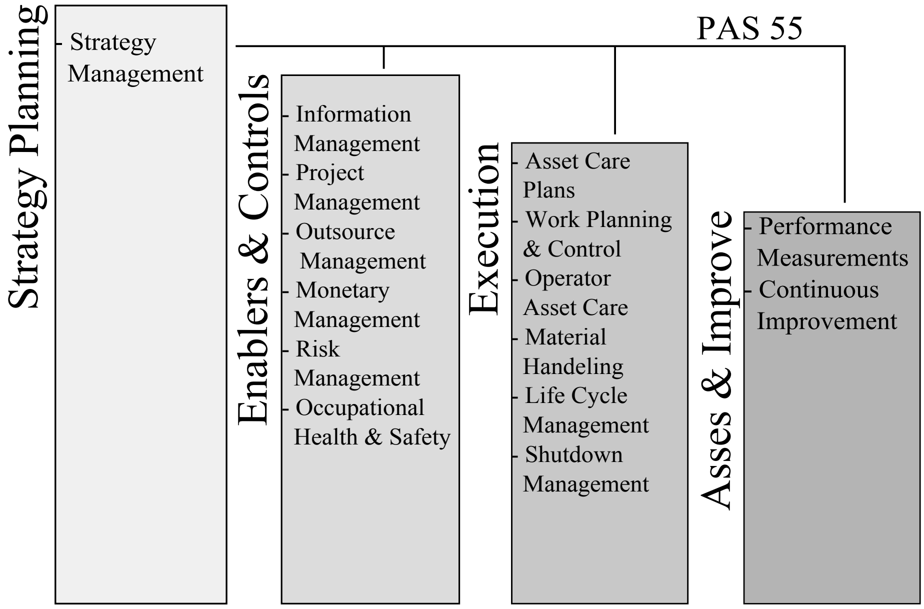


Figure 2.3: 15 Asset Management Key Performance Areas

As part of an organizational strategic plan, *Strategy Planning* is a process for developing plans to reach organizational goals. The strategy for managing assets is developed in agreement with the organization's asset management policy. The purpose of such a strategy is to fulfill organizational objectives and goals set with regards to PAM. Moreover, this is done to successfully plan asset management activities and is taken together in an Asset Care Plan (ACP). The next section briefly discusses the importance of a strategy in PAM in striving for operational success.

Enablers and Controls are required in order to execute the planned activities. Included in this are aspects such as monetary and risk management, occupational health and safety, to mention only a few. These are all incorporated in the planning of the asset care activities. The *Execution* of the planned activities, which are taken together in ACPs, work planning and control, Life Cycle Management (LCM), etc. are continuously monitored and assessed. This includes the last categorization of the KPA's, *Assess and Improve*.

2.1.3 Asset Management Strategy

A PAM strategy strives to achieve specific PAM activities within a given time period and is vital for successful implementation of an AMS. Furthermore, to understand strategy as it is used here, a definition is provided by Johnson & Scholes (1998):

> *"Strategy is the direction and scope of an organization over the long-term, which achieves advantage for the organization through its configuration of resources within a challenging environment, to meet the needs of markets and to fulfil stakeholder expectations. "*

When compiling a strategy, an assessment of the current state of the organization is required in order to assess its improvement potential. Benchmarking with industry peers and best practices are helpful. A realistic focussed improvement agenda and desired future state, aligning with the organization's maintenance requirements, is required for the development of a strategy. However, according to Davis (2007), such a strategy does not only apply to the maintenance division but involves the entire organization. PAS (2008) defines strategy in a PAM context:

> *"A strategy is a long-term optimized and sustainable direction for the management of assets, to assist in delivery of the organizational strategic plan and apply the asset management policy."*

Of the various challenges which exist in the development of a PAM strategy, one of the greatest is to create and maintain a clear *line of sight*. A *line of sight* is essential to achieve successful operations. The strategy should be aligned with the PAM policy and should carry the requirements and objectives, originated in the policy, throughout all organizational levels, down to the very last operator. This shows the importance of such a strategy in the strive for excellent operations.

The following section discusses the concept of Operational Excellence (OE) which is followed by an elaboration on the areas that influence the fulfillment of related objectives.

2.2 Operational Excellence

Verweire *et al.* (2011) discuss OE as a leadership philosophy to continuously improve throughout the organization by optimizing current processes and focussing on customer satisfaction. OE provides a framework for understanding how asset performance needs to improve in order to achieve required objectives. This is supported by Clark *et al.* (2011) in the following statement:

> *"Attaining* OE *requires that industrial companies maximize the efficiency and profitability from their operations through excellent control and drive maximum business value from all their industrial assets, all while reducing negative environmental impact and improving safety."*

Four components of OE are defined by Clark *et al.* (2011), as shown in Figure 2.4. The first is *control excellence* which enables the level of operational efficiency to reach an optimum by maximizing operational throughput while minimizing the consumption of material and energy.

The second, *asset excellence*, is indicated by the effectiveness of managing the return on assets, or maximizing the operation's profitability. Achieving *asset excellence* is to balance the availability and utilization of assets in order to achieve maximum profitability.

Figure 2.4: Components of Operational Excellence

People excellence, as a third component, can be achieved through the empowerment of the production workers all the way down to the frontline operators and maintenance workers. This includes the understanding that every single person involved with the operation has a direct impact on the performance. Also, their actions are crucial to the drive of positive outcomes. Although the top goal is to achieve efficient and profitable operations it is also important to do so in an acceptable environment.

Lastly, *environment and safety excellence* is defined as the balance of social responsibility, safety, environmental sustainability and long-term profitability. It is not only about maximizing the efficiency of the operation but about driving profitability improvements as well. The aim is to continuously improve both efficiency and profitability in order to strive for OE.

Consequently it can be argued that OE can never be achieved but rather a goal to always strive for. The following section considers the areas with the greatest influence in achieving OE objectives within the PAM and maintenance environment.

2.3 Areas of Influence

In Figure 2.5 illustrates the elements of an AMS, as defined by PAS (2008). Within this system the areas of influence are identified with the aim to achieve successful PAM and always strive for OE.

An entire AMS is driven by the strategic plan of an organization, which lies outside the scope of PAS 55. The starting point of this strategic plan is to develop an *Asset Management Policy*, *Strategy*, *Objectives* and *Plans*.

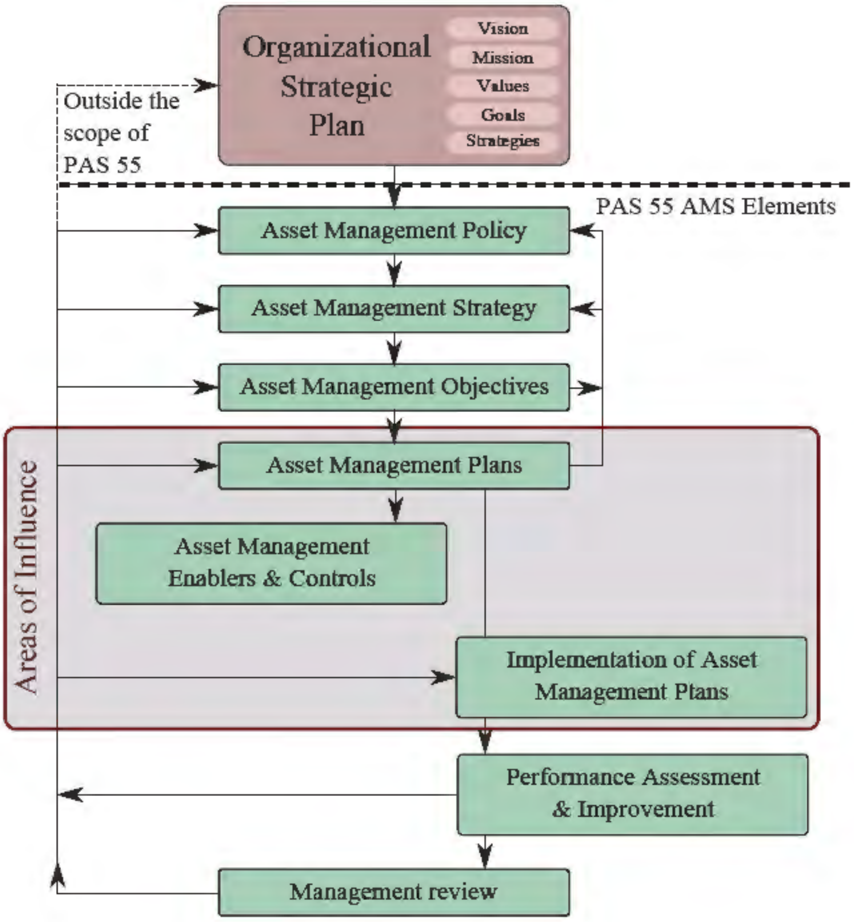


Figure 2.5: Areas of Influence within an AMS
Adapted from PAS (2008)

An *Asset Management Policy* is the key driver of an AMS and provides direction, principles and absolute requirements, as described by PAS (2008). It provides a framework for implementing an *Asset Management Strategy* and setting *Objectives* and executing *Asset Management Plans*.

An *Asset Management Plan*, or Asset Care Plan (ACP), involves the planning of activities in order to achieve desired organizational objectives in compliance with the related strategy and policy. According to PAS (2008), it ensures that "the right job is done right" rather than just "doing the job right". Appropriate maintenance tactics must be selected to deal with each type of failure in the most effective way. To determine the best course of action, a failure analysis is done to obtain the correct failure behaviour and statistics can be used for failure occurrence estimation or prediction.

Asset Management Enablers and Controls influence and apply to all the elements in an AMS. It involves authority and responsibilities, outsourcing of AM activities, training and competence, documentation and information management, risk management, etc. One of the purposes of all of these functions is to support the execution of ACPs. Moreover, *Risk Management* is of high importance when planning and executing asset care activities. It involves the identification, assessment and prioritization of risks. *Risk Management* is also applied to minimize, monitor and control the probability and impact of possible unfortunate events. This should be applied throughout the entire life of an asset. However, LCM is required to determine the feasibility of the plans before the final execution. LCM can be defined as the balanced and active management of assets for its' entire life cycle coupled with business objectives. The aim is to maximize usage of assets from cradle to grave.

The majority of PAM activity planning is combined in an ACP, with the aim to optimize PAM. The *Implementation of Asset Management Plans* is a crucial aspect, here the *line of sight* are brought to light. The implementation and execution of an ACP will reflect whether the *Asset Management Policy*, *Strategy*, *Objectives* and *Plans* were carried through properly in order to yield wanted results. These asset care activities are executed while taking into account related risks, over the entire life cycle of an asset. Therefore LCM is a very important task and is done parallel with all planned activities.

In order to continuously improve asset performances and system deliverables, *Performance Assessment and Improvement* is an important element. This includes performance and condition monitoring, investigation of asset failures and evaluation of compliance, to mention only a few. Continuous improvement can result in changes to any of the AMS elements, changes can even be required in the objectives or organizational strategic plan.

Performance and condition measurement and monitoring focus on the performance of an AMS. It also considers the performance and condition of the asset on a day-to-day basis. Figure 2.6 presents an AMS hierarchy which shows the intense inter-disciplinarity of the PAM field. This emphasizes the importance of decision making in order to balance the conflicting aspects of PAM in striving for OE.

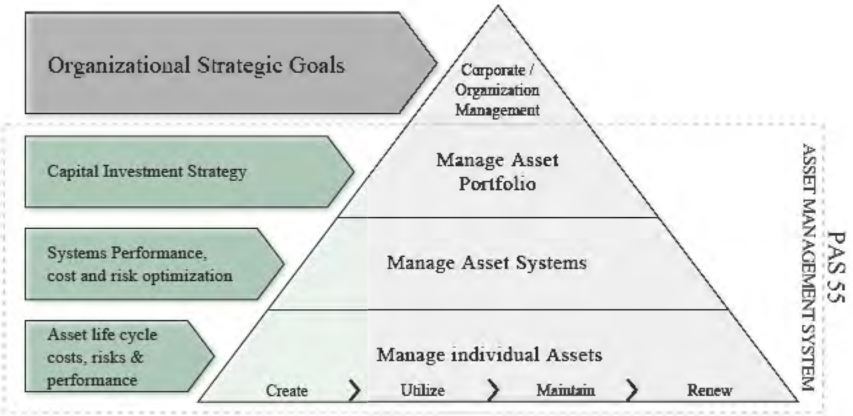


Figure 2.6: Asset Management System Hierarchy
Adapted from PAS (2008)

Weber & Thomas (2005) listed three areas in practice that need to be managed effectively to meet performance requirements.

- Design Practices which provide inherent capability to meet manufacturing requirements.

- Operating Practices which make use of the inherent capability of the equipment together with the documentation to assure consistent and correct operation of equipment to maximize performance.
- Maintenance Practices which focus on maintaining the inherent capability to minimize deterioration.

For the reason that this study focusses more on decision making on an operational level and managing individual assets, it is clear that the base of the AMS hierarchy can be identified as the basis for this study. Three areas are identified as most influential and relevant to this study: *Asset Care Plans*, *Risk Management* and *Life Cycle Management*. These areas are also highlighted in Figure 2.5. The reason for selecting these areas is that, according to PAS (2008), these areas comprise the planning and execution of asset care activities and involves with the optimization of assets, leading to continual improvement. These three areas of influence are briefly discussed in the following sections.

2.3.1 Asset Care Plans

An asset care plan is define in PAS (2008) as follows:

> *"A document specifying activities and resources, responsibilities and timescales for implementing the asset management strategy and delivering the asset management objectives."*

PAS (2008) requires organizations to improve and maintain processes that manage all phases of an asset life cycle system. Wheelhouse (2009) explained that an ACP allows a business to plan, repair and replace equipment and facilities so that it can suit requirements. It also helps to find an optimum balance of cost, safety, performance and availability while taking the short-term constraints and long-term needs into consideration.

A typical ACP comprises of three main sub-plans namely, *Risk*, *Maintenance* and *Operations*. These plans include activities such as service and maintenance, inspections, shutdowns, spares management, asset strategy and performance monitoring, as supported by Wheelhouse (2009). Although PAM is regularly mistaken for maintenance, it is also stated that asset care does not only involve maintenance but also includes stakeholders who have interest in the performance of the plant, equipment and systems.

ACP helps to improve asset performance and gives strategic benefits to an organization. It is argued that a company with consistently dependable assets leads to consistent financial performance. An important element of ACPs is conscious decision-making on what to treat and how it should be treated. The work of Vanier (2000) supports the statement that PAM focusses on using assets for the main purpose of delivering value and achieving organizational objectives. To streamline this process the *Six Whats* are suggested as a framework for the development of an ACP.

- *What* do you own?
- *What* is it worth?
- *What* is the deferred maintenance?
- *What* is its condition?
- *What* is the remaining service life?
- *What* do you fix first?

The operating context has to be understood in order to identify possible failures and how it will occur. Risk and criticality can be used to balance this type of decisions on consequence and probability. Processes and procedures can be established, implemented and maintained to instigate corrective actions for eliminating the cause of poor performance. These can also be used for instigating preventive actions for eliminating potential causes of poor performance.

Maintenance activities makes up a substantial part of ACPs. The reason for this is that maintenance keeps the productive or critical assets available for use. Campbell & Reyes-Picknell (2006) mentioned that maintenance keep an asset performing the standard that is required in order to achieve organizational goals. Weber & Thomas (2005) point out that the primary function of maintenance is to reduce or eliminate all consequences of physical asset failures. Different types of failure consequences are categorized as follow:

- Hidden consequence - A failure that only increases risk, there is no direct consequence. Another failure has to occur to experience the consequence.
- Safety consequences - A failure that result in damages such as function losses that could injure or kill someone.
- Environmental consequences - A failure that result in environmental damages according to a standard or regulation.
- Operational consequence - A failure that has direct negative effect on the operational capability.
- Non-Operational consequence - A failure that only involves the cost of repair, not the operational capabilities.

In addition to this, Weber & Thomas (2005) stated that the process effectiveness is maximized by maintenance through performing the *"Right Work at the Right Time"*. Various different ways of maintenance exist, as mentioned in Chapter 1, and are explained in detail in Section 2.4. The following section discusses the concept of risk management.

2.3.2 Risk Management

Risk is defined by Carpenter & Hughes (2004) as follows:

> *"The uncertain probability of occurrences leading to unfavorable outcomes or even disaster and is measured in terms of probability and consequences."*

The management of risk is a process that aims to reduce or eliminate the risk of certain kinds of events that have an impact on achieving the business goals. McNeil *et al.* (2005) provides a broad definition of risk management:

> *"Risk management is a discipline for living with the possibility that future events may cause adverse effects."*

From this definition it can be argued that one of the objectives of risk management is to manage activities in order to minimize the possibility of adverse events. It is also mentioned that risk management is also designed to reduce financial risks, protect employees, physical facilities, data and physical assets a system owns or uses. Expanding on this definition, Partanen *et al.* (2007) defines the management of risk, in the context of PAM as a foundation for proactive asset management with an overall purpose of understanding the cause, the effect and the likelihood of the occurrence of unwanted events.

Mobley (2011) discusses the risks involved in PAM and states that physical assets in a system have the potential for off-specification operation that could result in poor product quality, lower output, or increased production costs. To manage these risks a *Risk Management Plan* should be implemented. ISO 31000 provides a standard on the implementation of risk management and provides the following principles of a *Risk Management Plan.*

> *"Risk management should:*
>
> - *Create value*
> - *Be an integral part of organizational processes*
> - *Be part of decision making*
> - *Explicitly address uncertainty*
> - *Be systematic and structured*
> - *Be based on the best available information*
> - *Be tailored*
> - *Take into account human factors*
> - *Be transparent and inclusive*
> - *Be dynamic, iterative, and responsive to change*
> - *Be capable of continual improvement and enhancement"*

Other unavoidable characteristics of effective risk management are also discussed in this standard. There are a few different ways to measure risk. Webster (2012) compares two techniques to calculate risk: traditional risk and positional risk.

However, it is stated that there are no one correct method to use, one method can either yield better or poorer results than another method. *Traditional Risk* is defined as the likelihood and consequence of an event. The expected value of risk is expressed as:

$$\text{Risk} = \text{Consequence x Probability} \tag{2.1}$$

Whereas *Positional Risk* is calculated by the use of the Euclidean distance method. This method is simply the straight line distance between two points and with the measurement of risk on a grid on point, the origin, will remain constant. However, this calculation of risk can potentially provide a poor understanding of risk. A typical approach to illustrate risk is presented by Carpenter & Hughes (2004) in Figure 2.7. In this illustration quantitative scales have been added to the qualitative descriptions of risk.

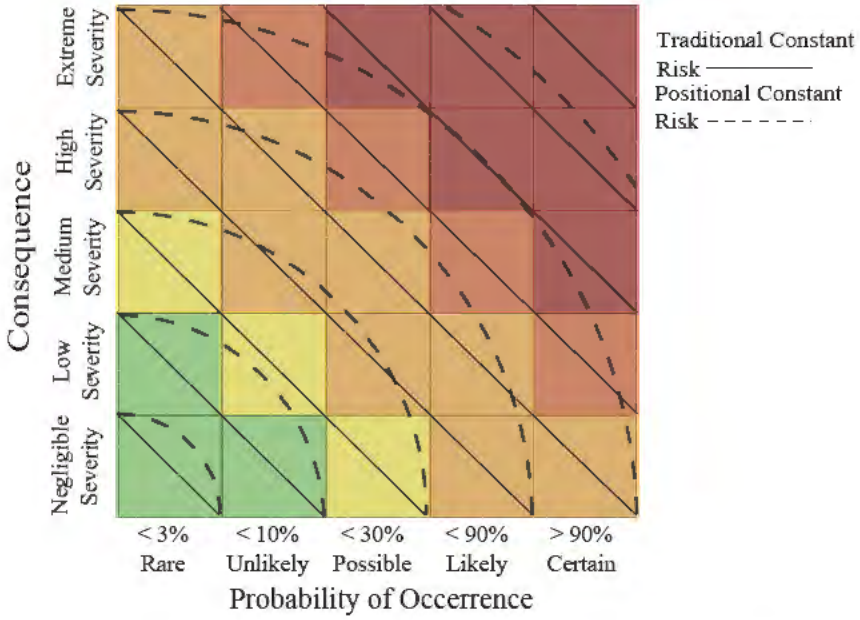


Figure 2.7: Traditional vs. Positional Constant Risk
Adapted from Webster (2012)

The risk classification can be divided into four levels: low risk, medium risk, significant risk and high risk. The following guidelines are suggested for the different levels:

- A *Low Risk* to not achieve objectives requires no change, risk only needs to be monitored.
- A *Medium Risk* to not achieve objectives requires slight change in strategy as part of normal management.
- A *Significant Risk* to not achieve objectives requires strategy modification as soon as possible.
- A *High Risk* to not achieve objectives requires immediate implementation of a proper modified strategy.

Webster (2012) visually presents *Traditional Risk* vector with straight lines, whereas *Positional Risk* vector is a fixed distance from the origin, creating concentric quarter circles, as shown in Figure 2.7.

The quarter circles for the different levels of constant positional risk penetrate through more than one risk level as proposed by the traditional risk method. This clearly shows that, with positional risk, risk is not as linear as presented traditionally.

The identification of risks associated with assets is done together with the identification of critical assets. This is helpful in prioritizing and planning the asset management and maintenance actions. Risk consideration should be embedded in all activities and procedures so that risk can be managed effectively.

2.3.3 Life Cycle Management

Life Cycle Management (LCM) is an approach that can be used by all types of organizations to improve products and services. According to Schuman & Brent (2007) Asset Life Cycle Management (ALCM) is subsequently proposed for assets in the process industry. It integrates the concepts of systems engineering and generic project management with operational reliability. PAS (2008) lists typical activities of an asset's life cycle as follow: creation, acquisition, enhancement, utilization, maintenance, decommissioning and disposal.

An ALCM program establishes the processes and procedures that should be implemented and maintained across the entire life cycle of an asset. In Figure 2.8 Blanchard & Fabrycky (1998) identified two distinct phases in ALCM namely the acquisition phase and the utilization phase.

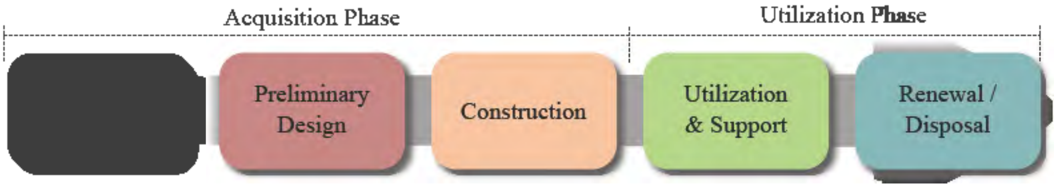


Figure 2.8: Asset Life Cycle Management Pases

These phases are explained as supported by Schuman & Brent (2007). During the acquisition phase the challenge is to implement within boundaries of a prescribed time frame and approved budget. This should be done while ensuring that the facility conforms to all technical specifications. The utilization phase is primarily driven by associated costs of maintenance, spares and inventory, training and product distribution, to name just a few.

Although all of the phases included in the life cycle of an asset are of high importance, the utilization phase is more relevant for this specific study. The reason for this is that the focus is on an operational level. Therefore the condition of assets should be maintained to obtain maximum benefit in its' operations.

A fundamental technique used with ALCM is Life Cycle Costing (LCC). This investigates the financial side of LCM and also involves environmental impacts caused by the existence and operation of an asset. A definition for LCC is provided by Boussabaine & Kirkham (2008):

> *"A technique which enables comparative cost assessment to be made over a specific period of time, taking into account all relevant economic factors both in terms of initial capital costs and future operational costs."*

This definition provides a broad understanding of LCC. LCC adds all costs over the entire life period of an asset. This is done for different alternatives in order to evaluate these alternatives on a common basis for the time period of interest. Although it is argued that LCC is widely used for procurement purposes, by focussing on initial capital costs and future operational costs. It can be used to determine the ideal replacement time of an asset. The entire life cycle of asset options are predicted and analyzed to determine the feasibility of procurement options. Barringer & Weber (1996) briefly discusses common event occurrences in which LCC are beneficial:

- If engineering avoids cost effectiveness specifications, redundant equipment needs to accommodate expected costly failures in order to meet capital budgets.
- The procurement of lower grade equipment to get favorable price variances.
- If maintenance defers require corrective/preventive actions to reduce budgets it might influence long term costs increase because of negligence in meeting short term management goals.

These conflicts are treated under the goal of operating the lowest long term cost ownership. LCC aids the process of making cost effective long term decisions. Within a LCC analysis all relevant operational and maintenance costs are also taken into account. Rahman & Vanier (2004) mentions that the most commonly used LCC methods are the Present Value (PV) method and the uniform annualized cost method.

The PV method calculates the PV for further expenses. It takes into account the anticipated inflation and discounting that amount by a predicted rate over the period between the anticipated time of future expenses and present time. On the other hand, the annualized cost method is used to transform the present or future value into a uniform annual cost. Equations 2.2 and 2.3 RE used to calculate this, with the notation as follows:

PV = present value of expenses,
FV = future value of expenses
A = end of year expenses
n = number of years between time of analysis and time of expense
i = discount rate

$$\mathrm{PV} = \mathrm{FV}\left[\frac{1}{(1+i)^n}\right] \tag{2.2}$$

$$\mathrm{A} = \mathrm{PV}\left\{\frac{[i(1+i)^n]}{[(1+i)^n - 1]}\right\} \tag{2.3}$$

These methods are used to determine the cost-effective alternative. It can be used to assess investments or any business divisions from an economic perspective. Time is a critical factor in these analyzes. The reason for this is that specific time periods are identified for the present valuing of costs and benefits. The costs of maintenance and operations are also important to take into account with these analyzes. These costs can vary over time and should thus be calculated carefully.

Schuman & Brent (2007) also discuss the importance of maintenance in ALCM to maintain operational reliability of assets. Operational reliability is a flexible process that enables a system to be more effective by optimizing the people, processes and technology involved. There are four elements that contribute to operational reliability: *people reliability*, *equipment maintainability*, *equipment reliability* and *process reliability*. These elements highlight the importance of an extensive maintenance approach that will help to expand the life cycle of an asset. Different failure types and system behaviours require different maintenance tactics. To understand these tactics the different ways of maintenance are discussed in the next section.

2.4 Maintenance

Up to about the 1940s maintenance was only done after a failure occurred, which is known, in present times, as corrective maintenance. This was the only known form of maintenance and was considered unavoidable. Murthy *et al.* (2002) mentions that over the past century dramatic changes in the maintenance approach has occurred. Today various types of maintenance tactics exist such as preventive maintenance, predictive maintenance and design-out maintenance.

Although PAM is not only about achieving maintenance excellence, in many industries PAM is confused with maintenance. The management of physical assets is a high level multidisciplinary approach under which maintenance and the planning thereof are regarded as vital elements. However, maintenance is also considered a multidisciplinary approach with the following aspects, as pointed out by Murthy *et al.* (2002):

- Technical and commercial issue integration
- Quantitative approaches involving mathematical models
- Using all relevant information
- Continuous improvement in maintenance management

According to Visser (1998), to yield good maintainability in a maintenance process, various elements are involved such as labour, tools, materials, spares, money, information and other external services. It is also stated that the availability of production facilities, the volume, cost and quality of operations as well as operational safety are influenced by the way maintenance is performed. The interaction is illustrated in Figure 2.9.

It was found that the use of formalized maintenance tactics alone are not necessarily the optimal way to maintain equipment. It is necessary to optimize decision making in life limiting maintenance strategies such as preventive strategies. The waste of residual life of equipment can cause an industry to suffer major losses. Although, Mitchell (2007) argues that in most cases the prevention of unexpected failures is much more expensive than planned preventive actions. Unexpected failures may involve high cost secondary damages to equipment, production losses, late delivery penalties and overtime labour, to name just a few. Corrective maintenance, on the other hand, can be more expensive than preventive actions caused by damage to the asset.

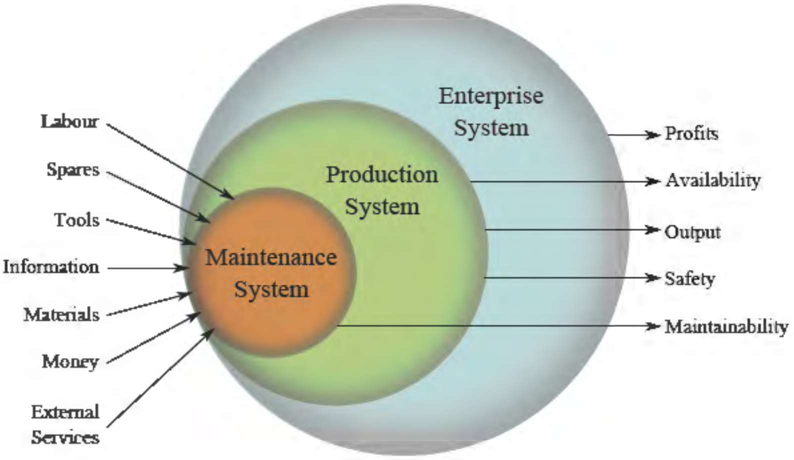


Figure 2.9: Input-Output Model for Maintenance System Phases
Adapted from Tsang (2002)

In Chapter 1 different maintenance tactics were presented in the form of a maintenance hierarchy. The different tactics will be discussed in the sections that follow.

2.4.1 Design-out Maintenance

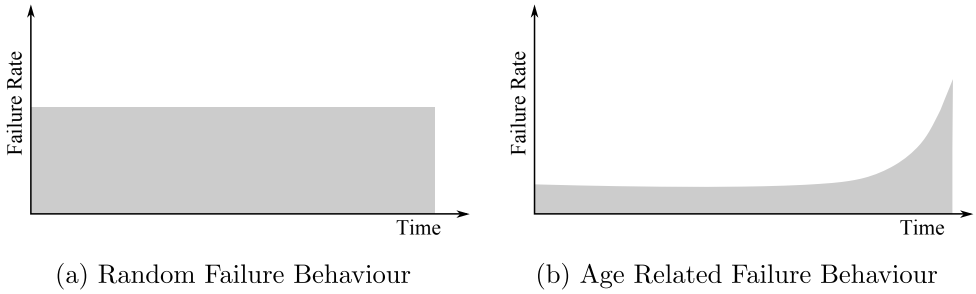
According to Coetzee (2008) Design-out Maintenance (DOM) is to do a redesign in order to increase reliability and to decrease the need for maintenance by eliminating all unwanted failure modes. This is done when it can solve the problem permanently in a cost-effective way. It is also used for the elimination of failure modes of which no suitable preventive task can be found.

2.4.2 Corrective Maintenance

Corrective maintenance is a fire fighting strategy to restore operability of an asset after a failure emerged. It is also known as "do nothing" or "run-to-failure".

It is sometimes too difficult to predict or prevent a failure thus corrective maintenance is then an acceptable option. Labib (1998) discusses that corrective maintenance is used for unpredictable failure occurrences. It is also used when it is not possible to identify an appropriate maintenance tactic or if the asset has a random or hidden failure pattern. Figure 2.10a illustrates the distribution of random failure occurrences. Some failures may occur due to poor maintenance, in such cases repairs may be necessary and thus making corrective maintenance a result of insufficient preventive maintenance.

Corrective maintenance was the only maintenance strategy used in earlier years. Over time other maintenance tactics such as preventive and predictive maintenance were developed. Still, a thorough investigation of a failure's behaviour is required in order to select the most appropriate tactic for failure elimination.



(a) Random Failure Behaviour (b) Age Related Failure Behaviour

Figure 2.10: Failure Behaviour Curves

2.4.3 Preventive Maintenance

PM is defined by Smith & Hinchcliffe (2004):

> *"Preventive maintenance is the performance of inspection and/or servicing tasks that have been preplanned (i.e., scheduled) for accomplishment at specific points in time to retain the functional capabilities of operating equipment or systems."*

PM is either performed based on the reliability characteristics of an asset or periodically. PM is also known as Time-Based Maintenance (TBM) or Use-Based Maintenance (UBM), indicating it is related to time and is only applicable when the possibility of failure or failure rate increase with age. This is shown in Figure 2.10b.

In addition Coetzee (2008) presents two categories of UBM:

- Age based maintenance: maintenance actions are undertaken based on the age of the asset or system. The age can be measured in terms of running hours, production troughput, kilometers traveled, etc.
- Calender based maintenance: maintenance actions are undertaken on a regular basis based on calendar time i.e. annual or bi-annual shutdowns to perform statutory work.

Another objective of PM, presented by Mirghani (2009), is to minimize the total inspection and repair costs and also equipment downtime. Schmidt (2000) identifies factors related to PM action identification:

- Prevent occurrence of failures.
- Discover hidden failures.
- Do nothing, due to constraints.

Related PM action types are identified as follow:

- TBM - aims to prevent failures.
- Failure finding actions - aims to make hidden failures evident.
- Run-To-Failure (RTF)- run item to failure because other tasks are not feasible.

With PM it is assumed that asset degradation happens over time, for this reason maintenance is done before the expected point of failure.

2.4.4 Predictive Maintenance

PdM is defined by Staller (2012) as a task that is performed continuously to diagnose and monitor the condition of an asset in order to determine the most appropriate time for maintenance execution. The failure behaviour of an asset sometimes follows a certain pattern which can be used to predict when possible failures in the future will occur. PdM uses technologies and/or statistics to combine and use available performance data, failure history, operations data and design data to predict when the best time for maintenance would be. Statistical analysis is used to estimate when the next possible failure might occur.

PdM results in early fault identification which is used to prevent failures. A variant of PdM is Condition-Based Maintenance (CBM) which is used to determine whether an asset is operating successfully or not during a given operation period. Niu *et al.* (2010) explains that an asset condition is monitored with techniques, such as vibration monitoring, lubricating analysis and ultrasonic testing. These techniques are known as common CM techniques. Pariazar *et al.* (2008) mentions that results obtained from the CM indicate whether the situation is normal or not. Allowing for the development of a necessary maintenance plan to implement before a failure occurs. Maintenance tasks are recommended only when there is evidence of abnormal behaviours, this helps to avoid unnecessary maintenance.

TPL Technology (2012) describes CM as the process of monitoring the condition parameters of equipment with the aim of finding a change in condition, to provide an early indication of possible faults. The health of an asset is measured periodically. CM is an important component of PdM. It assists in planning PdM tasks.

Planning maintenance activities is crucial to the execution of PAM. The four mentioned maintenance tactics consist of different types of maintenance that can be applied, as presented in the first chapter (Figure 1.3, p. 9). Various decisions are generated when selecting the most appropriate tactic.

The sections presented in this chapter, up to now, an overview of PAM were provided. Three main areas are selected, in accordance with PAS (2008), and are considered as the most influential in striving for OE. Maintenance, being a great influence in the execution of PAM, is discussed in detail. This explains the environment in PAM in which decisions are made on an operational level. The following section discussed the decision making in accordance with PAS 55 and also decisions related to the areas of influence.

2.5 Decision Making

The importance of decision making was briefly discussed in Chapter 1. In this section decision making is discussed in reference with PAS 55 to emphasize the need for decision making techniques. Decisions related to the areas of influence are presented in order to ultimately identify the decisions most relevant to the study.

2.5.1 PAM Decision Making in Accordance with PAS 55

PAS 55-1 clause 4.3.1 states that an AMS shall;

> *"...clearly state the approach and principle methods by which an asset and asset systems will be managed. This may include, for example, the criteria to be adopted for determining asset criticality and value, the life cycle and sustainability basis for asset management planning, the approach to asset risk and reliability of optimization and decision making."*

Leading from this clause, it is important to make decisions not simply by discussion and experience but with fixed techniques and clearly stated methods. These techniques and methods should have thorough description and boundaries. This is to ensure consistency in the decision making process.

PASS 55-2 clause 0.4 states the importance of decision making in PAM. The necessity of adequate information for good decision making is also discussed. This includes information associated with the weaknesses and strengths of an asset, as well as opportunities and threats.

> *"In particular, it is important to understand the relationship between asset management activities and their actual or potential effect upon short-term and long-term costs, risks, performance and asset life cycles. Only then can informed decisions be made about the optimal mix of life cycle activities."*

PASS 55-2 clause 0.4 also discusses the various tools and methodologies available such as value engineering, Reliability Centered Maintenance (RCM), LCC, risk based inspections, etc.

> *"However, it is essential for organizations to recognize that good asset management cannot be achieved successfully through the use of these tools alone, and no single such tool can address, control or solve all the problems."*

In addition, human judgement is needed in collaboration with such tools to achieve good decision making. This motivates the development of a combined tool, combining numerical decision assistance with human judgement in order to achieve successful decision making. It is necessary to consider the full impact of these asset management decisions, otherwise it will result in various adverse effects, as discussed in PAS 55-2 clause 4.3.3.1 (c):

> *"extensive downtime for maintenance, etc; increased health or safety risk to personnel; additional cost or lost income due to the poor timing of planned activities."*

This clause highlights the necessity of taking all of these aspects into account in the decision making process, with the aim of minimizing or eliminating such unwanted events. In PAS 55-2 clause 4.3.3.2 the optimization of AMS is discussed and it is stated that:

> *"Organizations should adopt robust and auditable methods for optimization, appropriate to the criticality and complexity of the decisions being made, and ensure consistent assumptions about the significance of contributing factors."*

In context, optimization involves the identification of influential factors, determination of its significance, analysis of alternatives and ultimately selecting the best value alternative. The aim is to find the lowest possible combination of costs, risks and performance losses.

Clause 4.4.7.3. of PAS 55-2 mentions that the combination of failure consequences and failure probability (i.e. risk) heavily influences the decisions that are made, specially with reference to the management of each type of failure. According to clause 4.4.7.7 a variety of decision support tools are available to support risk assessments.

> *"In particular, there are a number of reliability- and risk-based methodologies for determining appropriate inspection and maintenance strategies, and cost/risk optimization of such strategies."*

Consequently, decision making related to maintenance has a substantial influence on the management of physical assets. Even though the trade off between maintenance and replacement is very important, successful maintenance decisions have a big influence on keeping the assets in working condition. This keeps production going, reducing unexpected downtimes and optimizing the asset utilization.

2.5.2 Decisions Related to Areas of Influence

Managing substantial maintenance, repair and renewal are the asset managers' responsibility, as supported by Vanier (2001). It is the responsibility of asset mangers to optimize expenditures and maximize assets' value over the entire asset life cycle. As a result of this responsibility the asset managers are faced with various difficult decisions, for example how and when to repair or replace existing assets. Romero & Rehman (1987) suggests that this should be done with the help of different decision making techniques in order to support the asset managers in the decision making process. Decisions related to the identified areas of influence are discussed in the sections to follow.

2.5.2.1 Risk Management Decisions

When planning asset care activities, such as maintenance, the first important decision that should be made is to identify which assets should be maintained or replaced. The reason for this is to maintain the assets with the highest risk to operation first, rather than to maintain other assets unnecessarily. Assets with the highest risk to operation are those that will have the most severe consequences and are most likely to fail. Moreover, the failure probability and failure consequence of assets are assessed to identify the assets that are most critical to operations. These assets are treated first.

Available techniques to support decisions of this nature are *Criticality Analysis* and *Failure Modes and Effect Analysis (*FMEA) which are well known techniques in the field. Statistical failure analysis can also be applied to calculate an asset's reliability or to determine when to expect the next possible failure. Although this is a much more complex technique, requiring failure data history, it yields more accurate results and assets can be treated before the occurrence of a failure.

2.5.2.2 Asset Care Plans Decisions

As assets are used over time it tends to worsen due to wear and tear. According to Mathew & Kennedy (2003) this causes failure rates to increase. This results in a decrease in reliability of assets. With maintenance and repair the reliability and availability of the assets are improved but, in most times it will still not be restored to be Good-As-New (GAN). Therefore, when planning maintenance activities, replacement should always be considered. The purpose is to find the point in an asset's life cycle where replacement is a better option than maintenance. To determine this the most important aspect that should be taken account is: Which option is more economically feasible at the time?

As assets age, its' condition deteriorates which causes more frequent failures and thus resulting in more frequent maintenance. A replacement might not seem to be a good idea at the given time because maintenance is a more economical option, for the short-term. However, if a more long-term assessment is completed for the current maintenance frequency versus the maintenance frequency once it has been replaced, the decision might be different.

2.5.2.3 Life Cycle Management Decisions

Renewal or disposal is essential activities in ALCM. The challenge in executing one of these is to determine when it is most appropriate to renew or dispose. When a system becomes more and more unreliable and replacement is considered, various related questions are initiated of which a few is mentioned below:

- Should replacement be done at fixed time intervals?
- Does an optimal fixed replacement time exists for an item?
- What factors influence the calculation of an optimal replacement time?
- What is the optimal replacement time?

Infinite questions of this type can exist. The need for replacement is triggered by efficiency losses, leading to economic decline. As a system or asset undergoes deterioration the maintenance costs are set to increase to the point where the maintenance costs far exceed replacement cost. Mathew & Kennedy (2003) also discusses the necessity to decide whether to continue to repair at ever increasing maintenance costs and risk of failure, or to replace the item. LCC analysis are done on the equipment to decide what option is more economically beneficial. Due to the fact that LCC analysis are long term analysis, conducted throughout the entire life cycle, it should be done parallel with other regular maintenance activities.

In order to determine when replacement should occur Nurock & Porteous (2008) explains an approach to determine the optimal life of an asset but also mentions that there is no standard approach to assess this. Techniques that are available to determine replacement of equipment are mostly associated with LCC. A well-known technique for for analyzing the replacement of an asset is the *Challenger vs. Defender* technique. The *Challenger vs. Defender* is a replacement analysis triggered by common questions such as:

- When should the existing be replaced?
- When should a process be redesigned?
- When should a product be redesigned?
- When does a system's technology have to be redefined?
- Is a more technologically advanced alternative beneficial?

The defender represents an existing asset and the challenger represents the proposed best available replacement candidate. If the defender is more economical, it should be retained, if not the challenger should be installed.

Statistical analysis can be used to predict the residual life of an asset. The residual life of an asset or component is also known as the remaining service life until the next failure. This can be used to determine replacement times or to predict failures and planning maintenance activities. The reason for this is that the prevention of the next failure event of an asset is only achieved by being serviced, upgraded, repaired or replaced before the end of a given time window. In statistical analyzes systems or assets can be categorized as one of two types for which residual useful life estimation can be done: they are repairable and non-repairable systems respectively. These two are discussed separately according to Vlok (2011). Hastings (2003), Bulmer & Eccleston (2003) and Kumar & Crocker (2003) also discuss residual life calculations, associating the Weibull distribution with non-repairable systems and the Log-linear and Power law Analyzes with repairable systems.

2.5.2.4 Decision Selection

The execution of maintenance actions insures that the system or asset reliability and required capability are in a condition to best meet the needs of the organization. Achieving maintenance excellence is to perform the necessary work in the most appropriate manner, as productively and effectively as possible.

There are various mathematical decision making tools available to assist the decision making process in maintenance. As stated previously, the use of such tools are not popular, typically because of the inherent complexity of the mathematical models. The use of decision making techniques also require time and with time being a limited resource these techniques are disliked. Replacement decisions, as discussed in this section, involve long term analyzes and should be monitored throughout the entire life cycle of an asset or system. For this reason and due to limited time and also the fact that the combination of techniques primarily focusses on operational level, replacement analyzes are not considered to be included.

Various other decisions made constantly in the maintenance environment, on operational level, are identified. However, only a selected set of decisions are included in the development of the decision making toolbox. By considering only a specific set of decisions, related techniques can be identified which can provide sufficient support as a combinatory tool. The selected decisions are:

- What assets should be maintained?

- Which asset should be maintained first?
- What failures cause the need for maintenance?
- Which failures should be treated first?
- What type of maintenance should be done?
- How urgent are the required maintenance actions?

These decisions will be used as a basis to develop a numerical decision making toolbox that can assist PAM related decisions. Geared towards improving the decision making process on an operational level by supporting consistent and accurate decision making, primarily focussing on maintenance.

2.6 Chapter 2 Concluding Remarks

In this chapter an overview on PAM and OE was provided. Relevant areas of influence for achieving successful PAM and ultimately strive for OE were identified in accordance with PAS 55. A description of these areas was presented in order to realize the importance of decision making in each. Maintenance, as an important part of PAM and the areas of influence, was discussed together with the different tactics.

A discussion on decision making and the importance thereof, with reference to PAS 55, was presented. Decisions related to the influential areas were discussed as well and possible techniques for decision support were mentioned. It was decided to focus primarily on the maintenance aspect. Therefore, a set of specific decisions was selected to serve as a guideline for selecting applicable techniques to combine and develop a simplified numerical decision making toolbox.

This toolbox development is triggered by the fact that currently decision making techniques are not used effectively to support the decision making process in practice. As mentioned earlier, numerical decision making techniques are not used due its' inherent complexity, limited time and various other reasons. There is a need for decision support in PAM decision making, especially maintenance related decisions on an operational level. These decisions usually have multiple objectives that should be balanced in order to achieve successful PAM.

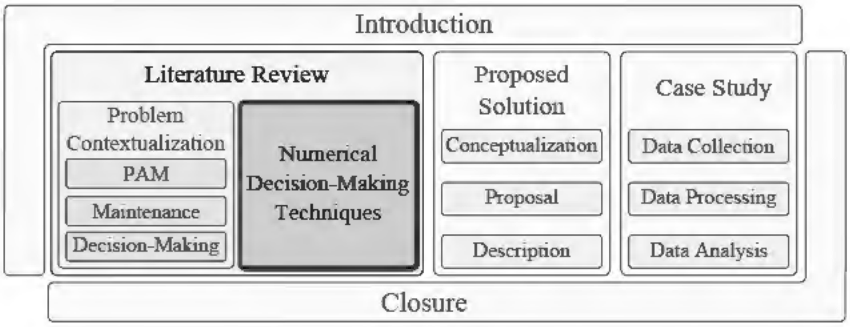
In order to develop a simplified toolbox, the knowledge of best practice numerical decision making techniques is required. A conceptional toolbox idea is needed to determine essential properties and phases. These phases and properties will influence the technique selection. Each technique studied should be assessed to determine whether it satisfies the toolbox properties, with the main goal to keep it simple. For this reason, the challenge is to camouflage the complexity of the techniques in the useability of the combined toolbox.

The next chapter consists of a few numerical decision making techniques, available in literature, that can be used to support the selected set of decisions. These techniques are discussed and explained thoroughly in order to evaluate and select the most appropriate techniques to combine.

Chapter 3

Literature Review of Numerical Decision Making Techniques

In previous chapters it was determined that various numerical decision making techniques are available but not used. However, it was established that there is a need for numerical decision making techniques to support PAM related decisions on an operational level. The figure below shows that this chapter provides a literature review of available numerical decision making techniques. Best practice techniques, relevant to the set of decisions selected in Chapter 2, are explained extensively.



The aim of this chapter is to understand the complexity of available numerical decision making techniques and why they are not used in industry. Further, to understand the capabilities and value of numerical techniques to support PAM related decision making.

3.1 Numerical Decision Making

The importance of decision making was discussed in previous chapters. It was noted that the majority of decisions in practice are currently made based on practitioner's judgement, experience and discussion. Limited evidence of applying numerical decision making techniques in practice was found and it was also confirmed by practitioners that these techniques are disliked and not used. However, Baldwin (1986) states that the use of quantitative decision making techniques provides the decision maker with a range of alternatives and supports the decision in finding the best solution.

It was established that there is a need for numerical decision making techniques. Moreover, the real need is for these techniques to be simple and easy useable to make effective PAM related decisions on an operational level. Lindley (1991) discusses three basic principles to make effective decisions numerically.

- Assign probabilities to the unwanted events.
- Assign utilities to the possible consequences.
- Find a solution with maximum expected utility.

An unwanted event represents any type of failure or fault that influences the operational capabilities of an asset. The probability of unwanted events goes hand in hand with the reliability of a system. If the system is reliable there is a low probability that unwanted events might occur, and vice versa. In order to maximize the expected utility the reliability of a system needs to be maximized and the adverse consequences need to be minimized. Multiple attributes are involved when balancing different objectives such as minimizing consequences, maximizing availability and reliability, to mention only a few. The reason for this is to make successful PAM decisions, especially related to maintenance, and therefore numerical decision support is useful.

In the sections to follow different numerical decision making techniques are explained with the aim to identify which techniques are relevant for the development of a PAM decision making toolbox, according to the decisions selected in Chapter 2. The selected techniques should be adequate to be combined in a manner that the complexity is camouflaged by the simplicity of the toolbox usability.

3.2 Reliability Theory

Kececioglu (2002) provides the following definition of reliability:

> *"Reliability is the probability that parts, components, products or systems will perform its designed-for functions without failure in specified environments for desired periods at a given confidence level."*

Another more brief definition is provided by the SRC (2001):

> *"Reliability is the probability that an item will perform its intended function for a specified interval under stated conditions."*

According to Blischke & Murthy (2003), the theory of reliability deals with the interdisciplinary applicability of statistics, probability and stochastic modeling. To determine the reliability of items, the analysis of past failure occurrences are often required. A failure is defined by Saravanan *et al.* (2006) as the termination of an item's ability to perform its specified function. Over the years operation and failure data has become much more readily available, and with today's computerized maintenance environment data can be logged at high frequencies and stored for years.

The analysis of past failure data includes the statistical analysis of an item's failure data, with the time of failure occurrence as the point of interest. A failure can happen at any point of time, hence it is important to define how the arrival times to failure are measured. This is done for the reason to be consistent in the analysis. Different failure arrival times are illustrated in Figure 3.1 by means of a typical example.

X_i represents the *interarrival* times between the failure events, also known as the *local time*. The variable x_i refers to the time elapsed since the most recent failure and is known as the *real variable*. T_i is the time to the i^{th} event measured from 0

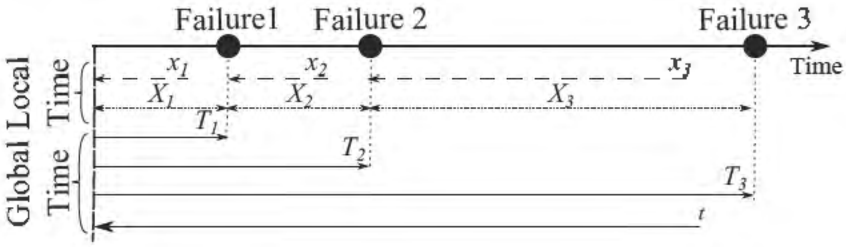


Figure 3.1: Time Measurement of Failure Events
Adapted from Vlok (2011)

which is the *arrival* time of failure i, also known as the *global time*, with t being the overall time scale.

As the performance of a component decreases over time the probability of failure increases, as illustrated in Figure 3.2.

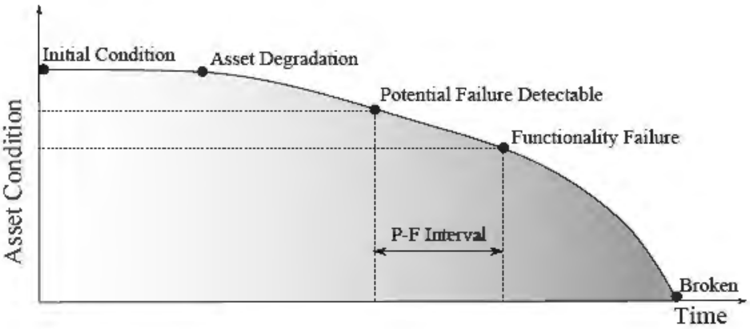


Figure 3.2: Performance Degradation and Failure Progression
Adapted from Rausand (1998)

There is a point in time when a possible failure is detectible, the interval from that point to the time of failure is the interval in which the failure may occur and is named the P-F (Potential Failure) interval. This interval is used to either prevent the failure or leave the system to fail. The estimation of the P-F interval is directly related to the degradation of an item. When the degradation of an item has reached a critical level it serves as a warning limit for inspection, which is the starting of the P-F interval. The time span related to this interval is determined by the analysis of past failure data.

Normally failures do not occur at a uniform rate. Kececioglu (2002) describes that the failure rate of a component is typically a function of time. This is demonstrated in Figure 3.3 by means of a curve, named the *bathtub curve*, which is commonly used to illustrate the failure behaviour of a system or asset.

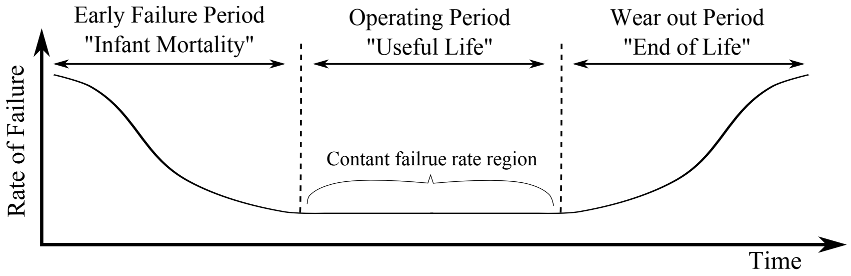


Figure 3.3: Reliability Bathtub Curve
Adapted from Hjorth (1980)

Speaks (2004) discusses three distinct phases of the *"bathtub curve"*:

- *Infant Mortality* is the early failure period and is characterized by a decreasing failure rate. Initially the failure rate is very high, but decreases promptly over a short period of time. The cause of this may typically be manufacturing faults within the design.

- *Useful Life* is the normal operating period. In this phase failures occur randomly throughout the entire operation period. Although it is difficult to predict failures during this phase, there are methods available to do relatively accurate predictions.

- *End of life*, also called the wear out period, is when the failure rate starts to increase rapidly. These failures are typically age-related degradation such as corrosion, wear, erosion etc.

Furthermore, Wilkins (2002) discusses the given stages of the bathtub curve from a quantitative perspective in order to analyze the failure behaviour of items. However, to effectively analyze the failure behaviours of a system appropriate failure data is required and thus a thorough failure data analysis is of high importance.

3.3 Statistical Failure Analysis

With the analysis of a system's failure behaviour, one of the purposes is to test whether a trend is present in its failure behaviour data or not. This is determined by reliability improvement or weakening of the system. According to Wang & Coit (2005) to test for a trend is to determine whether the rate of failure occurrences is changing significantly with time. A trend of increasing successive time between failures indicates that the system's reliability is improving. On the other hand, for a reliability is decreasing trend, the time between successive failures is decreasing and thus a trend of deterioration is found.

Different trend tests are available to test if a trend is present in a system's failure data or not. The Laplace trend test is suggested by Vlok (2011) and Wang & Coit (2005). Tobias & Trindade (2010) mention that the Laplace trend test tests if an observed series of failure occurrences can be identified as a Homogeneous Poisson Process (HPP) or Non-Homogeneous Poisson Process (NHPP). An HPP is characterized by failure data which has a constant failure rate, whereas the failure data of an NHPP does not have a constant failure rate but one that varies and can be either of decreasing or increasing nature. The hypothesis for this test is:

$$\begin{aligned} H_0 &: \quad \text{HPP} \\ H_1 &: \quad \text{NHPP} \end{aligned}$$

From HPP principles, consider r as the total number of failure event arrivals with arrival times: $T_1, T_2, ..., T_{r-1}, T_r$. The Laplace trend test makes use of the fact that the first $r-1$ arrival times are the order statistics from a uniform distribution on $(0, T_r)$. To calculate the Laplace value for identifying the presence of a trend, Equation 3.1 is used T_i = the interarrival time elapsed from the $(i-1)^{\text{th}}$ arrival to the i^{th} arrival, $i = 1, 2, 3, ..., r$.

$$L = \frac{\frac{\sum_{i=1}^{r-1} T_i}{r-1} - \frac{T_r}{2}}{T_r\sqrt{\frac{1}{12(r-1)}}} \tag{3.1}$$

Figure 3.4 presents the categorization of the value obtained from Equation 3.1 to identify the presence of a trend.

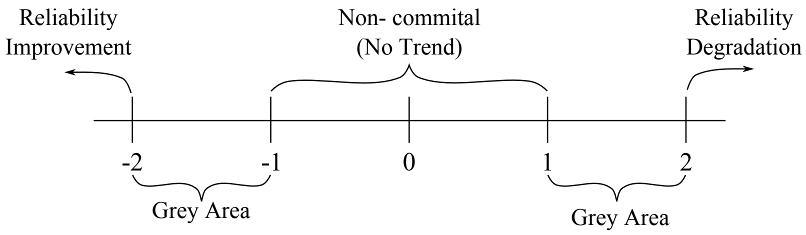


Figure 3.4: Possible Outcomes of the Laplace Trend Test
Adapted from Vlok (2011)

If the Laplace test yields results with $1 \geq L \geq -1$, there is no evidence of an underlying trend. Data with no trend is referred to as a non-committal data set. If a trend is present in the collected data, the results will be $L \geq 2$ or $L \leq -2$, indicating that a trend of reliability improvement or degradation, respectively, is present. If the Laplace results are $2 > L > 1$ or $-1 > L > -2$ are not able to determine whether a trend is present or not with certainty. Therefore, an alternative test such as the Lewis-Robinson Test, the Crow Test or the Pair-wise Comparison Nonparametric Test should be used. However, the investigation of different trend tests falls beyond the scope of this thesis and will not be discussed in any detail. Tobias & Trindade (2010) and Wang & Coit (2005) discuss the application of different trend tests.

A common reliability metric, Mean Time Between Failure (MTBF), is used to characterize the failure behaviour of systems. However, more complex and accurate prediction can be done with statistical analyzes of past failure data.

Once a trend is identified in the data set of a system, the system is referred to as a *Repairable System*. It has been proven that an NHPP analysis is applicable. To analyze these systems a well-known reliability metric, MTBF, is applicable. However, complex statistical analysis is also used to analyze the failure behaviour of such a system. Wang & Coit (2005) and Vlok (2011) suggests that the Log

Linear Model and Power Law Model are applicable to analyze the failure behaviour of repairable systems, this will be discussed in Sections 3.3.3 and 3.3.4 respectively.

If there is no notable trend in the data set the failure behaviour is modeled by use of a probabilistic approach and the system is referred to as non-repairable. A probabilistic approach fits the data to an appropriate distribution which is used to represent the failure behaviour of the system. For this a popular distribution in reliability modeling is used, named the Weibull distribution. It provides the ability to shape a distribution according to the relevant data in order to analyze and predict failure behaviours.

The next section discusses two reliability metrics that are available and useful to characterize failure behaviours.

3.3.1 MTBF and MFOP

Mean Time Between Failure (MTBF) and Maintenance Free Operating Period (MFOP) are widely used reliability metrics to characterize the failure behaviour of a system. The one, MTBF, is used much more frequently than the other. MFOP is commonly used in the aviation industry but has not been applied much elsewhere. These metrics can also be labeled *maintenance interval metrics*. The difference between these two metrics are discussed in this section.

MTBF is the most frequently reliability metric used and is defined by Smith (2005):

> *"Mean time between failures is 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 consecutive observed time to the total number of failures."*

Hence, MTBF is the expected time between two successive failures. The MTBF is calculated as the inverse of the failure rate, thus taking the average of the failure interarrival times, obtained from failure data history and not taking suspensions into consideration. A suspension is the detection of a non-favorable event without the observation of a failure and can be due to partial information of regression or truncated failure times for preventive maintenance. Figure 3.5 presents a graphical explanation of the elements involved for calculating MTBF. Time To Repair (TTR) and Time To Failure (TTF) are displayed in the figure. Using Equation 3.2 the MTBF can be calculated. The notation is as follows:

$N =$ Total number of failures
$x_i =$ The time elapsed from the $(i-1)^{\text{th}}$ failure to the i^{th} failure.

$$\text{MTBF} = \frac{\sum_{i=1}^{N} x_i}{N-1} \tag{3.2}$$

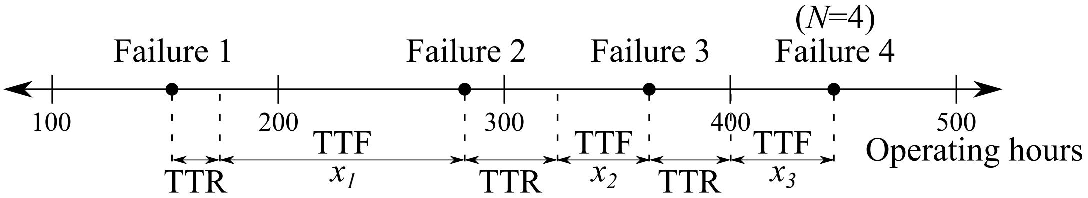


Figure 3.5: Information to Calculate MTBF

Although MTBF is a quick and useful reliability metric, there are a few imperfections. MTBF is the average time between consecutive failures and assumes a constant failure which are sometimes misleading. The greatest downside of this measurement is that it is influenced by the extremes. Depending on the distribution of the failure behaviour of an asset, MTBF is not always an accurate measurement. For example, if an asset fails according to an exponential distribution the MTBF can not be predicted because the times between failures increase exponentially.

MFOP is defined by Long *et al.* (2009):

> *"MFOP is a period of operation during which the equipment must be able to carry out all its assigned missions without any maintenance action and without the operator being restricted in any way because of system faults or limitations."*

In short, MFOP is simply a measurement of time in which a system or asset can utilize its full capacity without any maintenance requirements. Figure 3.6

illustrates the principle of the MFOP. Once the reliability of a system has dropped to a specified level, for example 80%, it is maintained to recover the reliability to a 100%. This time period is known as the Maintenance Recovery Period (MRP) and is a specified time for maintenance which is usually done in a periodic manner, keeping the system *failure free*. As shown, the MFOP and MRP together represents the Failure Free Operating Period (FFOP) during which the system operates without the occurrence of a failure.

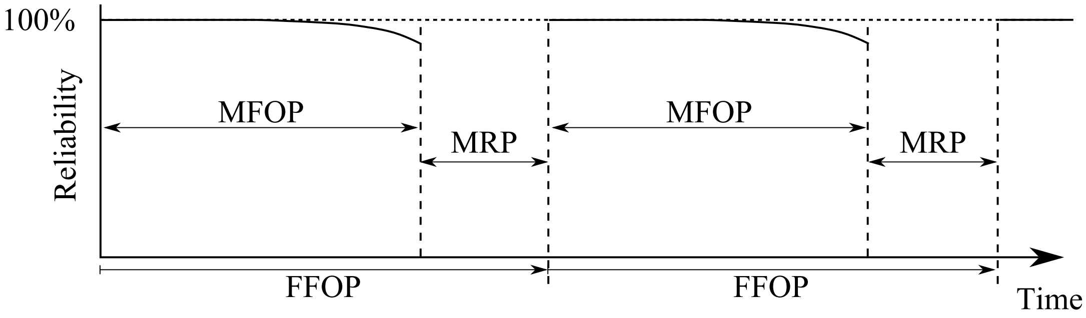


Figure 3.6: MFOP Principle

Dinesh Kumar *et al.* (1999) consider MFOP as an alternative metric to MTBF and the work of Al-Shalaane (2012) also suggests to replace MTBF with MFOP. However, the calculation of MFOP is more complex than MTBF. It is stated that it is almost impossible to calculate a 100% guaranteed MFOP and for this reason the survivability of this period is rather calculated. This is known as the Maintenance Free Operating Period Survivability (MFOPS) and is discussed by Long *et al.* (2009), Dinesh Kumar *et al.* (1999), Al-Shalaane (2012) and various others. A short definition of MFOPS is provided by Wu *et al.* (2004):

> *"MFOPS is the probability that the item will survive for the duration of the MFOP."*

It is explained by these authors that if the reliability requirement is a MFOP of x_s life units, the probability of surviving this amount of units, given that the system has already survived x life units, is:

$$\text{MFOPS}(x) = \frac{R(x + x_s)}{R(k)} \tag{3.3}$$

$R(k)$ is the system reliability at k life units. This reliability function are explained with the Weibull analysis in the next section. As mentioned previously, the Weibull analysis shapes a distribution according to relevant data. In order to do this, two parameters are involved, η and β, for the scale and the shape of the distribution. This will also be explained in the next section.

Followed by the MFOPS calculation, the maximum MFOP can be calculated for the given confidence.

$$\text{MFOP} = \eta \cdot \ln\left(\frac{1}{\text{MFOPS}}\right)^{\frac{1}{\beta}} \tag{3.4}$$

Although both of these metrics are of great value, MFOP focusses on the period of time in which operations can proceed without requiring maintenance. This may yield more accurate operational availability predictions. However, the calculation is much more complex than MTBF and it requires parameters from other statistical analysis such as Weibull analysis, which is discussed in the next section.

3.3.2 Weibull Analysis

The Weibull analysis analyzes failure data in order to characterize the failure behaviour by means of a Weibull distribution. This distribution represents the failure and repair characteristics which may be used in different failure models that calculate expected failure occurrences. According to Abernethy (2002) the result of a Weibull analysis can include failure forecasting and prediction, evaluating corrective action plans, maintenance planning, cost effective replacement strategies, etc.

The flexibility of this distribution enables it to take on the characteristics of other distributions types, depending of the shape parameter, β. Dodson (2006) provides Equation 3.5 that defines the Probability Density Function (PDF) of the Weibull distribution and has the following notation:

x = continuous time,
β = shape parameter for the Weilbull distribution
η = scale parameter for the Weilbull distribution

$$f(x) = \frac{\beta}{\eta}\left(\frac{x}{\eta}\right)^{\beta-1}.\exp\left(-\left(\frac{x}{\eta}\right)^{\beta}\right) \tag{3.5}$$

The PDF, $f(x)$, provides the probability of a system failure at instant x. The PDF curve presents the shape of the distribution and differs with different β values, where $0 < \beta < \infty$. Dodson (2006) listed a few β values that enables the Weibull distribution to take on the characteristics of some well-known distributions. The distribution with:

- $\beta = 1$ is equivalent to the exponential distribution,
- $\beta = 2$ is equivalent to the Rayleigh distribution,
- $1 < \beta < 3.6$ approximates the lognormal distribution,
- $3 < \beta < 4$ approximates the normal distribution and
- $\beta = 5$ approximates the peaked normal distribution

Figure 3.7 presents the graphical representations of $f(x)$ for different β values.

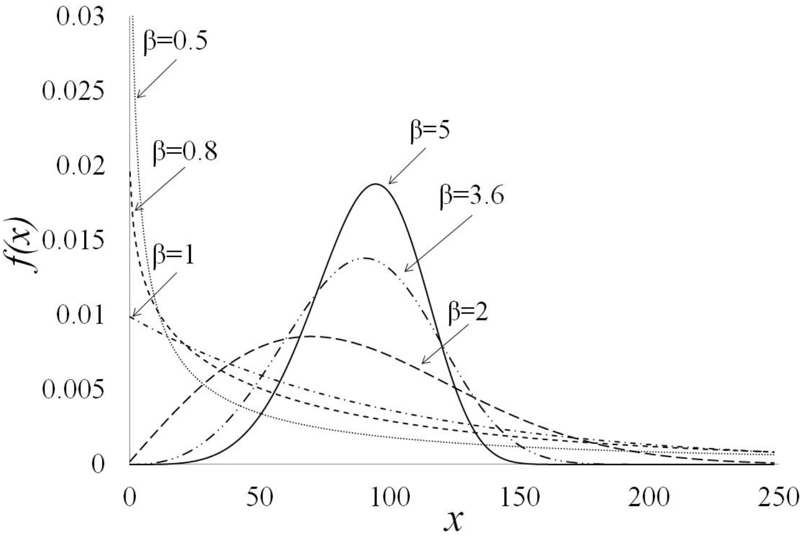


Figure 3.7: The Weibull pdf for Different β values

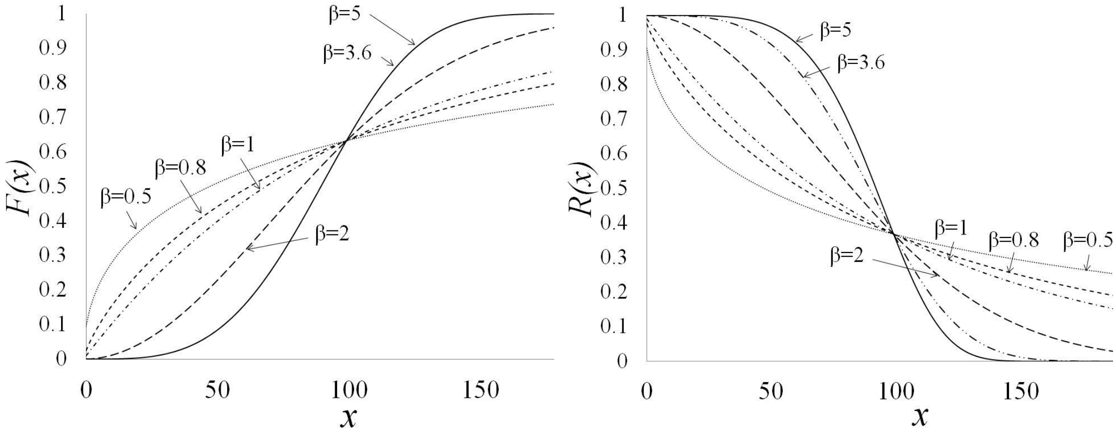
The cumulative failure distribution, up to time x, illustrates the probability that a failure will occur within the interval $(0, x)$. Thus by integrating the PDF from 0 to x, the probability of failure can be obtained.

$$\begin{aligned} F(x) &= \int_0^x f(\tau)d\tau \\ &= 1 - \exp\left(- \left(\frac{x}{\eta}\right)^{\beta} \right) \end{aligned} \tag{3.6}$$

The reliability or probability of survival of the system is presented by Equation 3.7.

$$\begin{aligned} R(x) &= 1 - F(\tau) \\ &= \int\limits_x^{\infty} f(\tau)d\tau \end{aligned} \tag{3.7}$$

A graphical presentation of the relationship between $F(x)$ and $R(x)$, for different β values, is shown in Figures 3.8 (a) and (b).



(a) Failure Probability Curve

(b) Reliability Curve

Figure 3.8: Relationship between $F(x)$ and $R(x)$

It is evident that $R(x)$ is the complement of $F(x)$. The relationship between the PDF and the reliability function, $f(x)$:$R(x)$, is known as the hazard function, and is used to characterize failures and measure the tendency to fail.

$$h(x) = \frac{f(x)}{R(x)} \tag{3.8}$$

$$= \frac{\beta(x)^{\beta-1}}{\eta^{\beta}} \tag{3.9}$$

This function is also known as the instantaneous failure rate, providing the probability of impending failure. Therefore, the higher the hazard rate, the higher the probability of impending failure. Figure 3.9 graphically presents the hazard function for different β values.

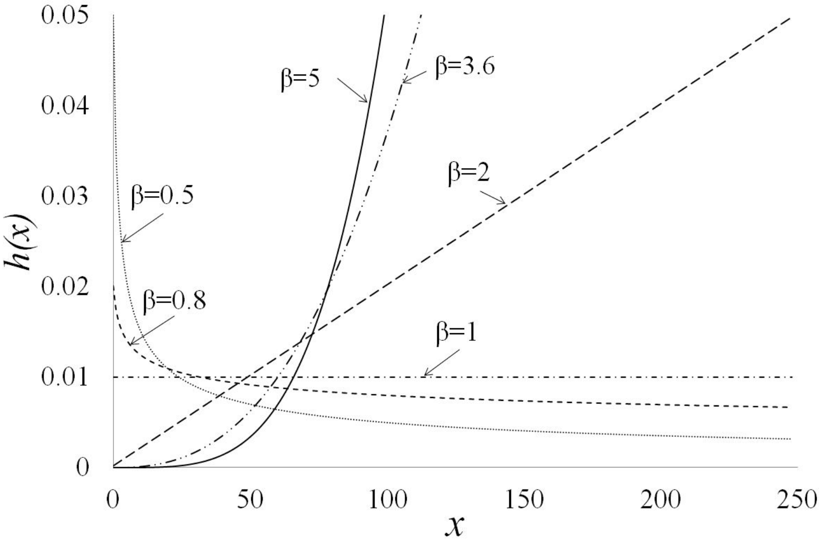


Figure 3.9: The Weibull Hazard Function for Different β values

It is noted that for $\beta < 1$ the hazard function decreases as x increases. This means that the instantaneous failure rate reduces as time progresses, which is also known as *infant mortality*, as described with the bathtub curve. For $\beta = 1$ the failure rate remains constant for all x, implying that the failure behaviour is totally random. This can also be referred to as the behaviour of a non-repairable system. When $\beta > 1$ the instantaneous failure rate increases with x and is referred to as the *wear out period*, as explained with the bathtub curve.

Example:

A machine runs 24 hours a day 7 days a week and fails according to a Weibull distribution with parameters $\beta = 1.2$ and $\eta = 240$ hours. The reliability of that system on day 3, approximately at hour 70, can be calculated as follows:

$$\begin{aligned} R(x) &= 1 - F(x) \\ &= e^{\left(-\left(\frac{t}{\eta}\right)^{\beta}\right)} \\ &= e^{\left(-\left(\frac{70}{240}\right)^{1.2}\right)} \\ &= 0.796 \\ &\Rightarrow 79.60\% \end{aligned}$$

The value of the hazard function at time 70 are:

$$\begin{aligned} h(70) &= \frac{\beta(x)^{\beta-1}}{\eta^{\beta}} \\ &= \frac{1.2(70)^{0.2}}{240^{1}.2} \\ &= 0.0039 \\ &\Rightarrow 0.39\% \end{aligned}$$

From these results it is seen that the machine has a 79.60% chance of surviving up to hour 70. At this time instance there is a 0.39% chance that a failure is about to occur.In having this information it can be determined which assets are critical. For example, if one asset's reliability is much worse than another with a high hazard rate, it can be considered as critical. Or the asset with the shortest time to its next expected failure, can also be considered as critical.

The parameters, β and η are estimated analytically by using methods such as Maximum Likelihood, Method of Moments and Least Squares Method. Al-Fawzan (2000) compared these methods and found that the Least Squares Method is best to use based on its accuracy and speed in delivering results. Although the Method of Moments gives a slightly more accurate estimation, it is more time consuming than the Least Squares Method. However, the estimation of parameters falls beyond the scope of this thesis and will not be discussed in any detail.

3.3.3 Log-Linear Model

This method is applicable to analyze the failure behaviour of a repairable system. Repairable systems are systems which can be restored to a functioning condition, by means of maintenance activities, after a failure has occurred. It was also explained earlier that a system is characterized as repairable when a trend is present in the failure behaviour and thus a NHPP is required. This is determined by one of the trend tests mentioned in Section 3.3.

Failure data is used in order to model the behaviour of a system. This behaviour can be used to predict future behaviour and thus when to expect failures. The Log Linear model is explained thoroughly by various authors such as Darroch & Ratcliff (1972), Lee (1980), Vlok (2011) and Wang & Yu (2012). If t is considered as continuous global time and T discrete global time, the Log Linear function is given by the following equation:

$$\rho_1(t) = \exp(\alpha_0 + \alpha_1 t) \tag{3.10}$$

α_0 and α_1 are the Log Linear parameters with $\alpha_1 > 0$. Various methods exist to estimate these two parameters. Sarhan & Tadj (2003) discusses the *maximum likelihood* and *Bayes procedures* to estimate these parameters. Another method that can be used is the *least squares* method.

By integration of the Log Linear function, $\rho_1(t)$, the expected number of failures, N, can be obtained between two time instants:

$$E[N(t_1 \to t_2)] = \frac{1}{\alpha_1}[\exp(\alpha_0 + \alpha_1 t_2) - \exp(\alpha_0 + \alpha_1 t_1)] \tag{3.11}$$

Following this, the MTBF can be estimated for the same time interval:

$$\text{MTBF}_{\rho_1}(t_1 \to r_2) = \frac{\alpha_1(t_2 - t_1)}{\exp}(\alpha_0 + \alpha_1 t_2) - \exp(\alpha_0 + \alpha_1 t_1) \tag{3.12}$$

Similarly, for the same time interval, the reliability of the system can be calculated as follows:

$$R(t_1 \rightarrow t_2) = \exp\left[-[\exp(\alpha_0 + \alpha_1 t_2) - \exp(\alpha_0 + \alpha_1 t_1)]/\alpha_1\right] \tag{3.13}$$

Accurate results are obtained within certain confidence bounds. As a result, with a certain confidence, there will be N failures between t_1 and t_2. The Log Linear model is used to predict the failure behaviour of a repairable system relatively accurate. It provides an estimated time within a certain confidence when the next failure might be expected. An alternative method to this is presented in the next section.

3.3.4 Power Law Model

The power law model also uses past failure behaviour to characterize the failure behaviour of repairable systems. It can be used to predict how the system might behave in the future. A power law function is defined as follows:

$$\rho_2(t) = \lambda \delta t^{\delta - 1} \tag{3.14}$$

λ and δ are the required parameters with $\delta > 0$. As mentioned in the previous section with the explanation of the Log Linear model, these parameters can be estimated by use of different available methods.

The expected number of failures can also be estimated with integration of the power law function, $\rho_2(t)$, similar to the Log Linear model. In short, this is done by use of the following equation and is determined for the time period t_1 to t_2:

$$E[N(t_1 \rightarrow t_2)] = \lambda(t_2^{\delta} - t_1^{\delta}) \tag{3.15}$$

Furthermore, the MTBF for the same time interval, t_1 to t_2, can be calculated:

$$\text{MTBF}_{\rho_2}(t_1 \rightarrow r_2) = \frac{t_2 - t_1}{\lambda(t_2^{\delta} - t_1^{\delta})} \tag{3.16}$$

As well as the reliability of the system for this time period:

$$R(t_1 \rightarrow t_2) = e^{-\lambda(t_2^{\delta} - t_1^{\delta})} \tag{3.17}$$

These results can also be calculated within a confidence interval. This is a helpful technique to estimate when the next failure might be expected.

Although both of these processes can be used for repairable systems, one can be more accurate than the other for certain systems. This is determined by fitting the past failure behaviour to the predicted failure behaviour of both processes. Although both of these NHPP's are only explained briefly, it requires complex calculations to obtain accurate prediction.

In the sections to follow different techniques are discussed that can support decision making with multiple alternatives or have multiple objectives.

3.4 Multi-Criteria Decision Making (MCDM)

Banville *et al.* (2000) mentions that the field of MCDM has recently become a very popular approach to assist decision-makers. The reason for this is that decisions are more complex with the need to optimize not only one but multiple objectives. When using MCDM a finite set of alternatives are prioritized in order to aid the decision-maker in selecting the correct alternative. According to Al-Najjar & Alsyout (2003) for the prioritization of the alternatives a finite set of criteria is created and weighted according to the importance. The sections to follow elaborate on a few different MCDM techniques.

3.4.1 Simple Multi-Attribute Rating Technique (SMART)

SMART is a structured methodology designed to handle the tradeoffs among multiple objectives and is one of the simplest methods used for MCDM.

Starfield (2005) describes that with SMART each alternative is given a direct rating value with respect to each criterion. This rate represents how well the alternative satisfies the criterion. The rating scale would typically be between 0 and 1, 0 being the worst case scenario and 1 the best. By multiplying the alternatives' rates, r_{ij}, with the criteria weights, w_i, and summarizing it, an evaluation value, $V(A_j)$, is calculated according to Equation 3.18. This value is used for the prioritization of the alternatives. This is explained in the work of Barron & Barret (1996).

$V(A_j) =$ evaluation value of alternative j, $j = 1, 2, ..., n$ and $0 \leq V(A_j) \leq 1$,
$r_{ij} =$ the rating value of criterion i for alternative j, $0 < r_{ij} < 1$,
$w_i =$ weight of the i^{th} criterion reflecting the relative importance, $0 < w_i < 1$ with $\sum w_i = 1$.

$$V(A_j) = \sum_{j=1}^{n} w_i r_{ij} \tag{3.18}$$

One example of an application of SMART is to assess maintenance tactics in order to select the most efficient approach relevant to given criteria. For example, if there are three different maintenance tactics (alternatives) and one has to be selected with the aim to minimize cost and maintenance time. Then the three alternatives are rated according to the influence of each strategy on both maintenance cost and time. Al-Najjar & Alsyout (2003) supports the fact that the use of efficient maintenance approaches will result in less unplanned replacements, reduced failures, higher component life utilization and thus adding value to production activities. This application of SMART is only one of many.

The objective, when selecting maintenance strategies, is to evaluate the ability to provide information about changes in behaviour of failure causes. This evaluation is used to rank the different maintenance strategies. The mathematical explanation is shown in the example that follows.

Example:

One maintenance tactic, from five possible alternatives, should be selected in order to maintain an asset. The tactics can include PM, PdM and corrective maintenance, to mention only a few. The selected tactic should satisfy four objectives such as, minimize maintenance cost, minimize spare parts required, maximize production time, etc. These objectives are used to develop applicable criteria between 0 and 1. For example when considering maintenance cost, 0 can be negligible cost and 1 can be extremely high maintenance cost. The SMART principle can be explained by use of Table 3.1.

Table 3.1: SMART Example

Criteria Weights	Criterion 1 0.2	Criterion 2 0.5	Criterion 3 0.1	Criterion 4 0.2	Evaluation Value
Tactic 1	0.4	0.9	0.8	0.6	0.735
Tactic 2	0.1	0.4	0.7	0.3	0.324
Tactic 3	0.3	0.8	0.7	1	0.708
Tactic 4	0.4	0.8	0.2	0.9	0.684
Tactic 5	0.8	0.4	0.6	0.4	0.524

From the rates in this table it is noticeable that *Tactic 1* is the worst option relative to *Criterion 2* and *Criterion 3*. *Tactic 2*, on the other hand, is the best option relative to *Criterion 1*. To take into account all of the criteria for each tactic Equation 3.18 (p. 73) is used to calculate the evaluation value. Below is the calculation for the first tactic:

$$\begin{aligned} V(A_1) &= 0.2 \cdot 0.4 + 0.5 \cdot 0.9 + 0.8 \cdot 0.1 + 0.2 \cdot 0.6 \\ &= 0.735 \end{aligned}$$

From the results shown in the last column, Tactic 1 is the best option with respect to the related criteria.

3.4.2 Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)

TOPSIS is described by Sachdeva *et al.* (2009) as a decision making technique that finds a solution, closest to the ideal and furthest from the negative ideal, to a multi-criteria problem. The negative ideal solution is considered the worst option. Olson (2004) states that TOPSIS only needs limited subjective input from the decision-maker, weighing alternatives against given criteria. According to Marović (2010) TOPSIS is an uncomplicated technique and is very useful for real world multi-criteria problem solving, providing the decision-maker with the best alternative.

The first step in TOPSIS is to build a judgement matrix $X = [x_{ij}]$, rating i alternatives against j criteria. This rating is done according to a given scale with $i = 1, 2, 3, ...m$ and $j = 1, 2, 3, ...n$. The rating is done similar to the SMART rating method. A weight, w_j, needs to be assigned to each criteria, representing its importance.

The next step is to normalize the matrix X, resulting in $R = [r_{ij}]$ with $0 < r_{ij} < 1$. The normalization of the judgement matrix is done by the following equation.

$$r_{ij} = \frac{x_{ij}}{\sum^{j} x_{ij}} \tag{3.19}$$

The normalized matrix, R, is multiplied with the criteria weights, w_j, to create the decision matrix, $D = [d_{ij}]$ with $0 < d_{ij} < 1$. The equation below is used to calculate decision matrix, D.

$$d_{ij} = r_{ij} w_j \tag{3.20}$$

From the decision matrix, the ideal option $P^+ = [p_j^+]$ and the negative ideal option $P^- = [p_j^-]$ is obtained. This is done by the following equations where $0 < p_j^+, p_j^- < 1$,

C^+ is associated with the beneficial criteria and
C^- is associated with the loss criteria.

$$p_j^+ = \{(\max\ d_{ij}|j \epsilon C^+), (\min\ d_{ij}|j \epsilon C^-)\} \tag{3.21}$$

$$p_j^- = \{(\min\ d_{ij}|j \epsilon C^+), (\max\ d_{ij}|j \epsilon C^-)\} \tag{3.22}$$

These options are used to calculate the separation measures, $S^+ = [s_i^+]$ and $S^- = [s_i^-]$ with $0 < s_i^+, s_i^- < 1$. This measures the distance from the ideal and the negative ideal to the values of the decision matrix, D. Thus the measures represent the distance from each alternative to the ideal and negative ideal options.

$$s_i^+ = \sqrt{\sum_{j=1}^{m}(p_j^+ - d_{ij})^2} \tag{3.23}$$

$$s_i^- = \sqrt{\sum_{j=1}^{m}(p_j^- - d_{ij})^2} \tag{3.24}$$

The relative closeness is calculated to create the final solution matrix, $C = [c_i]$. The solution closest to the ideal and furthest from the negative ideal is obtained. This is done by using the separation measures according to the following equation:

$$c_i = \frac{s_i^-}{s_i^+ + s_i^-} \tag{3.25}$$

$0 < c_i < 1$ from which the maximum value, $c_{i_{max}}$, presents the best solution to be alternative i. A comprehensive example follows.

Example:

A maintenance decision has to be made. Which particular maintenance tactic, from four alternatives ($i = 4$), is best to apply when taking into account productivity, costs, reliability and power consumption. Hence, the criteria consist of four elements ($j = 4$), two beneficial criteria (productivity and reliability) and two loss criteria (costs and power consumption). The aim is to find an alternative that maximizes the benefits and minimizes the losses. The criteria are weighed according to importance and the alternatives are rated against the criteria. This is shown in Table 3.2, creating the judgement matrix, X, which is normalized to obtain matrix R by the use of Equation 3.19.

$$X = \begin{bmatrix} 2 & 4 & 8 & 4 \\ 8 & 6 & 8 & 6 \\ 10 & 8 & 4 & 2 \\ 4 & 2 & 6 & 4 \end{bmatrix}, R = \begin{bmatrix} 0.08 & 0.20 & 0.31 & 0.25 \\ 0.33 & 0.30 & 0.31 & 0.38 \\ 0.42 & 0.40 & 0.15 & 0.13 \\ 0.17 & 0.10 & 0.23 & 0.25 \end{bmatrix}$$

Table 3.2: TOPSIS Example: Criteria Weights and Alternative Rating

Weights, w_j	0.4	0.2	0.3	0.1
Criteria	Productivity	Cost	Reliability	Power Consumption
Alternative 1	2	4	8	4
Alternative 2	8	6	8	6
Alternative 3	10	8	4	2
Alternative 4	4	2	6	4
Total	24	20	26	16

The normalized matrix, R, is now multiplied with the criteria weights, according to Equation 3.20 (p. 75), to get the decision matrix,

$$D = \begin{bmatrix} 0.03 & 0.04 & 0.09 & 0.03 \\ 0.13 & 0.06 & 0.09 & 0.04 \\ 0.17 & 0.08 & 0.05 & 0.01 \\ 0.17 & 0.02 & 0.07 & 0.03 \end{bmatrix}$$

Now the ideal and negative ideal options are obtained, according to Equation 3.22 (p. 75).

$$\begin{aligned} P^+ &= \{0.17, 0.02, 0.09, 0.01\} \\ P^- &= \{0.03, 0.08, 0.05, 0.04\} \end{aligned}$$

These values are used to calculate the separation matrices, according to Equation 3.24 (p. 76).

$$S^+ = \begin{bmatrix} 0.1354 \\ 0.0578 \\ 0.0757 \\ 0.1034 \end{bmatrix}, S^- = \begin{bmatrix} 0.0623 \\ 0.1119 \\ 0.0136 \\ 0.0735 \end{bmatrix} \tag{3.26}$$

Finally the relative closeness for each alternative is calculated according to Equation 3.25 (p. 76) to create the solution matrix.

$$C = \begin{array}{l} \text{Alternative 1} \\ \text{Alternative 2} \\ \text{Alternative 3} \\ \text{Alternative 4} \end{array} \begin{bmatrix} 0.3153 \\ 0.5696 \\ 0.6419 \\ 0.4155 \end{bmatrix}$$

The results clearly indicate that *Alternative 3* is the option closest to the ideal and furthest from the negative ideal solution. Consequently, *Alternative 3* should be purchased for maximum productivity and reliability at minimum cost and power consumption.

3.4.3 Analytical Hierarchy Process (AHP)

The AHP approach is developed by Dr. Thomas L. Saaty in 1980. Saaty (1990) states that the development of the AHP was triggered by the lack of decision making methodologies that are easily understood and easily implemented to enable complex decision making. Bushan & Rai (2004) mention that the effectiveness and simplicity of this approach caused it to rapidly become acknowledged in multiple disciplines, globally. Fülöp (2005) states that an AHP is to convert subjective assessments of relative importance in order to a set of overall weights. The subjective data is obtained by the comparison of attribute or alternative pairs, determining which is more important than the other, as supported by Laininen & Hämäläinen (2002). Consequently, only two alternatives are considered at a time and are compared according to the given criteria.

Bushan & Rai (2004) explain the AHP procedure as a top down approach where the problem or decision is broken down into a hierarchy. The problem or decision considered is the goal of the analysis branching out into various attributes and alternatives. The attributes can be criteria categories with relevant sub-criteria, if necessary. Relationships between the elements, from one level to the next, are indicated with line connections. Figure 3.10 presents a generic example of such a hierarchy.

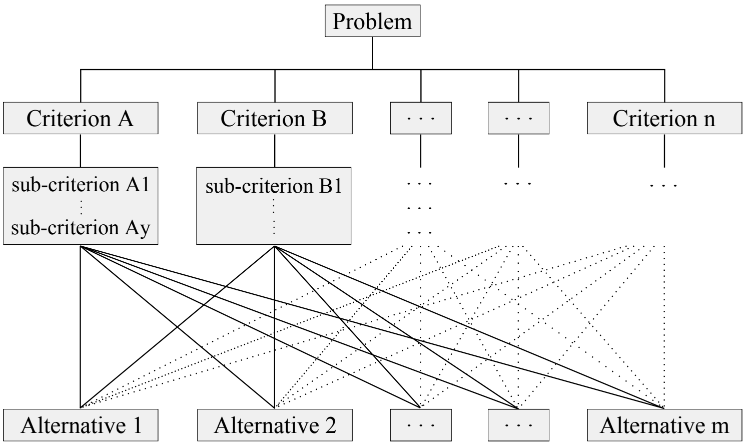


Figure 3.10: Generic Illustration of AHP Structure
Adapted from Bushan & Rai (2004)

The alternatives are compared pairwise, with regards to the given criteria. This criteria consists of quantitative rates with qualitative descriptions and is shown in Table 3.3. Expert decision-makers are needed for this comparison because the alternatives should be understood. Laininen & Hämäläinen (2002) describe that the comparison of the attributes is done with the use of a comparison matrix. Alternatives are compared with respect to each attribute.

Table 3.3: AHP Rating Scale

Rate	Qualitative Scale	Description
1	Equal	The two attributes contribute equally to the criteria
3	Marginally Strong	Experience and judgement slightly in favor of the one attribute over the other
5	Strong	Experience and judgement strongly in favor of one attribute over the other
7	Very Strong	An attribute is strongly favored and its dominance demonstrated in practice
9	Extremely Strong	The evidence favoring one attribute over another is of the highest possible order of affirmation

Adapted from Bevilacqua & Bragliab (2000)

The comparison values are presented in an n x n square matrix, with diagonal values equal to 1. Each level of the hierarchy is compared in this manner. As mentioned, this is a top down approach, therefore the highest level attributes are compared first which is usually the top criteria. Each level is compared, down to the alternatives considered as possible solutions to the problem.

The comparison of each level in the hierarchy creates a comparison matrix. This matrix is squared and normalized iteratively in order to find a steady state eigenvector. The eigenvector is also considered as the priority matrix representing the individual priorities of each alternative. If the hierarchy consists of three criteria and four alternatives, all four alternatives will have a separate priority for each criteria. These priority matrices are multiplied by another matrix, consisting of the criteria weights. This result in the final decision priority values for all alternatives. A mathematical explanation of this is shown in the AHP example.

When using AHP the consistency of the decision-maker is measured to ensure that the comparisons remain consistent. Escobar *et al.* (2004) explain the calculation of a Consistency Ratio (CR) relative to large samples of purely random judgement. The CR must be below 0.1 to consider the judgement to be accurate. This CR is calculated by the use of Equation 3.27.

$\lambda =$ eigenvalue, also calculated as the sumproduct of the columns and the eigenvector of the decision matrix,
RI = Random Consistency Index according to Table 3.4,
CI = consistency index calculated according to Equation 3.28.

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{3.27}$$

$$\mathrm{CI} = \frac{\lambda - n}{n - 1} \tag{3.28}$$

For the calculation of the eigenvalue with the use of Equation 3.29, the following notation is relevant:

$n =$ the matrix size, n x n,
$\sum^{j} r_{jn} =$ sum of the j number of ratings in column n,
$E_n =$ priority value for the n^{th} criterion

$$\lambda = \sum^{n} (\sum^{j} r_{jn}) E_n \tag{3.29}$$

The Random Consistency Index (RI), presented by Saaty (1987), is used for the calculation of the CR, as mentioned. The random value selected for the CR calculation is based on the matrix size, n x n.

Table 3.4: AHP Random Consistency Index

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Hence, the smaller the CR the more consistent is the decision-maker. A consistency ratio of 0 will be a result of $\lambda = n$ and the decision-maker is thus considered to be 100% consistent. A thorough mathematical explanation of AHP is explained in the example that follows.

Example:
A system has six core machines (assets) that are crucial for operation. When one of these assets fail the entire system comes to a halt. Therefore, the critical assets should be identified in order to plan the maintenance activities. There are three elements that have an influence on the prioritization of the assets: impact on production, impact on maintenance cost and impact on safety. Accordingly, the AHP structure for this problem is presented in Figure 3.11.

Table 3.5 illustrates the pairwise comparison of the criteria. It is shown that when comparing *Production Impact* versus *Safety Impact*, *Production Impact* is more important (Strong). Whereas, with the comparison of *Safety Impact* versus *Maintenance Cost*, *Safety Impact* is marginally more important than *Maintenance Cost*. Lastly, comparing *Production Impact* with *Maintenance Cost*, *Production Impact* is much more important than *Maintenance Cost*.

Table 3.5: Example: Criteria Comparison

Criteria	9 Extremely Strong	7 Very Strong	5 Strong	3 Marginally Strong	1 Equal	3 Marginal Strong	5 Strong	7 Very Strong	9 Extremely Strong	Criteria
Production Impact			x							Safety
Safety				x						Maintenance Cost
Maintenance Cost								x		Production Impact

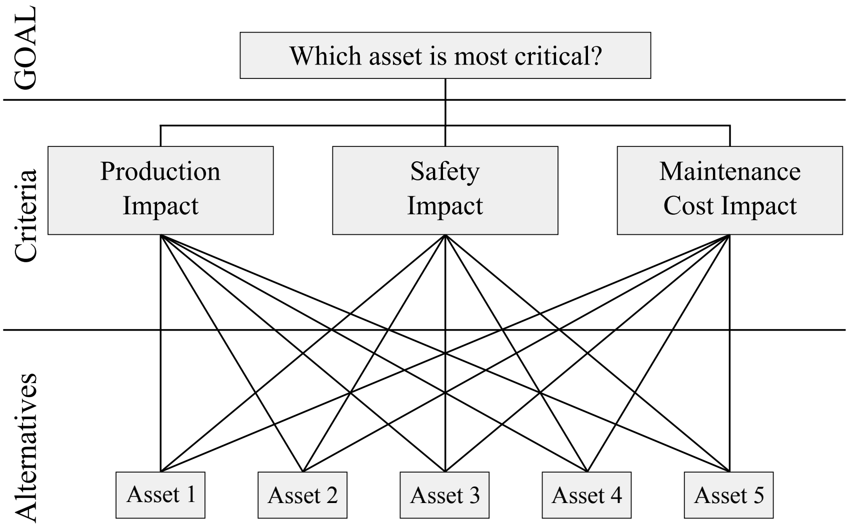


Figure 3.11: Example: AHP Structure

The comparison values are written in matrix form, as shown below:

$$\begin{array}{c} \\ P \\ S \\ M \end{array} \begin{array}{c} \begin{array}{ccc} P & S & M \end{array} \\ \begin{bmatrix} 1 & 5 & 7 \\ 1/5 & 1 & 3 \\ 1/7 & 1/3 & 1 \end{bmatrix} \end{array} = C$$

Criteria Comparison Matrix (C)

This is done for all the alternatives, with respect to each criterion. Consequently each alternative will have a priority value for each criterion. Dong *et al.* (2008) discussed the *eigenvalue method* which is used to calculate the priority weights from the comparison matrices. Laininen & Hämäläinen (2002) explains the method to calculate the weights, as proposed by Saaty (1990). The calculation is done as follows:

$$C^2 = \begin{bmatrix} 1 & 5 & 7 \\ 0.2 & 1 & 3 \\ 0.143 & 0.333 & 1 \end{bmatrix}^2 = \begin{bmatrix} 3.001 & 12.331 & 29 \\ 0.829 & 2.999 & 7.4 \\ 0.3526 & 1.381 & 3 \end{bmatrix}$$

Now, the eigenvector is determined by normalizing C^2.

$$\begin{bmatrix} 3.001 & + & 12.331 & + & 23 \\ 0.829 & + & 2.999 & + & 7.4 \\ 0.3526 & + & 1.381 & + & 3 \end{bmatrix} \begin{matrix} = & 44.332 \\ = & 11.228 \\ = & 4.7336 \end{matrix} \Rightarrow \begin{bmatrix} 0.7353 \\ 0.1862 \\ 0.0785 \end{bmatrix}$$

This is done iteratively until a steady-state eigenvector is found. For the specific example, steady-state is found after four iterations:

$$\text{Eigenvector} = \begin{bmatrix} 0.7306 \\ 0.1884 \\ 0.0810 \end{bmatrix}$$

The steady-state eigenvector which is also the priority values, shows that production impact is the most important criterion and maintenance cost the least important criterion. The consistency of the decision-maker's judgement are now calculated as explained earlier. The eigenvalue, λ is calculated according to Equation 3.29 (p. 80).

	P	S	M
P	1	5	7
S	0.2	1	3
M	0.14	0.33	1
sum	1.34	6.33	11

$$\begin{aligned} \lambda &= (1.34)(0.7306) + (6.33)(0.1884) + (11.00)(0.0810) \\ &= 3.0649 \end{aligned}$$

The consistency index is

$$\begin{aligned} \text{CI} &= \frac{3.0649 - 3}{3 - 1} \\ &= 0.0324 \end{aligned}$$

followed by the CR for the criteria comparison which is calculated with Equation 3.27 (p. 80).

$$\begin{aligned} \text{CR} &= \frac{0.0324}{0.58} \\ &= 0.059 \end{aligned}$$

The CR is less than 0.1 which means that the criteria rating was done in a consistent manner and the results can be considered as accurate.

The same procedure is used to calculate the priority weights for the alternatives for each criterion together with the related CR's. The preference of each alternative over another with regards to a specific criterion is calculated. The following matrices show the pairwise comparison values. A_P, A_S and A_M represent the pairwise comparisons for *Production Impact*, *Safety Impact* and *Maintenance Cost* respectively. $A1$ to $A5$ represent the five alternative solutions.

$$\begin{array}{c} \\ A1 \\ A2 \\ A3 \\ A4 \\ A5 \end{array} \begin{array}{c} \begin{array}{ccccc} \text{A1} & \text{A2} & \text{A3} & \text{A4} & \text{A5} \end{array} \\ \left[\begin{array}{ccccc} 1 & 3 & 3 & 9 & 9 \\ 0.33 & 1 & 1 & 7 & 1 \\ 0.33 & 1 & 1 & 5 & 5 \\ 0.11 & 0.14 & 0.2 & 1 & 0.33 \\ 0.11 & 1 & 0.2 & 3 & 1 \end{array}\right] \end{array} = A_P,$$

$$A_S = \begin{bmatrix} 1 & 5 & 0.33 & 3 & 9 \\ 0.2 & 1 & 0.11 & 0.33 & 3 \\ 3 & 9 & 1 & 5 & 5 \\ 0.33 & 3 & 0.2 & 1 & 3 \\ 0.11 & 0.33 & 0.2 & 0.33 & 1 \end{bmatrix}, A_M = \begin{bmatrix} 1 & 0.2 & 0.33 & 3 & 5 \\ 5 & 1 & 3 & 7 & 9 \\ 3 & 0.33 & 1 & 5 & 9 \\ 0.333 & 0.14 & 0.2 & 1 & 3 \\ 0.2 & 0.11 & 0.11 & 0.33 & 1 \end{bmatrix}$$

The eigenvector for each matrix is determined, resulting in the following values which is also the priority values;

$$A_P \Rightarrow \begin{bmatrix} 0.506 \\ 0.163 \\ 0.213 \\ 0.035 \\ 0.084 \end{bmatrix}, A_S \Rightarrow \begin{bmatrix} 0.277 \\ 0.064 \\ 0.497 \\ 0.116 \\ 0.043 \end{bmatrix}, A_M \Rightarrow \begin{bmatrix} 0.127 \\ 0.510 \\ 0.270 \\ 0.062 \\ 0.031 \end{bmatrix}$$

Al of these priority values calculated are referred back to the AHP structure, see Figure 3.12. This figure shows the priority of each asset for each criterion.

It is evident that for *Production Impact*, *Asset 1* has the highest priority. *Asset 3* has

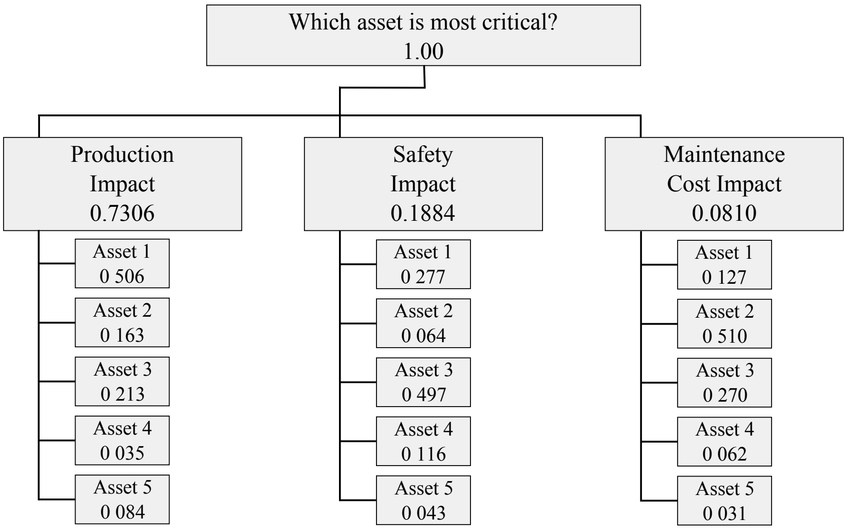


Figure 3.12: Example: AHP Structure with Alternative Priority Values

the highest priority with regards to *Safety Impact* and *Asset 2* for *Maintenance Cost*. Thus, if only one of the aspects needs to be improved, attention should be given to these assets first.

The CR results for the alternative comparisons for each criterion are as follow:

Rated w.r.t.	λ	CI	RI	CR
Production	5.343	0.0857	1.12	0.077
Safety	5.406	0.1015	1.12	0.091
Maintenance	5.232	0.0581	1.12	0.052

With all of the CR's lower that 0.1, the results can be accepted as reliable. For the final prioritization the priority values of the alternatives are combined into one matrix which is then multiplied by the criteria priority values.

$$\begin{array}{c} \\ A1 \\ A2 \\ A3 \\ A4 \\ A5 \end{array} \begin{array}{c} \begin{array}{ccc} P & S & M \end{array} \\ \left[\begin{array}{ccc} 0.506 & 0.277 & 0.127 \\ 0.163 & 0.064 & 0.510 \\ 0.213 & 0.497 & 0.270 \\ 0.035 & 0.116 & 0.062 \\ 0.084 & 0.043 & 0.031 \end{array}\right] \end{array} * \begin{array}{c} P \\ S \\ M \end{array} \left[\begin{array}{c} 0.7306 \\ 0.1884 \\ 0.0810 \end{array}\right] = \begin{array}{c} A1 \\ A2 \\ A3 \\ A4 \\ A5 \end{array} \left[\begin{array}{c} 0.432 \\ 0.172 \\ 0.273 \\ 0.052 \\ 0.072 \end{array}\right]$$

From this can be seen that *Asset 1* is the most important asset and *Asset 4* is the least important. Consequently, the AHP provides a logical quantitative framework to calculate the benefit of each alternative relative to the criteria. AHP is a systematic and very accurate process, however, it is time consuming and expert judgement is required.

Some pitfalls discussed by Bushan & Rai (2004). One is that the ranking process may become repetitive due to the fact that all ranking values change when an alternative is added. Also, Fülöp (2005) states that potential inconsistencies may occur with the use of the theoretical foundation of the rating scale. However, Bushan & Rai (2004) discusses the evolution of the AHP application over the years and states that it has also been used in conjunction with other mathematical techniques.

3.5 Criticality Analysis

Critical assets are those that are most likely to have a negative impact on business performance. Smith (2009) states that asset criticality analysis is used to identify equipment that, if it fails, has the most serious consequences on business performance. Francis (2003) describes criticality as the combination of failure likelihood and severity of failure consequences. It can be sorted by use of categories or levels as an illustration of capability dangers and losses of a system. A criticality analysis can be performed both qualitatively and quantitatively.

Francis (2003) states that the qualitative approach is applicable when failure data is unavailable, otherwise the quantitative approach is preferred. Failure data is used to calculate criticality numbers for the quantitative approach and for the qualitative approach the probability of occurrences is used.

3.5.1 Qualitative Criticality Analysis

As mentioned, the qualitative approach is based on probability of occurrences and possible effects which is categorized according to level of severity. Tables 3.6 (a) and (b) present examples of qualitative failure probability and failure consequence severity scale.

Table 3.6: Qualitative Criticality Scales

(a) Failure Probability

Scale Level	Description
A	Great probability of failure
B	Moderate probability of failure
C	Relatively low probability of failure
D	Very low probability of failure
E	Almost no probability of failure

(b) Consequence Severity

Scale Level	Description
A	Catastrophic
B	Critical
C	Marginal
D	Negligible

Similar qualitative scales, based on other aspects, can be used to assess the criticality of an asset. By adding various different aspects, multiple scales can be combined to asses an asset with multiple criteria similar to the SMART method.

Example:

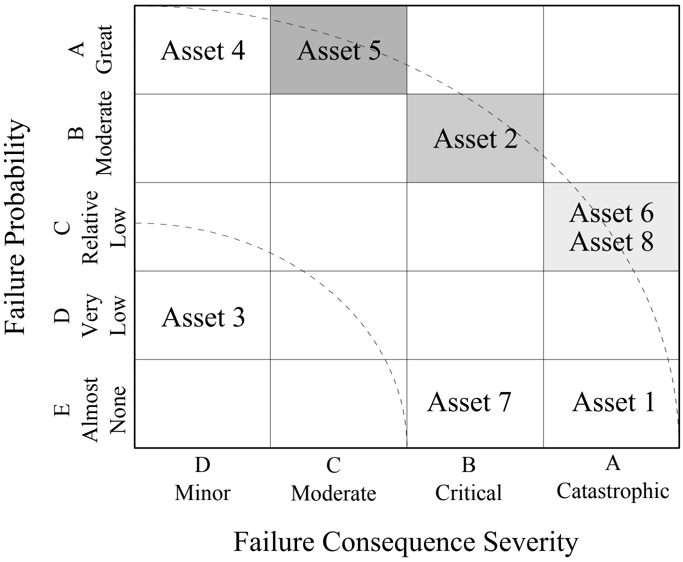
To analyze the criticality of an entire system, all the assets or equipment that contribute to the production are included. This analysis determines which assets are critical to the operation. It is useful to know which assets are critical because those are the assets that should be maintained and require attention in order to maximize operations. The system analyzed in this example consists of eight main assets that are responsible for the operation of the system. No data is available for the analysis, therefore the qualitative method is used. Table 3.7 shows the completed qualitative analysis according to the rating scales presented in Tables 3.6 (a) and (b).

Table 3.7: Qualitative Criticality Analysis Example

	Severity Level	Failure Level
Asset 1	A	E
Asset 2	B	B
Asset 3	D	D
Asset 4	D	A
Asset 5	C	A
Asset 6	A	C
Asset 7	B	E
Asset 8	A	C

These ratings are plotted on a criticality grid to get a graphical representation of the asset criticality (Figure 3.13).

The criticality zones are used according to positional risk, as explained in Chapter 2, Section 2.3.2. Figure 3.13 shows that *Asset 1*, *Asset 5*, *Asset 6* and *Asset 8* are the critical assets. Due to the fact that *Asset 5* has a great failure probability and a moderate severity it can be classified as most critical and should be treated first. Great attention should be given all critical assets in order to ensure that they are in working order, however this analysis prioritize the asset showing in what order they should be treated.



	D Minor	C Moderate	B Critical	A Catastrophic
A Great	Asset 4	Asset 5		
B Moderate			Asset 2	
C Relative Low				Asset 6 Asset 8
D Very Low	Asset 3			
E Almost None			Asset 7	Asset 1

Figure 3.13: Example: Qualitative Criticality Grid

3.5.2 Quantitative Criticality Analysis

The quantitative approach makes use of historical failure data to determine the criticality of an asset. Equation 3.30, presented by Francis (2003), is used to determine the criticality number. The notation is as follows:

$C_m =$ the criticality number of the m^{th} asset,
$\varphi =$ the probability of failure, expressed as a decimal fraction
$\gamma =$ failure rate of the asset, expressed in per number of hours and
$t =$ duration, in hours, of applicable operation time and
$\theta =$ the failure effect probability.

$$C_m = \theta\varphi\gamma t \tag{3.30}$$

The failure effect probability represents the probable effect if a failure should occur. This effect falls under one of four categories:

Substantial loss: $\theta = 1$
Reasonable loss: $0.1 < \theta < 1$
Potential loss $0 < \theta < 0.1$
No effect $\theta = 0$

The C_m values are used to prioritize the assets according to criticality, suggesting an order in which the assets should be treated.

Example:
The same example used for the qualitative criticality analysis is used for the quantitative analysis. In this case failure data is available for the criticality calculation. Table 3.8 shows the complete quantitative analysis on the eight assets. This type of analysis can be done on a regular basis, for example once a week. In this case the analyzing time will be seven days or 168 hours, for a system that runs 24 hours a day and seven days a week.

From Table 3.8 *Asset 2*, *Asset 5* and *Asset 6* are identified as the three most critical assets, with *Asset 6* being the utmost critical. When comparing the results qualitative and quantitative analysis, it is clear that both can be considered as accurate, obtaining similar assets to be critical. However, the quantitative analysis are more specific having the numerical values. The quantitative analysis shows that *Asset 6* is most critical. Although the qualitative analysis identified *Asset 8* to also be one of the top critical assets, the quantitative analysis shows that the criticality of *Asset 6* is not as much, relative to the other. With the quantitative analysis the assets can properly be prioritized according to the criticality.

Table 3.8: Quantitative Criticality Analysis Example

Asset	Effect Probability θ	Failure Probability φ	Failure Rate, γ	Time Period, t	Criticality C_m	Priority
Asset 1	1.00	0.001	0.083	168	0.014	5
Asset 2	0.60	0.150	0.063	168	0.945	2
Asset 3	0.00	0.006	0.042	168	0.000	6
Asset 4	0.00	0.300	0.021	168	0.000	7
Asset 5	0.04	0.400	0.208	168	0.560	3
Asset 6	1.00	0.070	0.104	168	1.225	1
Asset 7	0.03	0.000	0.042	168	0.000	8
Asset 8	1.00	0.030	0.006	168	0.030	4

3.6 Failure Modes and Effect Analysis (FMEA)

FMEA, as described by Clovák (2009/2010), is a bottom-up, analytical method that is useful for exhaustive listing of potential initiating faults. It identifies potential failure modes, the effects on the system and also to define actions in order to avoid failure occurrences. It is also used to prioritize potential failure modes, identifying which modes to address first. Ben-Daya (2009) defines FMEA as follows:

> *"Failure Modes and Effects Analysis is an engineering technique to systematically analyze potential failure modes to identify, define and eliminate known problems or errors with the aim to prevent all possible failures, minimize risk and to assure the highest possible yield, quality and reliability."*

From this definition three main activities performed by FMEA are identified:

1. Identify and recognize potential failures together with the causes and effects.
2. Evaluate and prioritize the identified failure modes.
3. Suggest actions that can be used to reduce or eliminate the occurrence of the possible failures.

Consequently, the main purpose of FMEA is to prioritize potential failure modes according to severity, occurrence and detection. The results of an FMEA is used to identify high-vulnerability elements of a system, guiding deployment of maintenance activities. This analysis can be applied throughout the entire life cycle of a system, from initial design onward.

Preparation for a FMEA is crucial to such an analysis. The system to be analyzed should clearly be defined and necessary data should be obtained to know exactly what is being analyzed. The analyzed system, whether it's an area, an asset, equipment or component, needs to be broken down into logical elements. It is also necessary to know whether the entire system is analyzed or only part of it.

All the possible causes per failure mode are listed. The effect or consequence of each failure mode together with a severity and occurrence rating is assigned to each cause. For each cause the possible prevention an detection are also listed together with the probability of detection. With this information a Risk Priority Number (RPN) is calculated for each possible cause of each failure mode. According to these RPN's the failure modes are ranked in the order of priority. The RPN is calculated as follows:

$$\text{RPN} = (\text{Severity})\text{x}(\text{Occurrence})\text{x}(\text{Detection})$$

Table 3.9: FMEA Rating Scale

Scale	1	10
Severity	no effect/danger	catastrophic effects
Occurrence	not likely to occur	almost inevitable
Detection	almost certain to detect	almost impossible to detect

The severity, risk and detection rates are selected according to a given scale with values between 1 and 10. Table 3.9 provides a guideline for the rate selection.

Mohr (2002) presents a typical process flow, shown in Figure 3.14, for a FMEA application consisting of three basic questions to answer:

- Will a failure result in an undesirable loss?
- What are the failure modes for each analyzed element?
- What are the failure effects for each failure mode?

The first question is usually to filter the analysis in order to avoid unnecessary work. If there is no undesirable loss it is not necessary to break down into subsystems and assemblies. The last two questions is the typical guide to a classical FMEA.

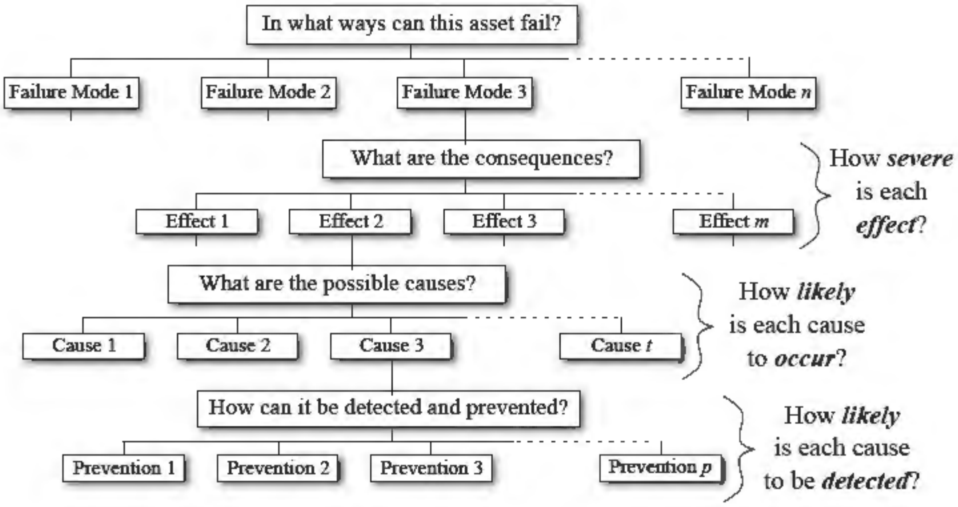


Figure 3.14: The FMEA Process

The breakdown structure of a system or asset's the failure modes can be done by the use of process mapping techniques such as Fault Tree Analysis (FTA) and Cause and Effect Analysis. Process mapping is done prior to the FMEA as part of the preparation. The purpose is to ease the FMEA and making it less time consuming.

Consequently, FMEA is used to discover potential failures of an asset. These potential failures are prioritized according to the RPN's. This aids the process of selecting maintenance strategies, leading to reliability optimization. The application of FMEA is explained by means of an example.

There are various limitations in the execution of FMEA such as overlooking human errors and not taking into account the combined effects of coexisting failures. This is simply due to the fact that failures are analyzed individually. Another limitation is the increase in time consumption and tediousness when analyzing a more complex system with multiple levels or sub-processes.

Example:

Table 3.10 presents an example of an FMEA done for an industrial water supply. The results obtained from the FMEA are used to rank the different causes according to the RPNs. This shows which causes should be addressed first. The FMEA information is

Table 3.10: FMEA Example

Item and Purpose	Failure Modes	Effects	SEVERITY	Detection Method	DETECTION	Potential Causes	OCCURRENCE	RPN
Cool Water Supplier: Supply water to condenser at 25° C at a rate of 3000 liters per minute	water temp higher than 25° C	Condenser not efficient, use more energy , air temp may rise.	6	Analyze water with temperature sensor	2	cooling tower malfunction, degraded pump	3	36
						Degraded pump	6	72
	water temp lower than 25° C	Condenser not efficient, use more energy .	2	Analyze water with temperature sensor	2	degraded pump	6	24
	Providing water at a rate less than 3000 lpm	Pump does not provide enough flow or pressure, condenser not efficient, use more energy	4	Flow or pressure sensor	3	degraded pump	6	72
	provide no water	Condenser will not function, air temp will rise significantly.	10	Inspection or flow or pressure sensor	3	broken pipe	4	120
						pipe blockage	8	240
Resevoir: contains 18000 liters of water	Leak	Water will not be contained, lower condenser efficiency	4	Inspection	4	Crack in wall	3	48
						Broken drain pipe	3	80
Pump	Transport water below the rate 3000 lpm	Condenser not efficient, use more energy	4	Flow sensor	4	Degraded impeller	4	80
						Gasket Leak	4	64
						Degraded pump	6	96
	No water flow	No condenser function, air temp will rise above maximum	5	Flow sensor	2	Broken coupling	6	60
						Leak on suction line	5	50
						Motor inoperable	3	30

documented and a next analysis is built on the current information. Therefore, as the information is collected and the analysis matures the result will become more and more specific and accurate in identifying which items should take priority.

Herman & Janasak (2011) state that FMEA is only applicable for comparing failures of single components. The information obtained from this analysis is useful to other analyzes, providing a good baseline to determine maintenance strategies. Another important fact mentioned is that an FMEA should be conducted regularly in order to keep the information updated and reliable. Effects of redundancy should be taken into consideration with the rating of occurrence, severity and detection to not, unknowingly, increase the availability because of redundancy errors.

3.7 Pareto Analysis

Ziarati (2006) describes a Pareto Analysis as a statistical approach in decision making that focuses on the problems that offer the greatest potential for improvement, showing their relative frequency in a descending order. It is based on the 80-20 principle which argues that 80% of problems are cause by 20% of the causes. This analysis highlights the causes that will have the greatest impact if remedied. This is a helpful technique to determine where to start maintenance activities.

Pareto diagrams are helpful to decision-makers in focusing only on a small number of critical items for major impact. It is used to establish priorities in showing where the critical points are within a system. Brownstein (1980) discusses the benefits of a Pareto analysis and states that it solves problems efficiently by hierarchisation according to importance. It shows where the focus efforts are needed, setting priorities for applications of process improvement efforts. A simple example follows.

Example:

The application of a Pareto analysis is illustrated by analyzing the complaints among staff in the mining industry. Table 3.11 shows an anonymous data collection for this analysis. The collected data is sorted from most to least complaints in order to calculate the cumulative frequency percentages. The Pareto graph in Figure 3.15 presents a graphical illustration of the information in Table 3.11.

Table 3.11: Pareto Analysis Example Calculations

.

No	Complaint category	Number of complaints	Relative frequency	Cumulated Frequency
1	Work orders not done	235	47.67%	47.67%
2	Lack of information flow	165	33.47%	81.14%
3	Unskilled personnel	40	8.11%	89.25%
4	Too many unnecessary formalities	29	5.88%	95.13%
5	Not adhering to time tables	16	3.25%	98.38%
6	Other	8	1.62%	100.00%
	Total	493		

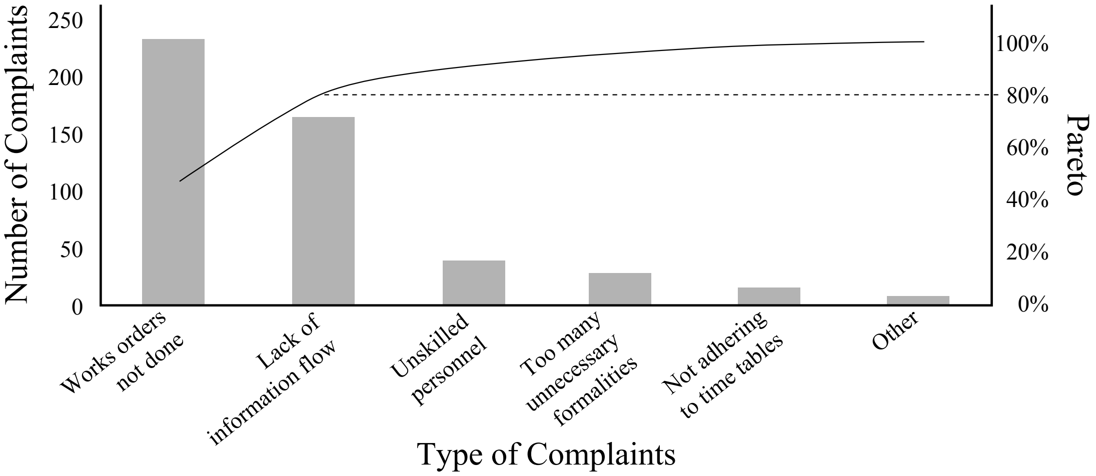


Figure 3.15: Example: Pareto Graph

From the results it is clear what the main complaints are "Works orders not done" and "Lack of information flow", which are about 80% of the total complaints. Therefore the improvement focus are placed on these aspects rather than the lower intensity complaint categories. Consequently, by addressing only these two aspects most of the complaints will be resolved. Once these two are resolved another analysis can be done in order to identify the next critical categories.

3.8 Simplicity

Numerical decision making techniques, as explained in this chapter, are not used due to the complexity thereof. People tend to move away from these tools and rather base decisions on experience and judgement. The purpose of this study is to combine numerical techniques in a manner that it is easy to use and not complex. Thus combining these tools in a simplistic manner with the aim that it is usable on an operational level to support the decision making process. In order to accomplish this the term *simplicity* needs to be understood completely. *Simplicity* is defined by OED (2007) as

"the quality or condition of being easy to understand or do"
or
"the quality or condition of being plain or uncomplicated in form of design."

Following this, simplicity results in easier mannerism and not needing to encounter unnecessary struggle. It can also be stated that simplification creates freedom from complexity. Nowadays, everything is being automated and simplified, from machinery in a production system to every day activities such as mobile phone banking. The reason for this is to minimize the effort to accomplish every day tasks, using minimal energy and achieving maximum function. Porter (2007) states that people tend to value simple things for the reason that it enables one to do what is needed easily and quickly. For the same reason Karvonen (2000) considers simplicity to be the key for success on various aspects. The understanding of simplicity is merged with the toolbox development idea, Figure 3.16 illustrates the conceptualization.

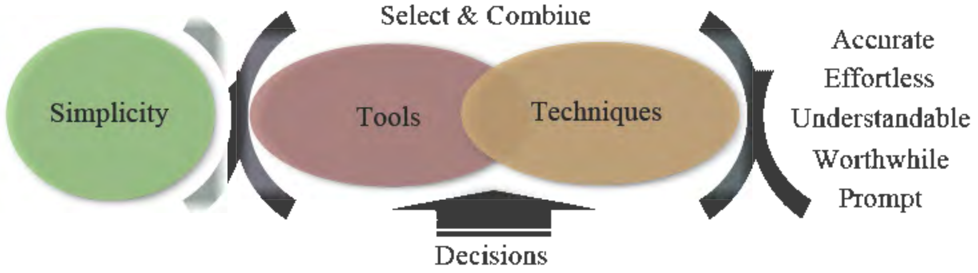


Figure 3.16: Simplistic Toolbox Development Conceptualization

It is shown that *simplicity* is the driving force for the development of a PAM decision making toolbox. This is because currently numerical techniques are not used, mainly because of it's complexity. When considering different techniques to combine, keeping in mind simplicity, various toolbox characteristics should be satisfied. A simplified numerical decision making toolbox for PAM related decisions is required to support the decision making process on an operational level. This toolbox should be quick and easy to use without requiring too much effort and should not confuse the decision maker. It should provide prompt and accurate results to make the use of the toolbox worthwhile. In order to select appropriate techniques for the toolbox development these toolbox characteristics can be used as a guideline.

3.9 Chapter 3 Concluding Remarks

The techniques discussed in this chapter are all relevant to the selected set of decisions from Chapter 2. With the discussion of statistical failure analysis it is clear that one has to be comfortable with the complex mathematical calculations and understand the principle behind basic statistics and reliability theory. Thus, in order to effectively use these techniques to support decision making, someone with the necessary knowledge, an engineer for example, is required to combine the numerical calculation with the practical relevance. This defeats the purpose of easy and effective decision making on operational level. It was also confirmed by practitioners that this type of statistical analysis is not used to support operational decision making. Some operational practitioners confessed that they have no knowledge of this type of decision support.

Another decision support category, MCDM, was discussed. Most of these techniques combine quantitative rating with qualitative reasoning. Although complex mathematical calculations are involved, these techniques can be understood on an easier level than statistical failure analysis. Some of these techniques also tend to be very time consuming and requires discussion. In order to effectively apply these techniques the decision maker should be familiar with the operations of the system it is applied to.

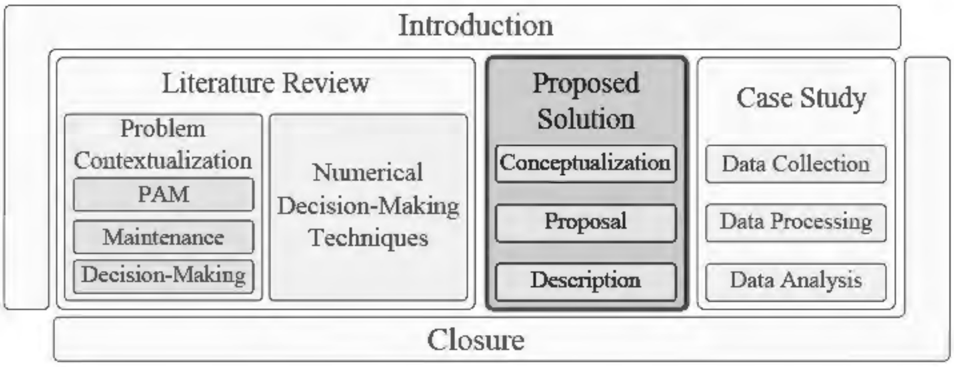
The term *simplicity* is briefly discussed in this chapter to contextualize the idea of developing a simplified numerical decision making toolbox for PAM decisions. The reason for this is to provide guidance in selecting the most appropriate techniques that satisfied the required characteristics.

In the next chapter the techniques are evaluated to identify those that are most appropriate and can be combined to develop a simplified PAM decision making toolbox. With this evaluation, *simplicity* is of high importance. The reason for this is that the key research question, in Chapter 1 (pg. 17), states the need for a decision making toolbox that can be presented and used in a simple and understandable manner.

Chapter 4

PAM Decision Making Toolbox

An understanding of PAM, OE and maintenance was obtained with the literature review presented in the previous chapters. The main areas of influence, with relevance to this study, were discussed together with typical decision making in these areas. A few available best practice numerical decision making techniques were explained. The understanding around the term *simplicity* and decision making was highlighted to conceptualize the development of a simplified PAM decision making toolbox.



In this chapter the research from the previous chapters is used to develop a simplified decision making toolbox with the aim to improve the maintenance decision making on an operational level. The techniques discussed in Chapter 3 are evaluated for the different phases in order to identify the most appropriate techniques. An extensive description of a proposed solution is presented.

4.1 Toolbox Conceptualization

The decisions selected for the toolbox development, presented in Chapter 2, are mentioned again for convenience:

- What assets should be maintained?
- Which asset should be maintained first?
- What failure causes the need for maintenance?
- Which failures should be treated first?
- What type of maintenance should be done?
- How urgent are the required maintenance actions?

These questions are used to formulate three objectives as a guideline to develop a simplified PAM decision making toolbox:

1. Identify assets critical to operations that require immediate maintenance.
2. Prioritize the failure modes of each critical asset to address these modes in order of importance/impact.
3. Select the most appropriate maintenance tactic for each failure mode.

These objectives are organized in chronological order to create three toolbox phases: *Identify*, *Prioritize* and *Maintain*. These phases can follow iteratively and thus a continuous cycle is created, as shown in Figure 4.1.

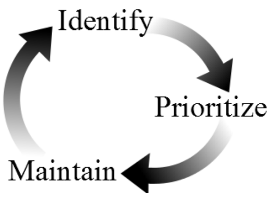


Figure 4.1: PAM decision making Toolbox Phases

The first phase, *Identify*, is the critical asset identification phase in which the critical assets of a system are identified. The reason for this is to highlight the critical focus point. These assets are analyzed and prioritized to identify which should be addressed first and how urgent the responses should be. The second phase, *Prioritize*, is where the failure modes of each critical asset are investigated further and prioritized according to importance. Lastly, in the third phase, *Maintain*, the most appropriate maintenance tactic is selected for each failure mode. As the failure modes are maintained, in the prioritized order, other assets in the system will become critical and thus this cycle should be repeated continuously.

For the purpose of convenience the key research question, presented in Chapter 1 (pg. 17), is shown below.

> *Is it possible to combine different numerical decision making techniques to assist complex PAM decisions-making and be presented in a simple and understandable manner?*

Furthermore, as understood by the term *simplicity*, in Chapter 3, the toolbox must be easy to understand and be uncomplicated. Therefore, the characteristics of the toolbox should be uncomplicated to use, easily understandable, effortless and it should be a relatively quick procedure. Anyone, with the necessary knowledge about the assets and operations, should be able to use it without a struggle or being confused. Eventually it should provide valuable support to the decision making process and achieving effective maintenance on assets. In the next section the techniques found in literature are evaluated. The evaluation is done based on various interviews with people in practice as well as application tests of the techniques. This is done to identify the most appropriate techniques that can be combined to fulfil the toolbox characteristics.

4.2 Decision Making Techniques Selection

Following from the key research question, the purpose of the toolbox development is to combine useful PAM decision making techniques in a simplified manner. Anyone with the necessary knowledge of the operations should be able to use it without it being a complex and time consuming procedure. The techniques considered for the toolbox development should be selected carefully, keeping in mind the required characteristics.

Each phase of the toolbox should be considered individually to select appropriate techniques. This is because the contribution of each phase to the final decision is on a different level. The *Identify* phase needs a technique that analyzes the core assets of an entire system on the highest level. The *Prioritize* phase is a more detailed analysis, investigating each individual failure mode of each critical asset. For this a simple and quick technique is required that takes into account multiple factors that are crucial to the operation. Finally, for the *Maintain* phase different maintenance tactics should be considered for each failure mode, finding the most appropriate tactic for each mode and should also be a quick and accurate procedure. In the sections to follow the techniques explained in Chapter 3 are considered for the different toolbox phases.

4.2.1 Considering Techniques for Critical Asset Identification

The critical assets of a system need to be addressed as soon as possible in order to avoid failures and to maintain effective operations. According to Smith (2009) critical equipment can be defined as the equipment whose failure has the highest potential impact on the business goals of the company. The risk of failure and production losses should be reduced by making these critical assets more reliable. Therefore, when planning maintenance activities, the critical assets need to be identified and prioritized in order to know which asset requires attention before other.

A technique is required that can be used to understand the entire system, analyzing its core assets. It is necessary to analyze the system on the highest level, identifying the critical assets of the entire system. The maintenance of these assets contributes greatly to the effectiveness of system operations. Table 4.1 compares the different techniques in accordance with the requirements of the *Identify* phase. A discussion of Table 4.1 follows below.

Critical assets can be identified by use of the Weibull analysis, Log-Linear Model or the Power Law Model. These methods use reliability theory to predict when the next failure can be expected and thus the asset with the shortest time to the expected failure is classified as most critical. Although accurate predictions are obtained, these techniques are either suitable for non-repairable or repairable systems, as aforementioned. To determine whether a system is repairable or non-repairable detailed past failure data is required and thus a thorough failure data analysis is necessary. This increases the complexity and timeliness of using these techniques. Even though a cost factor can be added with further statistical analysis, the technique itself, as explained in Chapter 3, only considers the failure event probability and not the associated costs.

Table 4.1: Technique Comparison for *Identify*

	Toolbox Characteristics in context of *Identify*								
Technique	Easy to Use	Easy to Understand	Easy to Implement	Not Complex	Not Time Consuming	Effortless	Minimum historical Data Requirements	Consistent	Analyze Entire System
Weibull Analysis								x	x
Log Linear Model								x	x
Power Law Model								x	x
SMART	x	x	x	x	x	x	x	x	
TOPSIS	x	x	x	x	x	x	x	x	
AHP	x	x	x	x	x	x	x	x	x
Qualitative Criticality Analysis	x	x	x	x			x		x
Quantitative Criticality Analysis	x	x	x	x					x
FMEA	x	x	x	x			x		x
Pareto Analysis	x	x	x	x	x	x	x	x	

An alternative is criticality analysis. This technique is well-known and has been used for many years for this purpose. It involves discussion and judgement to complete such an analysis, and therefore might become very time consuming. This process can also easily become inconsistent due to the fact that it involves agreement on circulating opinions and there is no consistency measure or confidence interval.

An applicable technique for identifying the critical assets is AHP. It is a structured technique that calculates an overall weight for each alternative by which a priority hierarchy of the core assets in the system can be created.

AHP is selected for the reason that it aims to quantify relative priorities for a given set of alternatives. A pairwise comparison is done on a ratio scale, 1 to 9, and is based on the decision-maker's judgement. This technique also measures the consistency of the decision-maker, indicating whether the result can be considered as accurate or not. One of the strengths of this method, mentioned by Palcic & Lalic (2009), is that it organizes intangible and tangible factors in a systematic way, providing a structured and simple solution. It takes into account the system as a whole and breaks it down to find a logical solution. It is especially suitable to find the best alternative with multiple criteria involved. This analysis can be applied on all the core assets of the system. It can also be applied to smaller sections, depending on the areas of assessment.

SMART and TOPSIS can also be alternatives for the selection of critical assets. However, these techniques are designed to be used in a more specific manner in terms of assessing individual components, failure modes or maintenance tactics.

An expansion of AHP, Tactical Analytical Hierarchy Process for Prioritization (TAHPP), is explained in Section 4.3.1 which is the selected technique for this phase. It creates a systematic hierarchy to understand the system as a whole and identifying critical assets on a high level. It also provides an asset priority for each criterion involved in the identification. Finally a criticality value is calculated for each asset which is used identify and prioritize the critical assets. The next section evaluates the discussed techniques for the *Prioritize* phase.

4.2.2 Considering Techniques for the Failure Mode Prioritization

The second phase requires a technique that takes into account specific data inputs of each failure mode, assessing each mode individually in order to prioritize it according to given criteria. The techniques are compared in Table 4.2 in accordance with the requirements of the *Prioritize* phase and discussed below.

Table 4.2: Technique Comparison for *Prioritize*

	Toolbox Characteristics in context of *Prioritize*									
Technique	Easy to Use	Easy to Understand	Easy to Implement	Not Complex	Not Time Consuming	Effortless	Minimum historical Data Requirements	Consistent	Analyze Individual Failure Modes	Adapt Criteria Description
Weibull Analysis								x	x	
Log Linear Model								x	x	
Power Law Model								x	x	
SMART	x	x	x	x	x	x	x	x	x	x
TOPSIS	x	x	x	x	x	x	x	x	x	
AHP	x	x	x				x	x		
Qualitative Criticality Analysis	x	x	x	x			x		x	
Quantitative Criticality Analysis	x	x	x	x					x	
FMEA	x	x	x	x			x		x	
Pareto Analysis	x	x	x	x	x	x	x	x		

Reliability theory, Weibull analysis or NHPPs can be used for the prioritization of failure modes. However, since this phase involves the prioritization of each individual failure mode the procedure can become increasingly time consuming and complex. Another difficulty is to collect relevant historical data for each of the failure modes in order to execute these analyses. Due to similar complexity reasons, the AHP is also not a good option for this phase.

Another alternative is the well-known FMEA which is specifically designed for this type of prioritizing analysis. Nevertheless, FMEA is considered to be very time consuming. Another downside to this technique is the fact that a general rating of severity, detection and occurrence is given for each failure mode. These rates are based on discussion and group judgement, as explained in Section 3.6 and might lead to results that are inconsistent, over or under rated.

The technique that is suitable for this phase is SMART. It enables the decision-maker to rate the alternatives according to multiple criteria. The rates are used to calculate a final priority value for each alternative. This priority value is then used for the prioritization of the failure modes. SMART also provides the opportunity of adjusting selected criteria to fit each failure mode's individual data inputs. Thus, prioritizing the failure modes based on its' capabilities and not only relative to general criteria.

SMART is one of the simplest MCDM techniques and is a relatively quick and easy analysis that provides meaningful outcomes. An asset can have a large amount of different failure modes and thus if an asset is identified as critical all of the failure modes need to be assessed to obtain accurate prioritization.

Further explanation of SMART in the context of the toolbox development is provided in Section 4.3.2. The technique evaluation for the last phase, *Maintain* follows in the next section.

4.2.3 Considering Techniques for the Maintenance Tactic Selection

The last phase requires a technique that weighs the different maintenance tactics against each other, according to specific criteria. It should be a simple and easy technique because it is also used for each prioritized failure mode. In Table 4.3 the techniques are compared in accordance with the *Maintain* requirements.

Table 4.3: Technique Comparison for *Maintain*

	Toolbox Characteristics in context of *Maintain*								
Technique	Easy to Use	Easy to Understand	Easy to Implement	Not Complex	Not Time Consuming	Effortless	Minimum historical Data Requirements	Consistent	Analyze Individual Failure Modes
Weibull Analysis								x	x
Log Linear Model								x	x
Power Law Model								x	x
SMART	x	x	x	x		x	x	x	x
TOPSIS	x	x	x	x	x	x	x	x	x
AHP	x	x	x				x	x	
Qualitative Criticality Analysis	x	x	x	x			x		x
Quantitative Criticality Analysis	x	x	x	x					x
FMEA	x	x	x	x			x		x
Pareto Analysis	x	x	x	x	x	x	x	x	

The technique that fulfils all the requirements of this phase is TOPSIS. It is an easy and quick rating technique that identifies the alternative closest to the ideal and furthest from the negative ideal. Evidently, the best maintenance tactic can be selected for each failure mode. Zeydan & Çolpan (2009) mention that TOPSIS is easy to understand, use and implement and yields reliable results. In the context of the toolbox, TOPSIS is further explained in Section 4.3.3.

4.2.4 Concluding Technique Selection

All three techniques selected for the toolbox development, TAHPP, SMART and TOPSIS, are based on MCDM. Pareto analysis is included as an additional technique. The Pareto analysis is used to determine the urgency of the critical assets and failure modes.

Assets that are prioritized as non-critical require an in depth investigation on its' failure modes. This is possible because no immediate attention is required. For this Root Cause Analysis (RCA) is included, providing a medium to long term investigation on the failure modes of non-critical assets.

Assets that are prioritized to be neither critical nor non-critical but in between should also need a prompt solution because there is a high possibility that these assets will become critical sooner rather than later. However, due to the fact that these assets are not as critical a decision was made to find a temporary solution. This way an accurate and quick solution can be obtained which is used until the most critical assets are eliminated. A Quick Tactic Selection (QTS) grid is derived from knowledge gained through literature. This guides the decision maker to find a temporary solution to the assets that are not identified as critical but are more critical than the "non-critical" assets. Further elaboration on the QTS follows in Section 4.3.3.1.

The two additional techniques, RCA and QTS, are not on an operational level, and is rather a medium to long term solution for the assets not identified as critical. For this reason, it falls beyond the scope of this study and the explanation of these techniques is limited.

The combination of selected techniques, TAHPP, SMART, TOPSIS and Patero propose a toolbox that delivers results, obtained numerically. These results are used to support the decision making process in PAM, specifically in the maintenance environment. The application of the proposed toolbox can be completed by just following a few basic and uncomplicated steps resulting in value assistance for a decision making process. The following section serves as an introduction to the proposed solution.

4.3 Toolbox Proposal

Marović (2010) discussed the fact that decision making in practice has become more complex which highlighted the need for new methods. Assistance is required due to the fact that the majority of business decisions are made in situations with multiple conflicting criteria. The incapability of single-criterion techniques are also brought to light with the acknowledged conflict quality of multiple criteria in maintenance related decision making. In this section the techniques selected for the toolbox phases are combined.

The first technique, TAHPP, prioritizes the critical assets by categorizing the assets into one of three priority groups. The criticality of the assets are plotted on a criticality grid, graphically showing the categorization of either an A-, B- or C-priority category. For each of these categories different strategies are used to further analyze the assets' failure modes.

A Pareto analysis is applied on the criticality of the assets to determine the urgency of the required actions. Figure 4.2 graphically explains the concept of the toolbox.

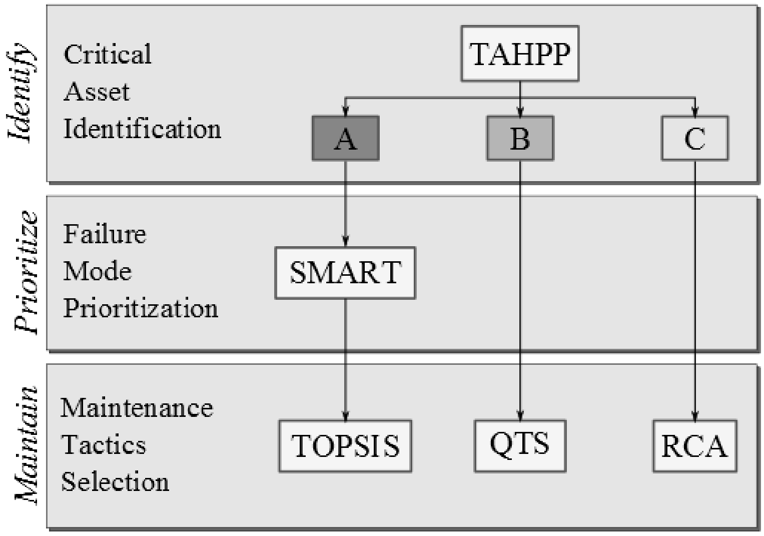


Figure 4.2: PAM Toolbox Concept

Assets with a C-priority are labeled as non-critical and thus a long term investigation is proposed to identify the root causes of the failures. For this a RCA is required to find the possible root causes for the failures of these assets. A further extensive investigation is then required to resolve the problems. Assets with a B-priority is of moderate importance, for this reason it was decided to do a QTS. This only serves as a temporary solution with the aim to keep it in working order until the majority of the criticality is addressed.

The most critical assets, A-priority, need immediate attention. An extensive investigation into its' failure modes is required to obtain valuable results. An assessment is executed to identify and prioritize all the possible failure modes as quick and accurately as possible. As aforementioned, the technique selected for this is SMART, as SMART is a quick and effective MCDM method. Even though the number of possible failure modes of an asset or a set of assets can become very large, SMART can be used to obtain accurate results in a relatively short time. The failure modes are also plotted on a priority grid to visually categorize the asset priorities. Furthermore, a Pareto analysis is also applied to determine the urgency of the actions to executed. Finally, in brief again, an appropriate maintenance tactic is selected for each of the failure modes by the use of TOPSIS. Figure 4.3 shows the combination of the selected techniques, proposing the PAM decision making toolbox.

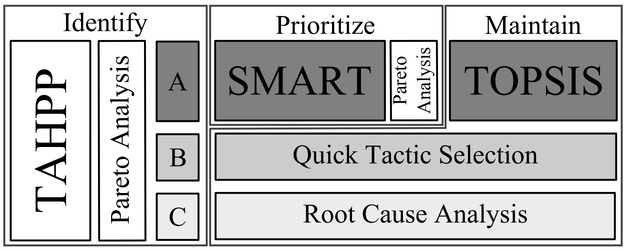


Figure 4.3: PAM Decision Making Toolbox Technique Combination

The aim is to continuously strive for OE with the use of PAM initiatives. By focussing on the maintenance aspects, an adequate combination of best practice techniques are developed and simplified in such a way that it is easy useable and understandable with the objective to enable optimal decision making at an operational level with low complexity and high value.

4.3.1 Critical Asset Identification

When identifying the critical assets various factors should be taken into account, mainly to determine the impact of an asset with regards to the system effectiveness. The impact of an asset is considered by means of consequence if the asset should fail. Such factors are typically the impact of the asset on production, safety, maintenance costs, system reliability, related risks and many more. These factors are weighed against each other in terms of a given rating scale, in accordance with failure occurrence consequences.

From the AHP, as discussed in Chapter 3, a tactical prioritization method evolves, namely TAHPP. It ultimately creates a priority hierarchy of assets according to relevant criteria. Due to the simplicity factor in the development of this toolbox, the critical asset analysis is formulated in a manner that requires minimal input. The following data is required for each asset in order to apply TAHPP:

- the current MTBF of the asset,
- the current Mean Time To Repair (MTTR) of the asset,
- the time since last event, and also
- the average maintenance cost of the asset.

The MTBF, MTTR and average maintenance costs are calculated from past failure data. The last event time is simply the time elapsed since the last maintenance or repair was done on the asset. The criteria used for the identification consists of two categories; the *consequences* of a failure occurrence and the *probability* that a failure will occur.

1. The *consequence* of failure occurrence has three elements:
    - maintenance cost,
    - safety impact and
    - production impact.
2. Whereas the *probability* of occurrence only has two elements:
    - MTBF and
    - last event.

If there are five assets included in the analysis, the TAHPP structure for these criteria elements is shown in Figure 4.4. The two criteria categories, *Failure Probability* and *Failure Consequence*, have an equal contribution to the identification of critical assets. Therefore both categories have a weight of 0.5. Furthermore, the consequence criteria are compared according to relative importance in order to determine the weight for each. This weighting of criteria is only required with the setup of the TAHPP and remains constant until changes need to be done.

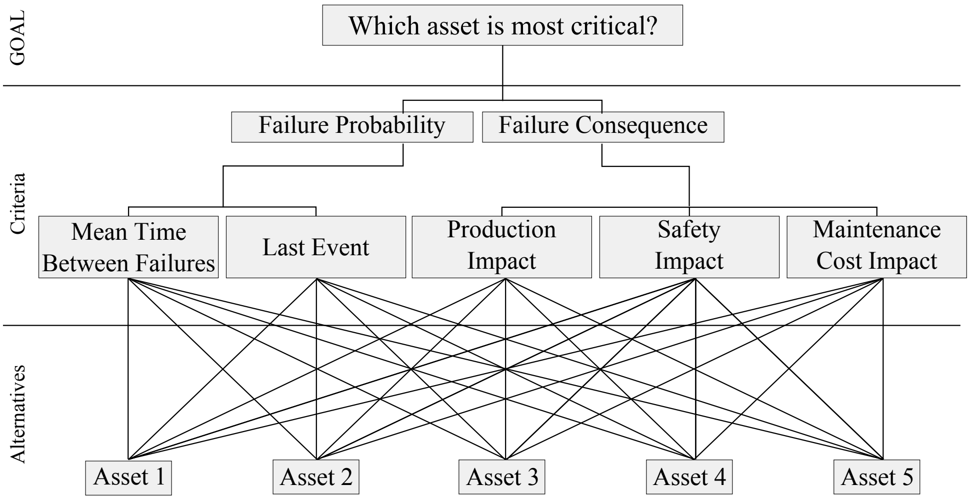


Figure 4.4: Analytical Hierarchy Structure for Identifying Critical Assets

The asset comparison is compulsory for each criterion involved, as explained with the AHP example in Section 3.4.3. This comparison is done each time critical assets need to be identified. The reason for this is that as critical assets are treated the conditions change and other assets can become critical. The rest of the calculations are completed according to the explanation in Section 3.4.3. Ultimately the final criticality value is calculated for each asset. The criticality results are plotted, consequence against probability, on a criticality grid. The risk matrix, as presented in Chapter 2 (pg. 37) are used for the criticality grid. The positional constant risk is used for the priority borders and only three different priority areas, A, B and C are identified, as shown in Figure 4.5.

The criticality value of each asset is plotted on this grid to visually prioritize the assets according to the different priority categories. Assets with a C-priority are of lowest priority and classified as non-critical assets. for these assets a root cause analysis is suggested. Furthermore, an extensive investigation on the identified root causes are required to thoroughly assess and eliminate the possibility of failure.

A quick maintenance tactic selection is used for assets with a B-priority which is explained in Section 4.3.3.1. The purpose of this QTS is to identify a temporary solution for immediate action to keep the assets in working order until the A-criticality assets are eliminated. Assets with an A-criticality need to be acted on as soon as possible and as accurately as possible. For this reason a full failure mode investigation is

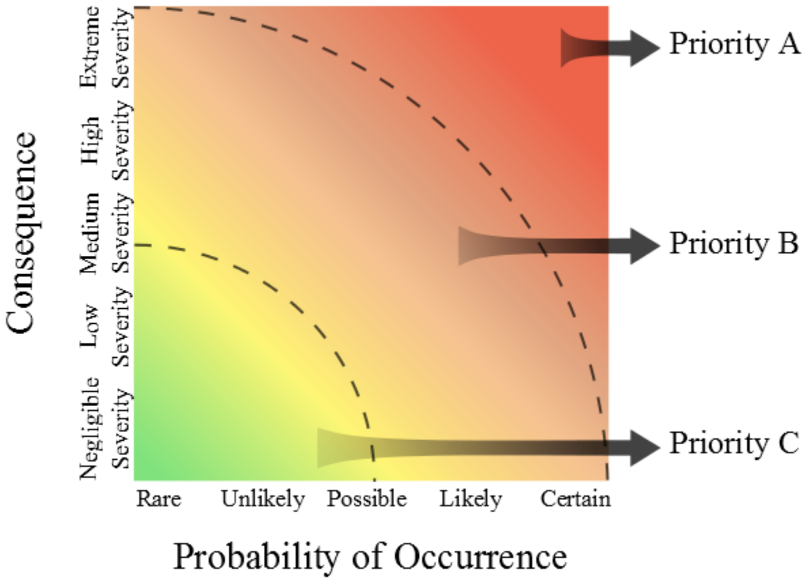


Figure 4.5: Criticality Grid for Prioritizing Assets

done to prioritize the failure modes of these assets and ultimately selecting the most appropriate maintenance tactic for each failure mode.

Once the assets' criticality is known, the next step is to determine how urgent these critical assets should be addressed. A Pareto diagram is used to arrange the asset criticality, as illustrated in example Figure 4.6. Moreover, for example if 80% of the criticality is due to 60% of the assets, it will be much more urgent than when 80% of the criticality is due to only 20% of the assets.

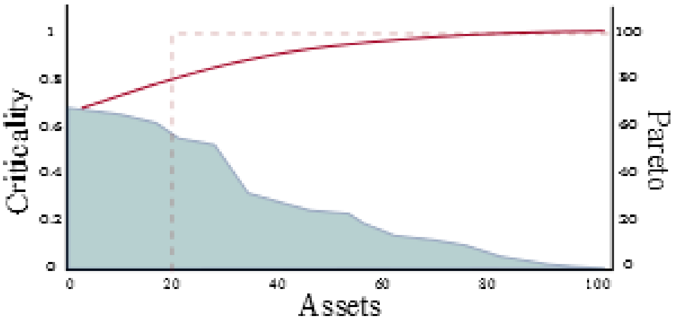


Figure 4.6: Pareto Chart of Equipment Criticality

Once the urgency is determined, it is necessary to investigate the failure modes of the identified critical and urgent assets. The reason for this is to plan maintenance activities in order of preference.

4.3.2 Failure Mode Prioritization

The prioritization of failure modes is done with the use of an analysis similar to SMART. For this analysis the same criteria and its weights used in TAHPP are used for this prioritization as well. However, quantitative values are generated for the criteria description of each failure mode. The input data required is also similar to the input data of the *Identify* phase. This data is used to derive the quantitative criteria descriptions:

- the current MTBF of the specific failure mode,
- the targeted MTTR for the specific failure mode,
- the time since last event, and also
- the average maintenance cost of the failure mode.

Similarly, as done before in the *Identify* phase, MTBF, MTTR and average maintenance costs are calculated from past failure data. The last event time is simply the time elapsed since the last occurrence of the specific failure mode. Again the criteria consists of two categories; the *consequences* of a failure mode occurrence and the *probability* that a failure mode will occur.

The ***Consequence of failure occurrence*** has three rating elements which are used to calculate the Failure Consequence Factor (FCF):

1. maintenance cost,
2. safety impact, and
3. production impact.

These elements are each rated by a value between one and ten, which is used to determine the FCF.

$$\text{FCF} = \sum_{i=1}^{k} w_i R_i \tag{4.1}$$

With the notation as follows

$w_i =$ the weight of the i^{th} criterion,

$R_i =$ the value rated for the i^{th} criterion and

$i =$ $1, 2, 3, ...k$

The rating is done according to the criteria generated for each failure mode. A thorough explanation for the criteria description generation follows.

1. Maintenance Cost Impact

The average maintenance cost input is used to calculate numerical description for the criteria. The worst case scenario, with a rate of 10, is when the maintenance cost is double or more than the average maintenance cost. The best case scenario, with a rate of 1, will be when the cost is a tenth or less of the average maintenance cost. Hence, the quantitative criterion description can be calculated with the following equation:

$$\text{Criterion Value} = 0.2 I r_i$$

The notation description is as follows:

$I =$ the average maintenance cost of the asset,

$r_i =$ the rating for the i^{th} criterion and

$i =$ $1, 2, 3, ..., 6,\ r = 1, 2, 4, ..., 10$

This value is then used to compare the average repair cost of the asset, if the average repair cost is greater than the i^{th} criterion value, but less than the $(i+1)^{\text{th}}$ criterion value, the i^{th} criterion rating will be applicable. The rating criteria for maintenance cost is shown in Table 4.4.

Table 4.4: Criticality Ranking of Maintenance Cost Impact

Criterion	Maintenance Cost Impact	Rating
1	Negligible total cost of maintenance	1
2	Low total cost of maintenance	2
3	Average total cost of maintenance	4
4	Above average total cost of maintenance	6
5	High total cost of maintenance	8
6	Very high total cost of maintenance	10

2. Safety Impact

The criteria description of the safety impact emerged from best practices found in literature and is shown in Table 4.5.

Table 4.5: Criticality Ranking of Safety Impact

Safety Impact	Rating
Negligible effect on safety & health performances	1
Exposure to minor health risk (first aid)	2
Exposure to major health risk (medical treatment)	4
Reversible impact on health (lost time injury)	6
Irreversible impact on health (fatality or lost of life quality)	8
Impact on health ultimately fata (multiple fatalities)	10

3. Production Impact

The qualitative descriptions for the criteria is shown in Table 4.6.

Table 4.6: Criticality Ranking of Production Impact

Criterion	Production Impact	Rating
1	Production aware of problem, negligible effect	1
2	Operation limited, minor effect	2
3	Operation limited, production restrictions	4
4	Operation limited, significant impact	6
5	No production, large impact	8
6	No production, major impact	10

A quantitative criterion description for impact on production is derived by using the MTTR. The worst case scenario, with a rate of 10, is when the repair time takes about three times as long as the MTTR, resulting in no production for some time. Whereas, the best case scenario, with a rate of 1, is when production is only aware of the problem but it does not influence the system production. Hence, the quantitative criteria description is calculated as follows:

$$\begin{aligned}
\text{Criterion 1} &= \text{Production is aware of problem}\\
\text{Criterion 2} &= \text{Limited operation for} < \text{MTTR hours}\\
\text{Criterion 3} &= \text{Limited operation for} < \text{MTTR x 2 hours}\\
\text{Criterion 4} &= \text{Limited operation for} < \text{MTTR x 3 hours}\\
\text{Criterion 5} &= \text{No production for} < \text{MTTR x 3 hours}\\
\text{Criterion 6} &= \text{No production for} > \text{MTTR x 3 hours}
\end{aligned}$$

The ***Probability of failure occurrence*** uses only two elements to calculate the Failure Probability Factor (FPF):

1. MTBF and
2. last event.

The FPF is calculated as follows:

$$\text{FPF} = \begin{cases} 9 & \text{MTBF} < \text{Last Event} \\ 10\left(1 - \frac{\text{MTBF}-\text{Last repair done}}{\text{MTBF}}\right) & \text{otherwise} \end{cases} \tag{4.2}$$

The final priority value calculation of each failure mode is:

$$\text{Priority Value} = \text{FCF x FPF} \tag{4.3}$$

The priority value results are also plotted, consequence against probability for visual prioritization. A Pareto analysis, similar to the critical asset denitrification, is also executed to determine the urgency of these failure modes.

4.3.3 Maintenance Tactics Selection

By using TOPSIS an appropriate maintenance tactic is selected for each failure mode. This is done in order of preference obtained with SMART. There are four different maintenance tactics that are considered:

- Corrective Maintenance
- Preventive Maintenance
- Predictive Maintenance

- Design-out Maintenance

Certain tactics are better for certain failure modes, therefore, the following criteria are used to analyze the applicability of these tactics:

- Damage to asset or asset condition after maintenance,
- Production loss or time to maintain, and
- Maintenance related costs

The aim is thus to minimize each of these with the execution of the selected maintenance tactic. The criteria is described in Tables 4.7a, 4.7b and 4.7c.

Table 4.7: TOPSIS Criteria

(a) Asset Condition

Rate	Description
0	Irreversible damage to asset, asset has to be replaced (Scrap)
2	Severe damage to asset, irreversible but do not have to replace asset (Worse-than-Old (WO))
4	Reversible damage to asset, has influence on asset productivity (Bad-As-Old (BAO))
6	Moderate damage to asset, can easily be repaired (Better-than-Old-Worse-than-New (BOWN))
8	Negligible damage to asset
10	Asset condition improvement (GAN)

(b) Maintenance Time

Rate	Description
0	No production for a relatively long time (Plant Stop)
2	No production for short time (Quick Plant Stop)
4	Severe decreasing production
6	Moderate decreasing production
8	No production loss
10	Increased production

(c) Maintenance Cost

Rate	Description
0	Extremely high maintenance cost
2	High maintenance cost
4	Moderate maintenance cost
6	Low maintenance cost
8	Very low maintenance cost
10	Negligible maintenance cost

After maintenance was done on an asset the asset condition is likely to change to one of four possible conditions; *Good-As-New (*GAN), *Better-than-Old-Worse-than-New (*BOWN), *Bad-As-Old (*BAO) or *Worse-than-Old (*WO). These conditions are taken into account in the TOPSIS criteria.

- *GAN* can be described as a perfect repair because the unit/system has been restored to the equivalent state of a new one.
- *BOWN* is when the condition after maintenance is better than before but still worse than the condition of a new system/unit.

- *BAO* is when minimal maintenance has been done, the operation life is just extended for a small time period, postponing failure.
- *WO* is to leave the unit/system in a worse state than before the maintenance was done.

The rating description is ordered in such a way that all of these criteria needs to be numerically maximized in order to minimize the impact and find the solution closest to the ideal solution. Each alternative is rated according to what the result of that specific maintenance tactic might be. The calculations is done, as explained in the TOPSIS Example in Section 3.4.2. Finally providing the best alternative closest to the ideal for each failure mode.

4.3.3.1 **Quick Tactic Selection** (QTS)

As explained, a quick tactic selection is applied to assets with a B-priority. Maintenance tactics are selected according to the failure behaviour of an asset which can be divided into four categories: *random failure behaviour*, *statistical failure behaviour*, *evident failures* or *hidden failures*. This is illustrated by means of four quadrants in Figure 4.7.

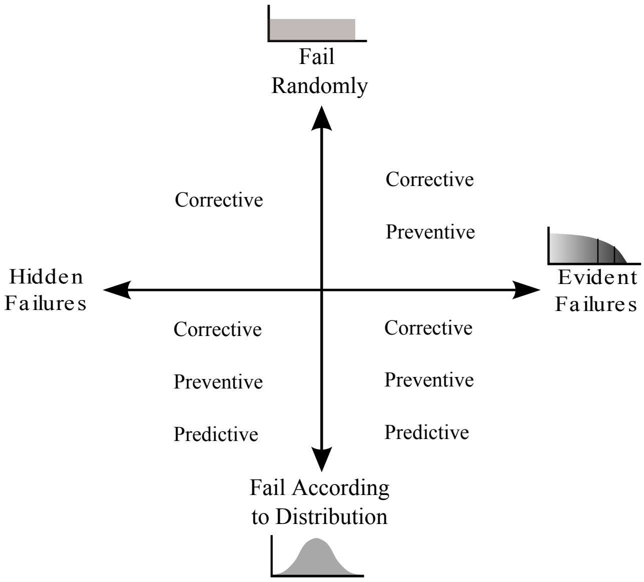


Figure 4.7: Quick Tactic Selection

This grid was developed with knowledge gained through literature and by means of dialogue with practitioners and expert asset managers. The failure occurrences of an asset can occur randomly or according to a defined distribution. The chance of a failure occurrence for an asset with a random failure behaviour remains the same at all times, within a selected time interval. This type of failure behaviour cannot be predicted because the probability of a failure is always the same. For this reason, and to avoid unnecessary maintenance, corrective maintenance is applicable. However, corrective maintenance can sometimes cause damage to assets, depending on the type of failure. Some failures may be more evident than others and are likely to give an indication prior to the occurrence of a failure. For this type of failures PM can be used.

Sometimes an asset's failure occurrence can be defined and characterized according to a specific distribution. This is useful for the prediction of failures and thus PdM is an applicable option for evident or hidden failures. Some failures are likely to give some type of visible warning before a failure occurrence and thus PM can also be used for more evident type of failures. If neither PdM nor PM is an appropriate option for a specific failure type, for economical or timely reasons, corrective maintenance can also be an option.

To apply this QTS, knowledge and experience of the specific assets and its' failure behaviour is required. This can be applied by anyone who regularly works with the asset and knows the behaviour of the asset through experience and have the necessary knowledge. Although this selection is done based on experienced and judgement, this solution is temporary. Eventually, all failure modes of all assets will be analyzed with SMART as they become more critical.

4.3.3.2 Root Cause Analysis

A RCA analysis is done on the assets with a C-priority, the reason for this is to find the root cause of the potential failure occurrences. Due to the fact that these assets are not that critical, extensive attention can be given to the root causes in order to eliminate the failure occurrences. A well known technique used for RCA is the "five whys". The question, "Why?" is simply asked until the root cause is discovered.

The RCA in itself is a relatively quick process to find the root cause. However, the investigation of the root causes in order to eliminate it is a medium to long term process. Thus, this analysis falls beyond the scope of this thesis, it is simply to guide the decision maker and will not further be discussed in more detail.

4.4 Chapter 4 Conclusion

In this chapter the different techniques, discussed in Chapter 3, were evaluated to select the most appropriate technique for each phase of the toolbox. The selected techniques are TAHPP, SMART and TOPSIS for the phases *Identify*, *Prioritize* and *Maintain* respectively. These techniques were combined in chronological order and explained extensively in the context of a PAM decision making toolbox. The three phases are applied consecutively and are repeated to create a cycle as shown in Figure 4.1. The three phases of the toolbox represent three basic steps to follow in order to obtain valuable output.

The aim of the study was to create a simplified numerical approach that can support the decisions selected in Chapter 2 effectively, also mentioned in the beginning of this chapter. The explanation of these techniques was done specifically in the context of the selected set of decisions. However, the calculations presented are still generic and can be applied to any type of operation with the same decision making needs.

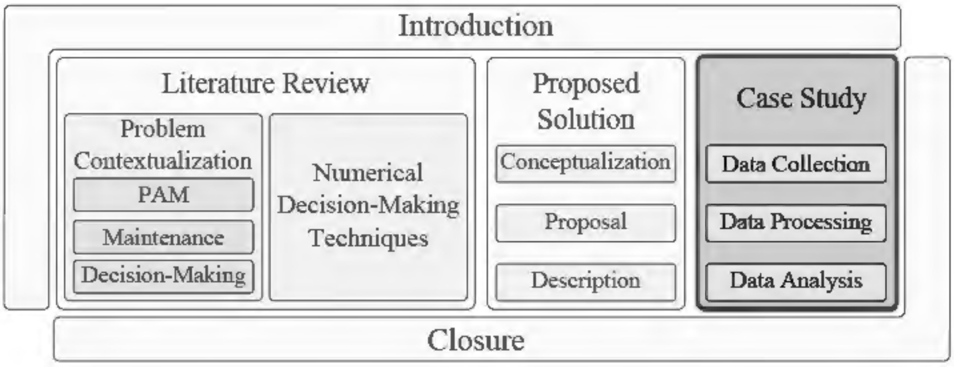
To evaluate and validate this theoretically combined toolbox it should be applied to a real world situation. In order to apply it successfully and fulfill all of the characteristics of the toolbox a user interface is created in Microsoft Excel. Thus, a simple presentation of the technique combination is created which can be used to by practitioners. This interface is not discussed in this document.

In the next chapter the toolbox, as proposed in this chapter, is applied by means of a case study conducted with Amplats.

Chapter 5

Case Study

This chapter comprises of a case study that was conducted in cooperation with Anglo American Platinum Limited (Amplats). The aim of this case study is to assess the validity of the toolbox developed in the previous chapter. An overview of the case study is provided to give background on Amplats and a description of the operation at the participating plant. A discussion on the data gathering process that was completed during a visit to the Amplats plant will also follow. The discussion includes data requirements, data collection as well as the synthesis of the data, as shown in the figure below.



The aim of this chapter is to apply the toolbox to a real world problem to evaluate its practical validity. Each phase is applied systematically and is followed by a discussion of the results obtained.

5.1 Case Study Overview

Amplats is a subsidiary of Anglo American PLC, the British multinational mining company. They are the world's leading platinum producer and accounts for around 40% of the global platinum supply. Amplats operates in the South African "Bushveld Complex" which is located in the Northern Province of South Africa, with their headquarters located in Johannesburg. Various Platinum Group Metals (PGM) are mined such as palladium, rhodium, iridium and osmium. However, platinum is the main product. Rustenburg Platinum Mines Limited is responsible for the smelting and refining operations of Amplats.

One of the Amplats plants was used for assessing and validating the research of this study. The plant covers an area of around 130 square kilometers and completes mining operations using an open-pit truck and shovel method. The mining consists of four open pits and has a life-of-mine plan that extends beyond 2060. The operations of the plant are completely dependent on machinery and physical assets. Thus the performance of these assets are crucial in keeping operations running to achieve organizational targets.

The research study was conducted in collaboration with the Asset Care Research Group (ACRG) which acts as an intermediary to facilitate interactions on PAM related aspects, between industry and research at the University of Stellenbosch. Great support from Anglo American PLC was also received.

During a visit to the selected plant the motivation and need for this study was established. There it was found that the use of numerical decision making tools in practice is rather limited, which confirms the findings in literature. During the visit the ineffectiveness of their maintenance planning process was noted and the applicability of the decisions identified in Section 2.5.2 (pg. 49) was confirmed. This also confirms the applicability of the research study.

In brief again the aim of this case study is to investigate the practical validity of a combined numerical decision making toolbox for making maintenance related decisions effortless and accurately.

5.2 Study Design

While visiting the Amplats plant a series of discussions was held with the plant manager, maintenance planner and other key role players. With the plant manager's knowledge and operational experience, a thorough understanding of the plant was obtained. A specific area of the plant was selected to which the study was applied to. Only the core assets in this area were chosen to be part of the study. The selected assets include the crushers and screens, and exclude the conveyors and milling operations. The flow of operations for the selected area can be seen in Figure 5.1.

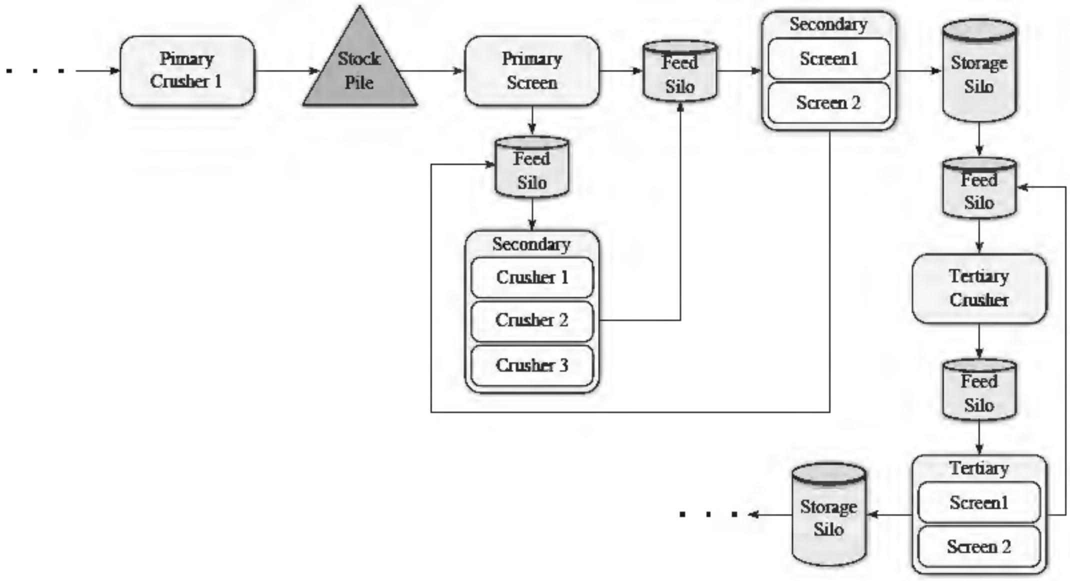


Figure 5.1: Operational Flow of Area Included in the Study

Trucks transport ore, with a size of about 1300mm^2 to 1400mm^2, from the mine pit to the plant. The *Primary Crusher* receives and crushes the ore. After the ore has been crushed by the *Primary Crusher* a conveyor transports it to a stock pile with a capacity of 45000t. The crushed ore is stored on the stockpile and conveyed from there to the *Primary Screen* which separates the bigger ore from the smaller ore. Ore smaller than 80mm^2 is conveyed to the *Secondary Screens* and ore bigger than 80mm^2 is conveyed to the *Secondary Crushers*. The *Secondary Crushers* crushes the ore above 80mm^2 to smaller pieces. The *Secondary Screens* also separates the bigger ore from the smaller ore. If the ore is still too big it is sent back to the *Secondary Crushers* and the crushing is repeated until it is small enough to pass the *Secondary Screens*. The ore should be about 40mm^2 to 50mm^2 to pass through the *Secondary Screens*. The secondary screening operation occurs at a rate of about 1450 tons per hour (tph). After the *Secondary Screens* the ore is stored in a storage silo with a capacity of 15000t. This is followed by the *Tertiary Crushers* where the ore is further crushed into smaller pieces and conveyed to the *Tertiary Screens*. To pass the *Tertiary Screens* the size of the ore should be about 12mm^2 to 25mm^2, otherwise it is sent back to the *Tertiary Crushers* to repeat the crushing until it is small enough. From the *Tertiary Screens* the ore is conveyed to another storage silo with a capacity of 15000t from which the ore is fed to the milling operations at a rate of about 1100tph. From the milling operations onward are excluded for the purposes of this case study.

The toolbox presented in Chapter 4 is applied to the selected area to validate its practical value. The application of the toolbox required different data types for the different phases of the toolbox. The data gathering process is discussed in the next section.

5.3 Data Gathering

Data gathering is a necessary step to validate the practical use of the toolbox. The data needed for this application has certain requirements to comply to in order to be effective.

5.3.1 Data Requirements

In Chapter 2 only a few decisions were identified to develop the decision making toolbox. Similar decisions were identified within the selected area of investigation. Due to the nature of the decisions, the data required for this study is mainly related to past failure, repair and maintenance events. Each phase of the toolbox requires a specific data type.

The *Identify* phase uses TAHPP to analyze the core assets of the system. The data required for this phase is:

- time of asset's failure occurrences,
- duration the failure repairs,
- last time an event (maintenance/repair) occurred, and

- average maintenance or repair cost per asset.

In the *Prioritize* phase, the failure modes are analyzed with SMART. Different failure modes of each asset are required together with:

- time of failure mode occurrences,
- duration the failure mode repairs,
- last time a specific failure mode occurred, and
- average maintenance or repair of each failure mode.

The *Maintain* phase requires expert judgement to rate the influence of each possible maintenance tactic on the asset.

5.3.2 Data Collection

The data collection was enabled by Amplats's electronic data capturing system named PI. This system records vast amounts of data on small increments and historize it for years. It provides readily available data of most operations. Data was collected using increments of 10 minutes for a period of 10 months, August 2011 to June 2012. Because of the large amount of data points, the data was exported and stored in Microsoft Excel files. Data was only collected for the assets included in this study. The data elements obtained from PI for each asset were named:

- Status
- Downtime reason
- Downtime reason commented
- Motor power

From this data the downtime of each asset could be obtained. The *Status* of an asset shows whether it was running or not at the specific time instant. *Motor power* was used to support this. *Downtime reason* and *Downtime reason commented* were used to identify different failure modes, failure times and times to repair.

The data capturing system, PI, eased the data collection process and made it relatively quick. Having such a system and if the required data is identified the data collection can easily and quickly be completed for another study at another plant.

5.3.3 Data Processing

Due to the large amount of data, having 10 minute increments for a period 10 months, the collected data points were processed manually. The data was sorted in a manner that was considered useable, transforming the data into information. In Section 5.2 the flow of operations was discussed and the main assets together with their functions were mentioned. The main crusher and screening assets, in the selected area, are included in the study:

- Primary Crusher
- Primary Screen
- Secondary Crusher 1
- Secondary Crusher 2
- Secondary Crusher 3
- Secondary Screen
- Tertiary Crusher
- Tertiary Screen

The reason for this asset selection is that these assets are crucial to the flow of operation. If one of these assets should be in a non working order, the operations of the working assets are dependent on the storage silo levels and thus the entire operation will come to halt if the silos run empty.

Setting system boundaries is an extremely important part with the processing of data. This is done to identify what specific data points, from the captured data mass, should be included in the calculations. The boundaries were selected to only include direct influences on the assets. For example, if a Secondary Crusher is down due to a conveyor failure, that data will not be included in the calculations for that specific crusher. The boundaries are shown in Appendix A, and are represented in terms of data points that were included and excluded for each asset.

In order to identify these boundaries the data was mainly used from the *Downtime reason* and *Downtime reason commented* elements, mentioned in the previous section. A short summary of the processed data is shown in Table 5.1.

Table 5.1: Asset Data Summary

Asset	MTBF (hours)	MTTR (hours)	Last Event (hours)	Average Maintenance Cost (Rand)
Primary Crusher	194.70	20.55	11.51	R 354 458.65
Primary Screens	328.50	3.48	151.34	R 93 883.65
Secondary Crusher 1	65.37	1.49	143.94	R 488 435.26
Secondary Crusher 2	32.35	2.30	154.40	R 218 711.33
Secondary Crusher 3	33.96	2.50	6.88	R 312 928.80
Secondary Screens	1645.00	1.34	268.39	R 63 787.89
Tertiary Crusher	44.15	3.72	0.51	R 369 328.71

Evidently, all three *Secondary Crushers* and the *Tertiary Crusher* fail much more regularly than the other assets (especially *Secondary Crusher 2* and *Secondary Crusher 3*). However, the time since *Secondary Crusher 2* has a failure is three times its MTBF which means the probability of failure is very high. A possible reason for this occurrence is due to some shortcomings of the MTBF calculation which does only take into account the number of failures and total time elapsed and thus MTBF can be misleading sometimes. Al three *Secondary Crushers* have a relatively short repair time, however the average maintenance cost is rather high. Although the *Primary Crusher* has the largest repair time, it doesn't fail as often but also have a high average maintenance cost. The *Secondary Screens* have the largest MTBF and is repaired the quickest which means that this will not become a focus point for maintenance any time soon. More detail on the processed data is shown in Appendix B.

5.4 Toolbox Application

This section discusses the practical application of the toolbox in the selected area of the Amplats plant. As mentioned earlier, this toolbox is developed for operational purposes and thus the results obtained in this study are in agreement with the collected data.

5.4.1 Critical Asset Identification

As explained previously, the first phase in the toolbox identifies the critical assets in the system. Therefore, the system's core assets are assessed on a higher level with the use of TAHPP (Figure 5.2). After the prioritization of the assets a Pareto analysis

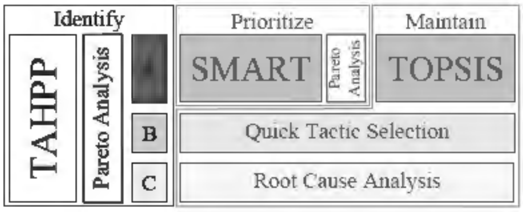


Figure 5.2: Toolbox Application Phase: *Identify*

is done on the asset criticality in order to determine the urgency of the required actions.

The TAHPP structure was developed according to the explanation in Chapter 4. The TAHPP structure for the selected area is shown in Figure 5.3.

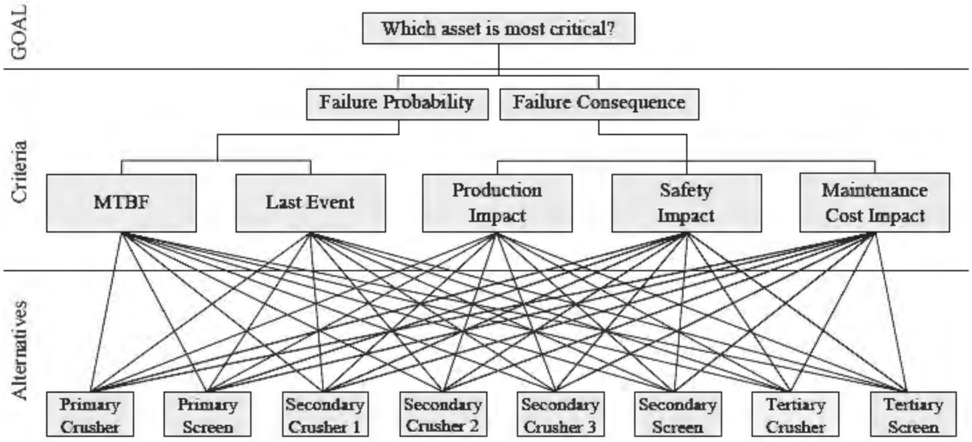


Figure 5.3: TAHPP Structure

The two criteria categories, *Failure Consequence* and *Failure Probability*, are both equally important to the critical asset selection. Therefore, a weight of 0.5 is assigned to each criteria category.

The *Failure Probability* category consists of two criteria, the *MTBF* and the *Last Event*, as explained in Chapter 4. Both of these criteria also have equal contribution in determining the failure probability and a weight of 0.5 is assigned to each.

To determine the weights of the *Failure Consequence* criteria a pairwise comparison is done according to relative importance. This is a once off procedure and might only change when the importance of an attribute changes or if criteria is added or removed, in this case the structure should be set up again. The pairwise comparison of the *Failure Consequence* criteria are shown in Appendix C (Table C.1) and the results are shown below in Table 5.2.

Table 5.2: TAHPP *Failure Consequence* Criteria Weights

Criteria	Weights
Production Impact	0.323
Safety Impact	0.110
Maintenance Cost	0.567

According to the consequence criteria weight results, *Maintenance Cost* is the most important criterion and *Safety Impact* the least important. Since weights are now assigned to all the criteria, the next step is to compare the assets in a pairwise manner which corresponds to the criteria. The pairwise comparisons are shown in Appendix C (Tables C.2 to C.6). The results of the comparisons are used to calculate the asset priorities, as explained in Section 3.4.3 (pg 78). Figure 5.4 shows the asset priorities for each criterion as a result of the pairwise comparison.

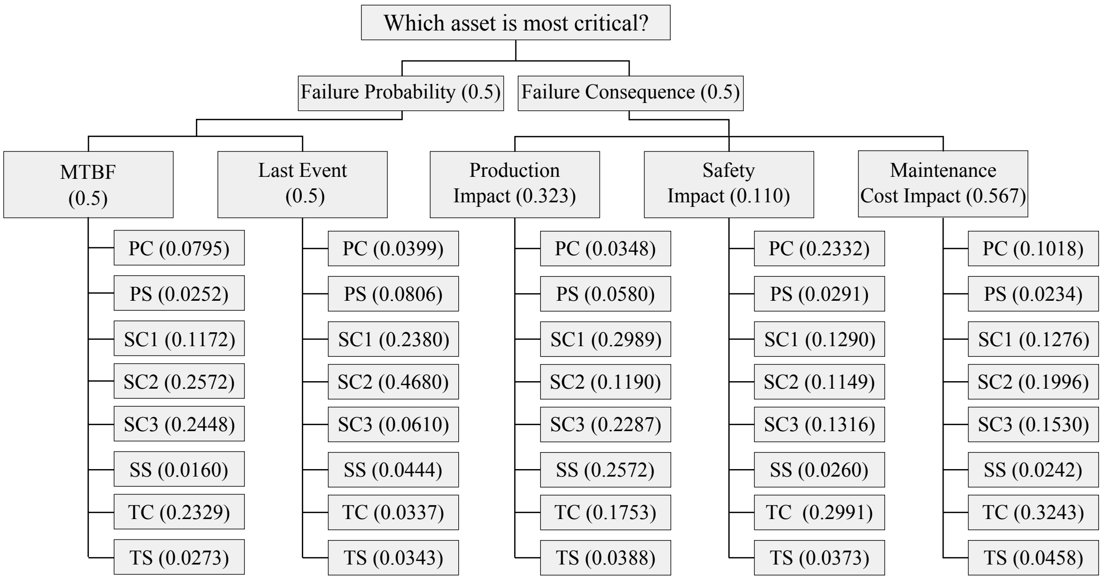


Figure 5.4: Asset Priorities per TAHPP Criterion

These priorities are used to calculate the consequence and probability weights of the assets. This is calculated by use of matrix multiplication, as explained in Section 3.4.3.

The individual priority weights for the consequence impact are presented in Figure 5.5. It is evident that *Secondary Crusher 1* will have the greatest impact on *Production* if it should fail. The *Tertiary Crusher* will have the greatest impact on *Safety* and *Maintenance Cost* is it should fail and thus also has the overall greatest consequence.

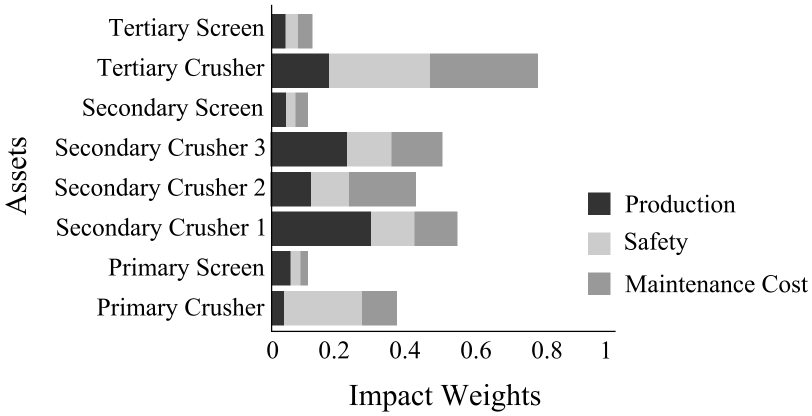


Figure 5.5: TAHPP Individual Consequence Weights

Even though the *Tertiary Crusher* will have the greatest consequence if it should fail and *Secondary Crusher 2* the second greatest, *Secondary Crusher 2* is much more likely to fail than the *Tertiary Crusher* or any other asset. *Secondary Crusher 1* as well as *Secondary Crusher 3* both have a greater failure probability that the *Tertiary Crusher*. Thus when adding the probability weight *Secondary Crusher 2* becomes the most critical asset. Figure 5.6 presents the final consequence and probability weights.

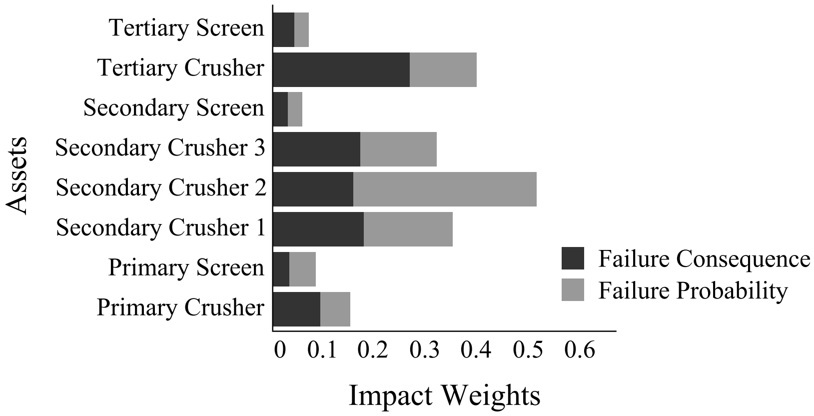


Figure 5.6: Final Consequence and Probability Weights per Asset

The assets are plotted, consequence versus probability, on the TAHPP priority grid which is shown in Figure 5.7. The three priority categories are presented on this grid to visually prioritize the assets.

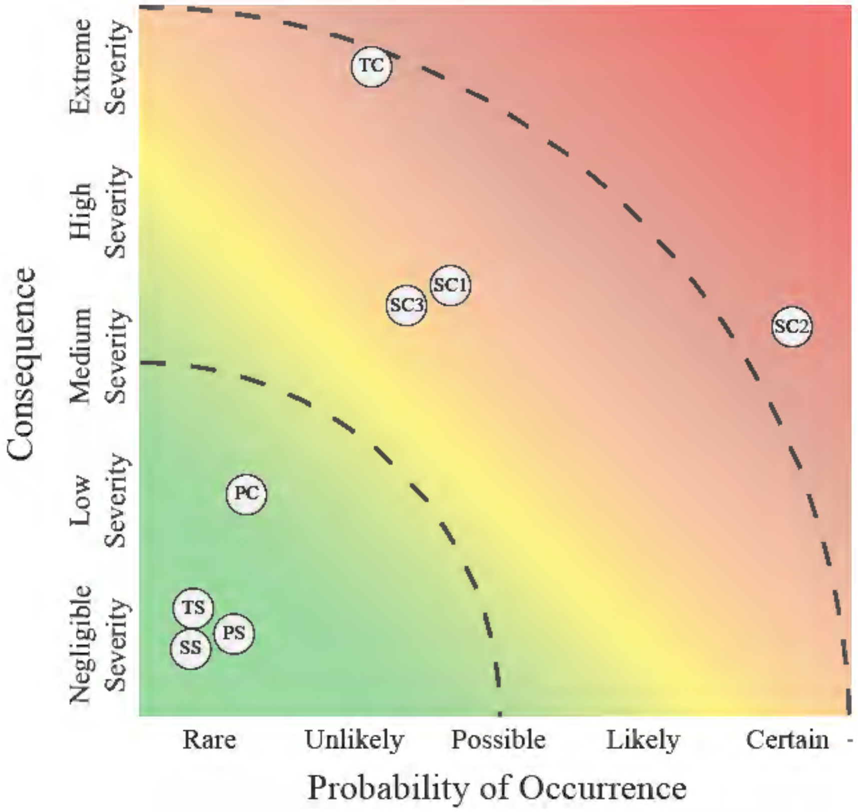


Figure 5.7: TAHPP Criticality Grid for Visual Asset Prioritization

According to this prioritization, *Secondary Crusher 2* is the only asset in the plant with an A-priority. For this reason the SMART failure mode prioritization will be applied on the failure modes of*Secondary Crusher 2.*

Three assets, *Secondary Crusher 1*, *Secondary Crusher 3* and *Tertiary Crusher*, are assigned a B-priority. The QTS are applied to these assets. As explained earlier, the QTS only gives a temporary solution until the critical majority is resolved. With a following critical asset identification, the B-priority assets are likely to become A-priority.

The four C-priority assets; *Primary Crusher*, *Primary Screen*, *Secondary Screens* and *Tertiary Screens*, are analyzed to find the root causes of failure. These causes are further investigated in order to eliminate them. A mentioned previously, RCA and QTS are only presented in a limited capacity for the purposes of this toolbox.

The numerical results of TAHPP are obtained from further matrix multiplication and are shown in Table 5.3 together with the asset priorities.

Table 5.3: Assets' Numerical TAHPP Criticality and Priority

Asset	Criticality	Priority
Secondary Crusher 2	0.2634	A
Tertiary Crusher	0.2034	B
Secondary Crusher 1	0.1804	B
Secondary Crusher 3	0.1640	B
Primary Crusher	0.0772	C
Primary Screen	0.0440	C
Tertiary Screen	0.0367	C
Secondary Screen	0.0309	C

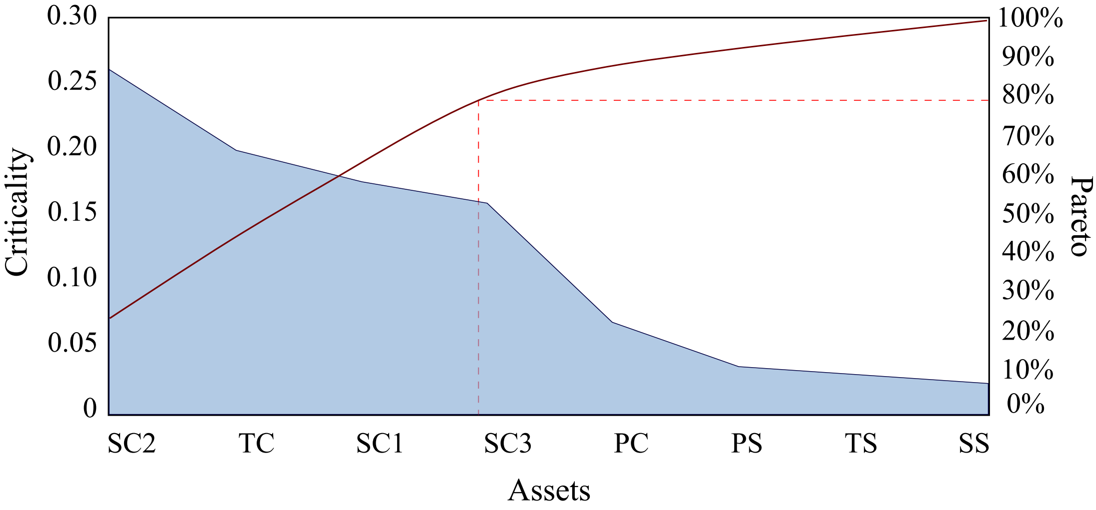


Figure 5.8: TAHPP Pareto Graph

A Pareto analysis is done on the TAHPP results to determine the urgency of the actions that are required in order to reduce the criticality. The Pareto graph displayed in Figure 5.8 shows that 80% of the criticality is due to four of the eight assets. Evidently, 50% of the assets are considered as critical which means that these different assets need to be treated to reduce the critical majority. This indicates that the urgency of the actions are rather high and needs to be implemented as soon as possible.

As mentioned previously, SMART prioritization is done on the failure modes of *Secondary Crusher 2* to ultimately select the most appropriate maintenance tactic for each failure mode. As a result from the TAHPP priority grid, the *Tertiary Crusher* is on the edge of being an A-Priority. It is also noted that the consequence of a *Tertiary Crusher* failure is very high, but the probability of such a failure occurring is unlikely. Possibly, the *Tertiary Crusher* is likely to be the next asset in line to have SMART prioritization applied to its failure modes.

5.4.2 Failure Mode Prioritization

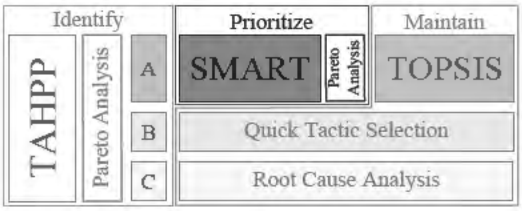


Figure 5.9: Toolbox Application Phase: *Prioritize*

The failure modes of *Secondary Crusher 2* are analyzed by use of SMART prioritization (Figure 5.9). As explained, the failure modes were selected with the data collection and are shown in Appendix A together with the system boundaries. As explained earlier in Chapter 4, the same criteria used in TAHPP are also used for SMART. In TAHPP the assets were pairwise compared according to a set criteria description, but in SMART a criteria description is generated for each failure mode, as explained in Chapter 4 (pg. 112). This criteria description derivation is done by use of a few required inputs for each failure mode. For each of these failure modes the required inputs were calculated by use of failure data analysis. A summary of the inputs for all the failure modes are shown in Table 5.4.

The cost associated with each failure mode was not available when data was gathered. For this reason, assumptions had to be made to calculate a relative cost that can be associated with each failure mode, only for the purpose of applying the case study.

Table 5.4: Secondary Crusher Failure Mode Inputs for SMART Prioritization

Failure Mode	**MTTR** (hrs)	**MTBF** (hrs)	**Last Event** (hrs)	**Average Maintenance Cost** (R)
Crusher				
Choked	0.33	94.50	245.76	R 166.42
High spider bearing temperature	2.54	78.54	21.31	R 1 054.71
Hydroset fault	1.67	53.73	142.08	R 473.13
Low spider bearing temperature	1.67	206.83	98.90	R 1824.92
Tighten bolts on top shell	1.50	107.83	75.05	R 854.54
Unhealthy speed switch	3.24	135.40	53.96	R 2 316.53
Feedback Fault				
Crusher overload	0.33	194.50	31.72	R 339.12
Thermal overload	0.28	52.83	37.61	R 77.54
Tripped	3.70	121.87	111.708	R 2382.32
Lubrication system				
High oil temperature	0.96	39.74	11.26	R 201.23
High pressure before filters	1.63	10.98	40.82	R 94.50
Leaking grease pipe	2.08	144.00	211.85	R 1 585.02
Low oil pressure before filter	2.44	5.06	153.57	R 65.29
Low oil temperature	0.33	26.00	129.28	R 45.33
Lube pump tripped	0.56	40.72	64.09	R 119.5
Oil flow low	1.19	14.86	141.23	R 93.54
Oil pipe leak	8.92	20.17	43.74	R 950.41
Unhealthy flow switch	0.89	39.74	54.72	R 114.66
Other				
Blocked chute	0.33	37.42	75.47	R 65.86
Comms failure	1.11	26.22	55.70	R 153.94

The criteria description for each failure mode is shown in Appendix D. The criteria is used to rate the impact of the failure mode if it should happen within the time period valid for the analysis. The inputs will not change very often. However, as the failure modes are maintained or eliminated changes might occur. The rating for all the failure modes are shown in Table 5.5 together with the FCF, FPF and the final priority value for each failure mode.

As explained, the FCF and FPF are calculated according to Equation 4.1 and 4.2 respectively and the priority value for each failure mode is calculated by use of Equation 4.3.

Table 5.5: SMART Failure Mode Rates and Priority Values

Number	**Failure Mode**	Production Impact	Safety Impact	Maintenance Cost	**FCF**	**FPF**	**Priority Value**	**Priority Order**
	Crusher							
F01	Choked	6	4	2	3.51	9.00	5.62	2
F02	High spider bearing temperature	6	4	4	4.65	2.71	3.55	14
F03	Hydroset fault	4	2	2	2.65	9.00	4.88	5
F04	Low spider bearing temperature	4	1	4	3.67	4.78	4.19	13
F05	Tighten bolts on top shell	2	4	1	1.65	6.96	3.39	16
F06	Unhealthy speed switch	4	1	1	1.97	3.98	2.80	18
	Feedback Fault							
F07	Crusher overload	1	2	4	2.81	1.63	2.14	19
F08	Thermal overload	4	2	4	3.78	7.12	5.19	4
F09	Tripped	1	1	1	1.00	9.17	3.03	17
	Lubrication system							
F10	High oil temperature	2	2	1	1.43	2.83	2.02	20
F11	High pressure before filters	4	1	6	4.80	9.00	6.58	1
F12	Leaking grease pipe	4	2	2	2.65	9.00	4.88	6
F13	Low oil pressure before filter	6	1	1	2.62	9.00	4.85	7
F14	Low oil temperature	6	1	1	1.97	9.00	4.21	8
F15	Lube pump tripped	4	1	1	2.62	9.00	4.85	12
F16	Oil flow low	6	1	1	2.54	9.00	4.78	9
F17	Oil pipe leak	4	1	2	3.18	9.00	4.78	10
F18	Unhealthy flow switch	6	1	2	2.54	9.00	5.35	3
	Other							
F19	Blocked chute	4	1	2	1.32	9.00	3.45	11
F20	Comms failure	2	1	1	1.97	9.00	4.21	15

The FPF and FCF are used to visually prioritize the failure modes on a priority grid. The failure mode priority grid is shown in Figure 5.10. Similar to the TAHPP criticality grid, this grid also has three priority categories. However, the same analysis is used for all of the categories. The purpose of this prioritization is to sequence the failure modes in an order in which they should be addressed.

In Figure 5.10 it is seen that there are no failure modes with a high probability of failure and a high consequence severity. Although majority of the failure modes are likely to happen, they all have a low consequence severity. Even though these failure modes have a low severity, they should still be maintained in order to minimize the total consequence severity. *Failure Mode 11* has a medium consequence severity and a high probability of failure. This failure mode is assigned to be the first priority and thus should be addressed first.

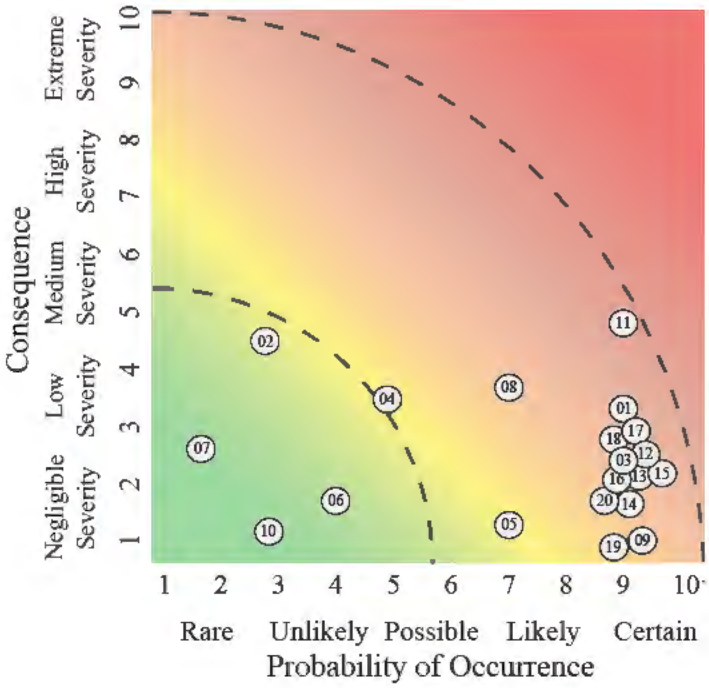


Figure 5.10: SMART Priority Grid for Visual Failure Mode Prioritization

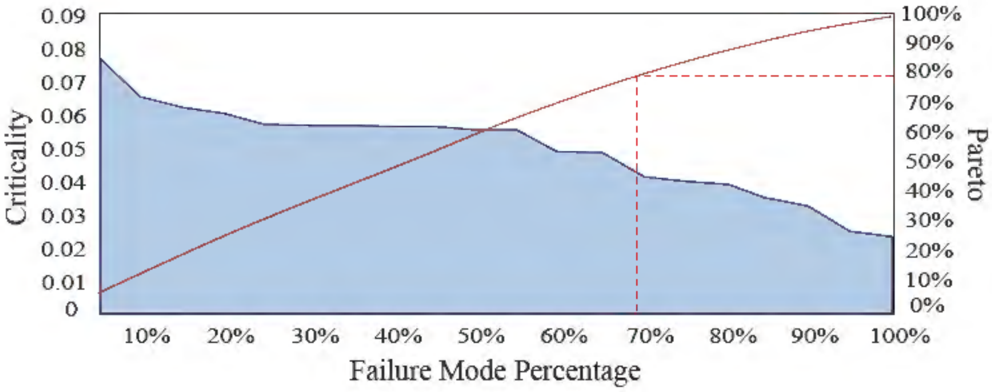


Figure 5.11: SMART Pareto Graph

A Pareto analysis is done on the priority values of the failure modes to get an estimated urgency, see Figure 5.11. As shown in the graph, 70% of the failure modes are responsible for 80% of the priority. This is due to the fact that the majority of failure modes are likely to fail, even though they do not have severe consequences. This result shows that maintenance on these failure modes are urgent.

The challenge is to treat all of these possible failure modes before they occur, or what ever might be the best maintenance tactic to follow. The following section discusses the maintenance tactic selection. This is done by use of TOPSIS, as explained previously.

5.4.3 Maintenance Tactic Selection

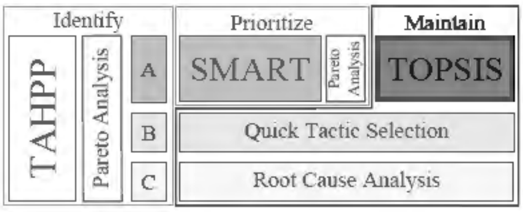


Figure 5.12: Toolbox Application Phase: *Maintain*

Finally, the best maintenance tactic for each failure mode is selected. This is done by using TOPSIS (Figure 5.12). This tactic selection is applied in the prioritized order, as determined with SMART. In Chapter 4 (pg. 115) the criteria used to select an appropriate maintenance tactic is explained. For convenience it is mentioned again below:

- Damage to asset or asset condition after maintenance,
- Production loss or time to maintain, and
- Maintenance related costs

The same criteria is used for all failure modes. The maintenance tactics are rated individually on a scale from one to ten for each criterion, corresponding to each failure mode. The TOPSIS rates are shown in Appendix E. The results are shown in Table 5.6 below and is sorted according to priority, as obtained from SMART.

In the previous section, with the Pareto analysis, it was shown that the urgency of the actions are high. This is because 70% of the failure modes need to be addressed in order to eliminate 80% of the priority unwanted events. This means that the first 13

Table 5.6: TOPSIS Maintenance Strategy Selection Results

	Failure Mode	Selected Maintenance Tactic
FM11	High pressure before filters	Preventive
FM01	Choked	Corrective
FM18	Unhealthy flow switch	Preventive
FM08	Thermal Overload	Design-out
FM03	Hydroset fault	Predictive
FM12	Leaking grease pipe	Predictive
FM13	Low oil pressure before filter	Preventive
FM14	Low oil temperature	Preventive
FM16	Oil flow low	Preventive
FM17	Oil pipe leak	Predictive
FM19	Blocked chute	Corrective
FM15	Lube pump tripped	Corrective
FM04	Low spider bearing temperature	Preventive
FM02	High spider bearing temperature	Preventive
FM20	Comms failure	Design-out
FM05	Tighten bolts on top shell	Corrective
FM09	Tripped	Corrective
FM06	Unhealthy speed switch	Preventive
FM07	Crusher overload	Corrective
FM10	High oil temperature	Preventive

modes need to be addressed as soon as possible. The best maintenance tactic for these failure modes are shown in Table 5.6.

The maintenance tactics for these 13 failures include seven preventive actions, three corrective actions, two Predictive actions and one design-out action. The remainder of the failure modes that also need to be treated include three corrective actions, two preventive actions and one design-out action.

It is clear that preventive maintenance is the preferred maintenance for the majority of the failure modes and that predictive and design-out maintenance is the minority. These two maintenance tactics are usually expensive, which explains the dislike in these tactics. Corrective maintenance may sometimes damage the assets more than other tactics. This is because corrective maintenance is to rectify and thus the assets run to failure. Preventive maintenance monitors the performance of the asset in order to give a warning before the occurrence of a failure. This provides the capability to treat a possible failure mode before the occurrence and thus can result in increased production and less downtime for maintenance and rectification.

5.5 Results Discussion

Now that the toolbox has been applied to the data collected from the Amplats plant, final interpretations can be made to evaluate the results. A summary of the results obtained from the toolbox application is displayed in Table 5.7.

Table 5.7: Results Summary

THAPP Assets	Strategy	SMART Failure Modes	TOPSIS Tactics
Secondary Crusher 2	SMART	High pressure before filters	Preventive
Tertiary Crusher	QTS	Choked	Corrective
Secondary Crusher 1	QTS	Unhealthy flow switch	Preventive
Secondary Crusher 3	QTS	Thermal overload	Design-out
Primary Crusher	RCA	Hydroset fault	Predictive
Primary Screen	RCA	Leaking grease pipe	Predictive
Tertiary Screen	RCA	Low oil pressure before filter	Preventive
Secondary Screens	RCA	Low oil temperature	Preventive
		Oil flow low	Preventive
		Oil pipe leak	Predictive
		Blocked chute	Corrective
		Lube pump tripped	Corrective
		Low spider bearing temperature	Preventive
		High spider bearing temperature	Preventive
		Comms failure	Design-out
		Tighten bolts on top shell	Corrective
		Tripped	Corrective
		Unhealthy speed switch	Preventive
		Crusher overload	Corrective
		High oil temperature	Preventive

As shown in the table above, from the eight assets that were included in the study only one asset, *Secondary Crusher 2*, was identified as critical with the use of TAHPP. Further analysis was done in which 176 failure events were found in the collected data. These failures consists of 20 different failure modes. These failure modes were analyzed to determine the required inputs for the SMART prioritization. For each of the failure modes TOPSIS is used to select a maintenance tactic which is considered to be the most appropriate for the specific failure modes.

From the seven remaining assets, three are considered to have a B-priority and four a C-priority. QTS and RCA, respectively, are applied to these asset priorities. The application of this is discussed in limited detail for the reason that the focus is on the numerical decision making techniques on an operational level. Even though QTS is a medium term temporary solution, SMART prioritization will eventually be applied once the failure modes of the A-priority assets are eliminated.

The results, as shown in the Table 5.7, can serve as a list of orders to complete. It provides the critical asset with its failure modes in a prioritized order together with the preferred maintenance tactic for each. The toolbox can be applied regularly on an operational level. It is quick, effortless, understandable and easy to use.

In the following section the validation of this simplified numerical decision making toolbox is discussed.

5.6 Validation of Toolbox

This section discusses the validation of the research conducted. The purpose of this validation is to confirm that the specific research has value, both theoretically and practically. It was also used to validate predetermined specifications.

The applicability of the developed toolbox is investigated theoretically to validate whether it is applicable to an actual situation or not. By means of a case study the toolbox is applied to an actual scenario in practice in order to validate the practical value of the toolbox.

Amplats provided the opportunity to collect data in order to apply the simplified numerical decision making toolbox to a real world situation. The purpose of this toolbox is to make effective maintenance decisions on an operational level by selecting the most appropriate maintenance tactics for different failure modes. This type of decision making is of informal nature, as discussed previously, and is thus done regularly or periodically. For this reason, the results obtained from this case study are only valid for the time period of the data collection.

The application of this toolbox requires someone who is familiar with the plant and has experience with its operations. Therefore, a senior maintenance planner was asked to participate. An interface was developed in order to present the toolbox in a simplistic manner so that the maintenance planner can easily use it.

After the application, the maintenance planner stated that the toolbox interface was easy to understand and use. The application was completed without struggle and within a reasonable time period. According to the maintenance planner anyone with the necessary knowledge about the plant and its operations will be able to use this toolbox without effort. All of the above mentioned confirms that the toolbox development adheres to its simplistic purpose.

With the interpretation of the results it was stated that the implementation of this toolbox will have practical value. The maintenance planner was satisfied with the results and said that this is an effective tool that can be used in planning maintenance activities. The toolbox is referred to as an applicable tool to identify where the focus area in the plant is and what assets need to be focussed on for the specific time period. The maintenance planner was impressed with the idea of the toolbox and stated that this is a useful tool to compile a list of maintenance actions that should be carried out in a prioritized order.

Consequently, the simplified PAM decision making toolbox was applied successfully. The application was easy, understandable, quick, effortless and referred to as a valuable tool in planning maintenance actions.

5.7 Chapter 5 Concluding Remarks

A case study conducted in collaboration with Amplats was presented in this chapter. The purpose of the case study was to test the practical validity of the simplified numerical decision making toolbox developed in Chapter 4.

A brief background about the Amplats plant that was included in the study was provided together with a discussion of its operations. The core assets of the included plant together with their purpose were mentioned with the discussion of operational flow. System boundaries were established for each asset to ease the data collection process in knowing what specific data are required.

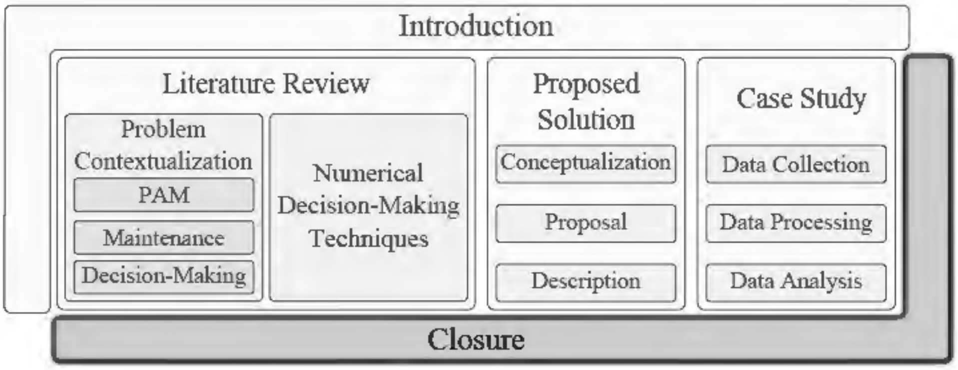
In order to apply the toolbox successfully the required data was collected as discussed in this chapter. The data was processed in order to calculate inputs for the application of the toolbox and execute its full functionality. As preparation for the toolbox application, the toolbox was set up with the processed data and ready for execution. For the reason that the aim was to develop a simplified numerical toolbox, a senior maintenance planner at the plant was asked to participate with the execution of the toolbox in order to evaluate the simplicity. With the completion of the application it was stated that the toolbox was easily understood and applied, confirming that anyone with the necessary knowledge will be able to use it. The maintenance planner was satisfied with the results obtained, stating that this tool will definitely be of great value in easing the maintenance planning process.

The next chapter discusses the closure of this study and also provides recommendation for further research.

Chapter 6

Closure

The final chapter merges the research findings of the study conducted in this thesis. As shown in the figure, it summarizes the entirety of this thesis to conclude the study conducted. Aspects that limited the execution of this study are discussed together with recommendations for further research.



The aim of this chapter is to provide a holistic overview of the study conducted and understanding the limitations that withheld certain outcomes. The recommendations clarify the scope for further research in identifying areas for improvement.

6.1 Summary and Conclusion

The management of physical assets become more and more acknowledged in multiple industries worldwide. Even though maintenance has a great contribution to managing physical assets successfully, some industries still see maintenance as an equivalent to PAM. However, this is not the case. PAM encompasses a much broader set of activities than only maintenance, whereas maintenance is primarily concerned with keeping existing asset in operating condition.

Historically maintenance was only done with the occurrence of a failure which is known as Corrective Maintenance. Over the years different maintenance tactics evolved such as Preventive Maintenance (PM), Predictive Maintenance (PdM) and Design-out Maintenance, to mention only a few. These maintenance tactics are all suitable for different types of failures. Therefore, an important part in maintaining equipment to keep it operable is to select the most appropriate maintenance tactic for the specific failure behaviour of an asset. This highlights the importance of decision making in maintaining equipment, deciding which tactic is the best for a certain failure mode.

Various decision making methods and techniques exist. Decisions can be made either by discussion and experience or numerical calculations. Numerical decision making is a very useful tool because it provides evident calculations, obtaining the best possible solution. However, this type of technique is not used very often because of various downsides to its useability such as it comes across to be complex, time consuming, requiring high intellect and understanding. Even though a vast amount of numerical decision making techniques exist and was found in literature, limited evidence of the application of numerical decision making techniques to PAM or maintenance related decisions were found. It was confirmed by practitioners that decisions in the PAM or maintenance environment are rather made based on experience and circulating opinions than numerical techniques. The reason for this is that practitioners move away from the complexity, timeliness, etc. of such techniques. Hence, the aim of the research conducted was to study different numerical decision making techniques in order to find appropriate techniques that can be used to support PAM decision making in a simple and uncomplicated manner. Recalling the key research question and null hypothesis:

> *Is it possible to combine different numerical decision making techniques to assist complex PAM decisions-making and be presented in a simple and understandable manner?*

H_0:	*Different numerical decision making techniques cannot be combined to assist PAM related decisions on operational level in a simple, understandable and effective manner.*

An overview of PAM together with PAS 55 were provided in the literature. Maintenance was also discussed as well as decision making in the context of PAM and in accordance with PAS 55. Through this, relevant maintenance decision making areas were identified within the context of PAM. These decisions were used as guidance to develop a simplified decision making toolbox that can be used to support PAM related decisions, primarily focussing on maintenance.

Three toolbox phases evolved from the selected set of decisions and three main techniques were selected, TAHPP, SMART and TOPSIS, one for each phase. The application of these techniques occurs in chronological order and are repeated, creating a continuous cycle for improvement of maintenance decisions.

The theoretically simplified numerical decision making toolbox was applied to a real world situation in collaboration with Amplats. The application was completed with the help of a senior maintenance planner. According to the maintenance planner, useful results were obtained which were used as a validation of the toolbox practical applicability.

Furthermore, by following the research methodology, as discussed in Section 1.7 (pg. 18), the following was achieved.

- Relevant literature was studied and a comprehensive understanding of PAM, maintenance and decision making was obtained;
- Various numerical decision making techniques were studied and understood thoroughly;
- The applicability of the different techniques were evaluated in accordance with a selected set of decisions, primarily related to maintenance;
- Three most appropriate techniques were selected and combined successfully;
- The combination of these techniques serves as a framework for maintenance related decision making and is thus named a decision making toolbox;

- The decision making toolbox was simplified in a way that anyone with the necessary knowledge can use it easily;
- The simplified numerical decision making toolbox was evaluated and validated by means of a case study in which successful results were obtained.

From the above mentioned it can be confirmed that with the completion of this study the research objectives, as listed in Section 1.6 (pg. 17), have been met.

1. It is establish that numerical decision making techniques can be combined and used in a simplified and easily understandable manner in order to support PAM related decisions on an operational level.
2. The most appropriate numerical techniques is selected and combined systematically in order to fulfill the need for a simplified and easy useable decision making tool.
3. The practical applicability of the developed toolbox is verified by the use of a demonstration a real world situation which was supported by Amplats.

Evidently, from all of the above mentioned the null hypothesis is rejected and the following can be stated:

> *Different numerical decision making techniques CAN be combined to assist PAM related decisions on operational level in a simple, understandable and effective manner.*

Various limitations came to light with the completion of this study and are discussed in the next section.

6.2 Limitations

An essential part of any research study are the limitations that are discovered during the study. The development and application of a simplified numerical decision making toolbox came across several limitation and are listed in this section.

- The collection of data is an important part in the application of the decision making toolbox. Although minimal input is required when applying the toolbox, it is important to use the correct data. The MTBF and MTTR are calculated by use of historical data. If no historical data is available it will be difficult to obtain accurate inputs and thus the results may be vague.

- The decision maker using the toolbox has to have the necessary knowledge about the asset and its operation. If one has no knowledge about it the decision making may become inconsistent and inaccurate.
- Because the setup of the toolbox is only done once, and will only be required again if changes in the criteria or criteria weights occur, the setup accuracy is of paramount importance. If the toolbox is setup incorrectly, by means of criteria, criteria weights, etc. all results will be faulty.
- Another important note is that the toolbox information should always be up to date. If assets are maintained according to results from the toolbox, the information should be updated. This is because of the cyclic aspect of the toolbox. If it is not kept up to date, the results of the following cycle might yield the same as the previous, which will thus be incorrect.

These limitations were dealt with during the progress of this study and valid results were obtained. The next section presents recommendations if further research were to be completed in this field of study.

6.3 Recommendations for Further Research

Even though the research objectives for this study were met and the null hypothesis was rejected, there are still areas for improvement. As the research progressed throughout this thesis further problem areas, ideas and questions were noted. This section discusses suggestions that can contribute in improving the study completed in this thesis by means of further research.

- During the application of the toolbox in the case study it was discovered that there is a lack of information to calculate reliability metrics such as MTBF and MTTR per failure mode. It is only calculated per asset, and not taking into account the failure occurrences per failure mode. The same is done with the average maintenance cost calculations. A recommendation is made to analyse failure occurrences by type or category. This way the impact of each failure mode will become visible and it will also ease the input calculations for the *Prioritize* phase.
- Various authors have considered to replace MTBF with MFOP and have shown that MFOP can successfully replace MTBF. In this thesis the metric MTBF was

used for the reason of simplicity. MTBF is a well-known and widely used metric and is easy to calculate. It is suggested that the applicability of MFOP should be researched in order to use this metric in the application of the toolbox and thus to simplify the calculation of MFOP in order still camouflage the complexity in simplicity.

- In the development of this toolbox the aim was to support operational decision making with simplified numerical decision making techniques. However, two additional techniques, QTS and RCA, were identified for assets that do not immediately require operational decision making. The discussion and explanation of these techniques were limited in this these because it falls beyond the scope of this thesis. For further research and improving the study of a simplified numerical decision making toolbox it is recommended to study the possibility of taking into account the medium and long term decision making as well and not only the operational decision making.
- A useful aspect in all industries and especially when focussing on simplification is automation. Future research is suggested to investigate the possibility of automating the toolbox application. The first phase, *Identify*, with the asset pairwise comparison can be automated by using the required inputs. The impact on production and safety if an asset should fail will not necessarily change often. The rest of the criteria, when comparing assets with regards to MTBF, maintenance cost impact and last event, can all be fully automated by use of inputs. The second and third phases, *Prioritize* and *Maintain*, can also be automated to present it in an easy rating system. The last aspect to automate is to keep the system up to date as maintenance is done. Consequently, the application of the toolbox will take minimal time and can occur continuously providing continuous outputs that can serve as prioritized works orders. More over, with a continuous process like this the critical assets and its' prioritized failure modes together with recommended maintenance tactics will be known at every instant of time.

All of the recommendations for further research mentioned above are suggestions to improve the research study conducted. These areas can open windows of opportunity and insight in the simplification of the decision making process of PAM and maintenance related decisions.

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Appendix A

System Boundaries for Data Processing

Table A.1: Primary Crusher Data Boundaries

Include	Exclude
Main Shaft	**Planned Maintenance**
Shear pins broken off	Cleaning spillage around the shaft
Unhealthy speed switch	Replacing beam on 102cv02
Liners loose	Feeder liner Replacements
Safety coupling pins lost	Refill grease drum
Lubrication System	Replace shaft coupling guard stand
Oil level low	Replacing crusher drive shaft
Bell hose burst	Repairs done on motor brushes
Eccentric bush oil level low	**No trucks**
Oil pressure low	Stopped crusher to avoid timeout
Rock bridge	Shift Change
Choked on big rocks	Waiting for Trucks
Other	Road scraping
Receiving bin leaking	**Bin Levels**
Mantle loose	Stockpile full
Shovel tooth in crusher	Rock box level
Counter shaft temperature high	**Other**
Brush gear lower limit	Cleaning bin for maintenance
Spider cap bolt loose	Conveyor Splice
Run time out	Excavator brake down
Counter shaft temperature high	

Table A.2: Primary Screen Data Boundaries

Include	Exclude
Choked	Conveyor failures
Bolts loose	Stops due to stockpile
Blocked chute	Secondary crusher feed silo levels high
	Secondary screen feed silo levels high

Table A.3: Secondary Crushers' Data Boundaries

Include	**Exclude**
Crusher	**Maintenance**
Choked	Planned shut
High spider bearing temperature	Inspections
Hydroset fault	**Conveyor**
Low spider bearing temperature	Splice repairs
Tighten bolts on top shell	Conveyor failures
Unhealthy speed switch	Removing steel from conveyor
Feedback Fault	**Bin Levels**
Crusher Overload	Tertiary crusher feed silo full
Thermal overload	Screen bin level high
Tripped	Feed silo full
Lubrication System	**Stops due to**
High oil temperature	Screens failure
High pressure before filters	Failure other secondary crusher
Leaking grease pipe	Primary screen failure
Low oil pressure before filter	
Low oil temperature	
Lube pump tripped	
Oil flow low	
Oil pipe leak	
Flow switch unhealthy	
Other	
Blocked chute	
Comms failure	

Table A.4: Secondary Screen Data Boundaries

Include	**Exclude**
Choked	Conveyor failures
Bolts loose	Low feed silo level
Blocked chute	High storage silo level
	Secondary crusher feed silo levels high

Table A.5: Tertiary Crusher Data Boundaries

Include	Exclude
Skewing	**Hopper**
Left skewing	Hopper level high
Roller control not working	Low hopper level
Rollers not opening	Struggling to build hopper level
Right skewing	Adjusting Auma gates
Absolute skewing	**Maintenance**
Lubrication System	Cleaning chute
Grease system not getting air supply	Conveyor failures
High oil temperature	Inspection
High oil pressure	Secondary crusher failures
Low oil pressure	Changing breaker
Other	Replace studs on rollers
Feedback Fault	
Unhealthy speeds witch	
Grease on speed switch	
Discharge chute damaged	
Low rolls pressure	
Cylinder oil leak on movable roll	
High temperature on bearings	
Bearing need grease	
Power failure	

Table A.6: Tertiary Screen Data Boundaries

Include	Exclude
Choked	Conveyor failures
Bolts loose	Low feed silo level
Blocked chute	High storage silo level
	Tertiary crusher feed silo levels high

Appendix B

Asset Data Processing

The data obtained from the PI system was processed with the use of Microsoft Excel. A summary of the processed data are shown in this appendix. Table B.1 presents the data summary of the failure times of all the assets included in the study.

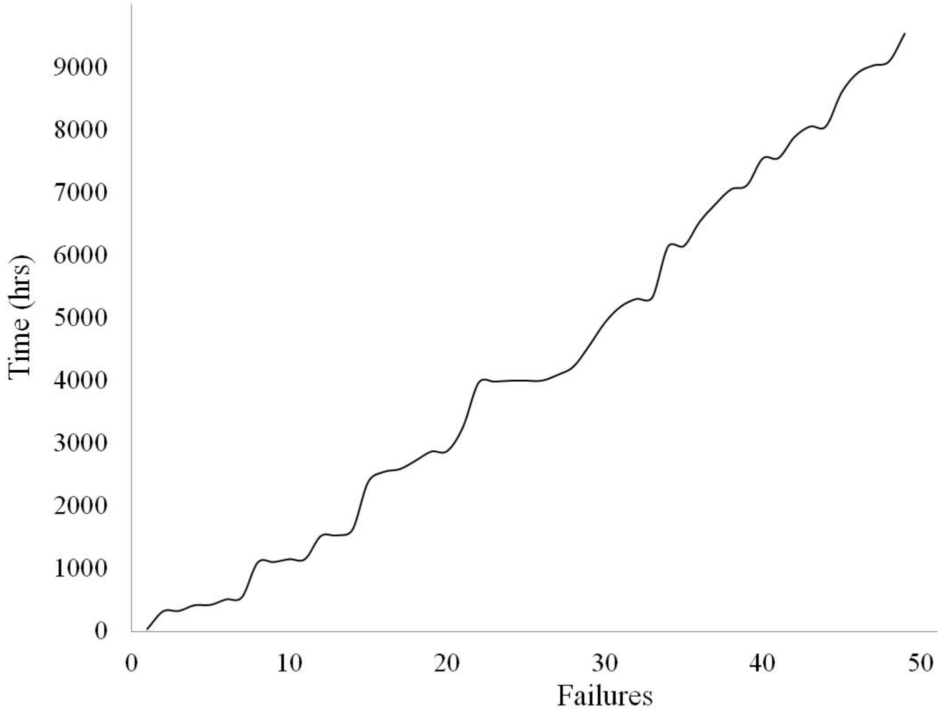
Table B.1: Asset Data Summary

Asset	Number of Failures	Total Operation Time (hrs)	Total Repair Time (hrs)	MTBF (hrs)	MTTR (hrs)	Last Event (hrs)
Primary Crusher	49	9540.50	1027.33	194.70	20.97	11.51
Primary Screens	9	2956.50	31.33	328.50	3.48	151.34
Secondary Crusher 1	96	6275.17	143.33	65.37	1.49	143.94
Secondary Crusher 2	176	5693.67	405.33	32.35	2.30	154.40
Secondary Crusher 3	168	5709.50	419.5	33.99	2.50	6.88
Secondary Screens	2	3290.00	2.6	1645.00	1.34	268.39
Tertiary Crusher	120	5298.17	446.67	44.15	3.72	0.51

The following graphs show the cumulative time between failures and also the cumulative repair times per asset.

Figure B.1: Primary Crusher

(a) Cumulative Time Between Failures



(b) Cumulative Repair Times

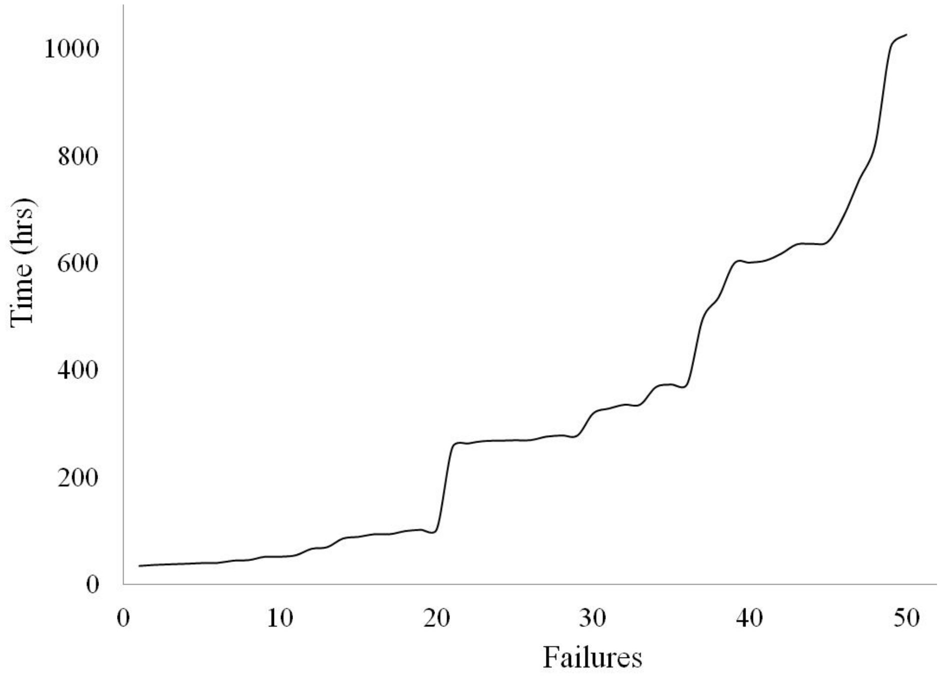
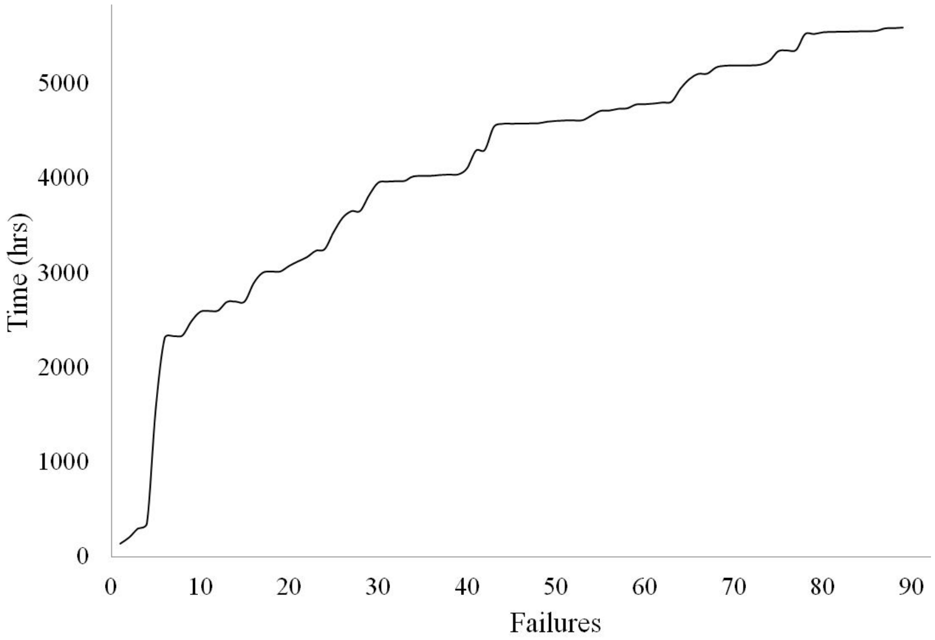


Figure B.2: Secondary Crusher 1

(a) Cumulative Time Between Failures



(b) Cumulative Repair Times

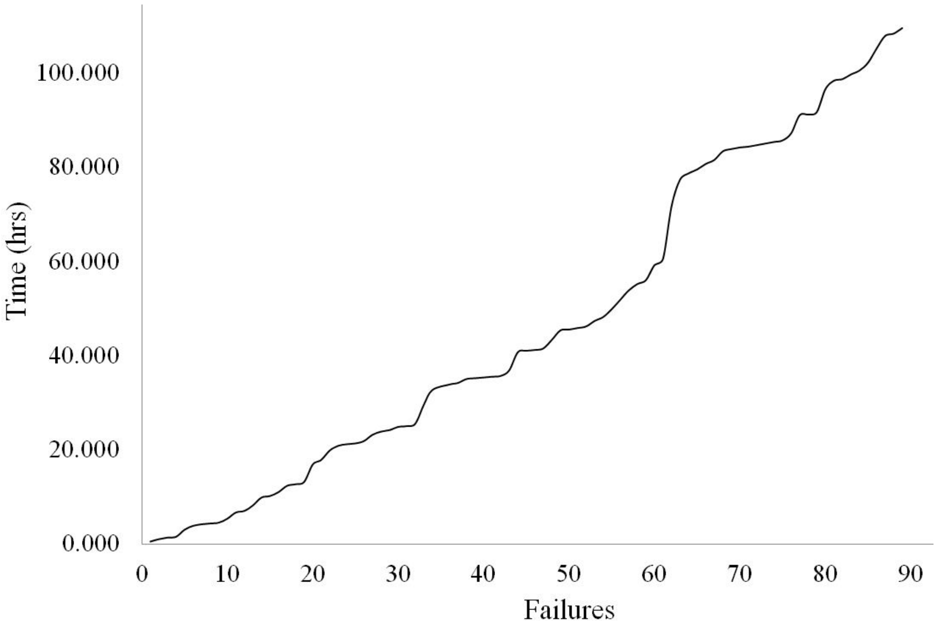
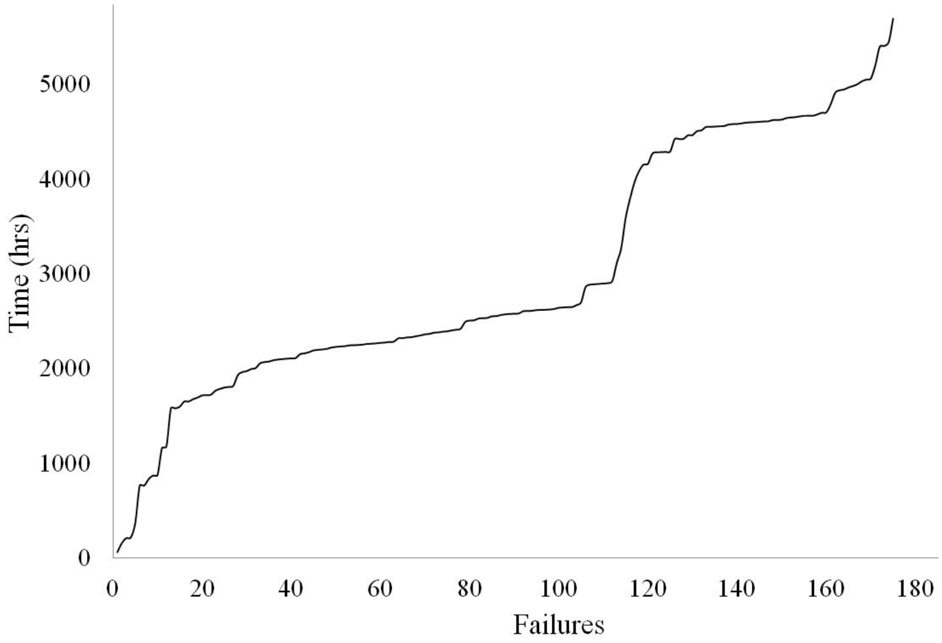


Figure B.3: Secondary Crusher 2

(a) Cumulative Time Between Failures



(b) Cumulative Repair Times

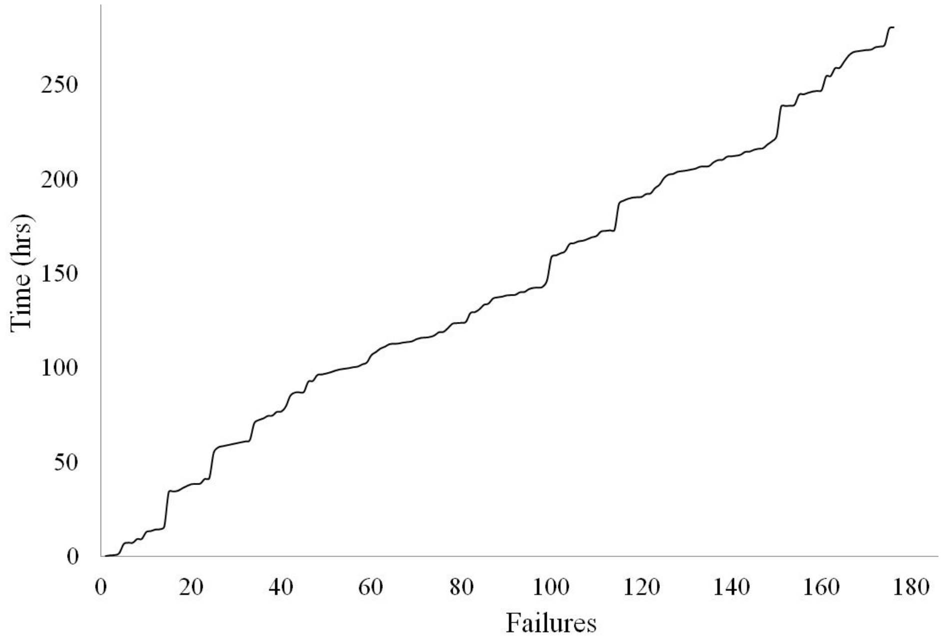
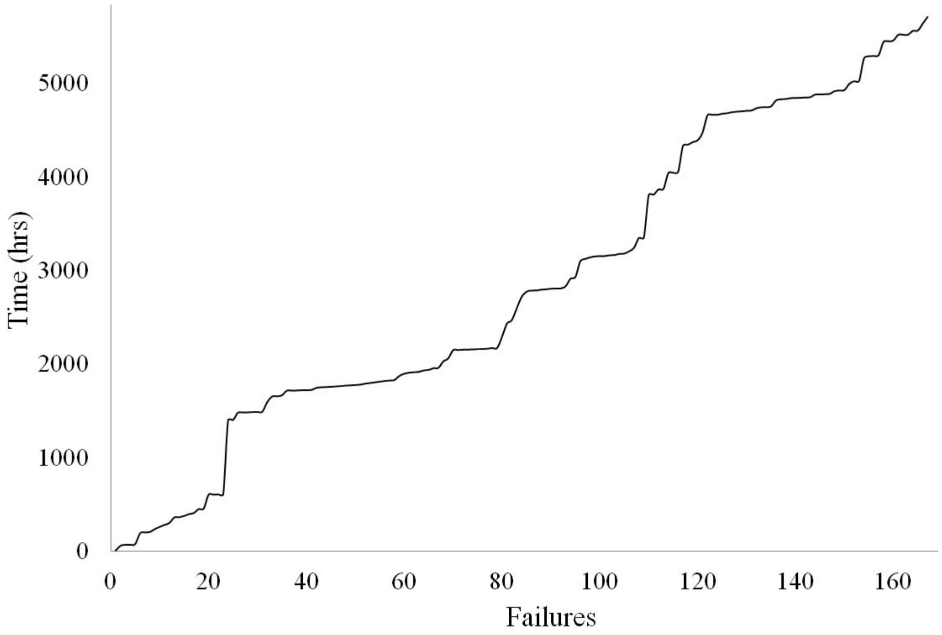


Figure B.4: Secondary Crusher 3

(a) Cumulative Time Between Failures



(b) Cumulative Repair Times

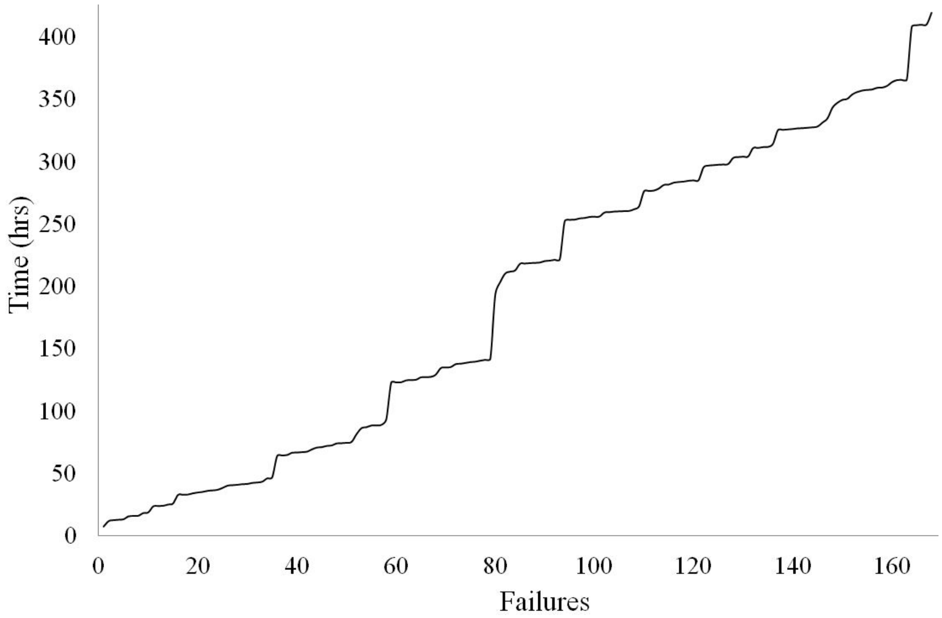
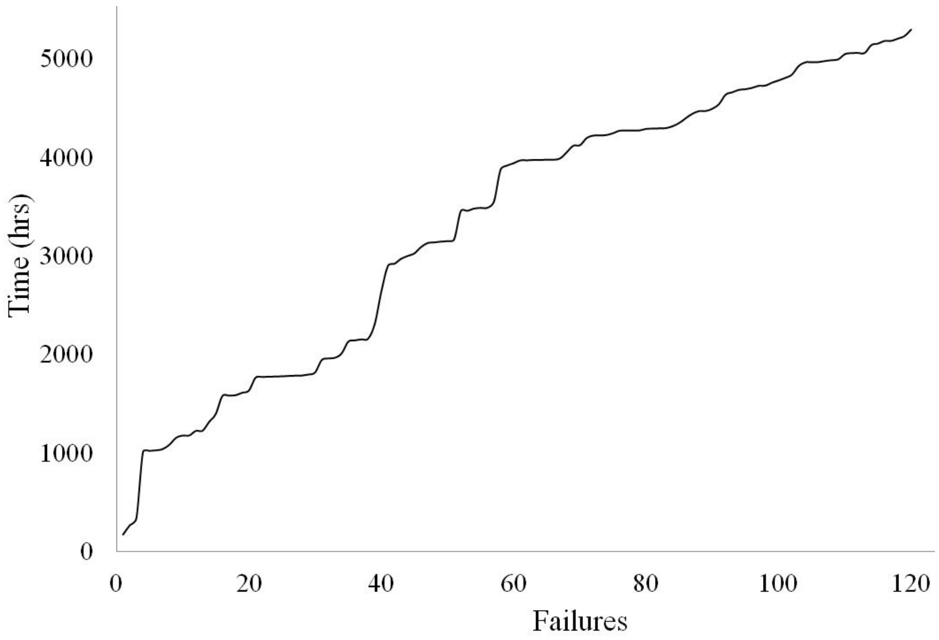
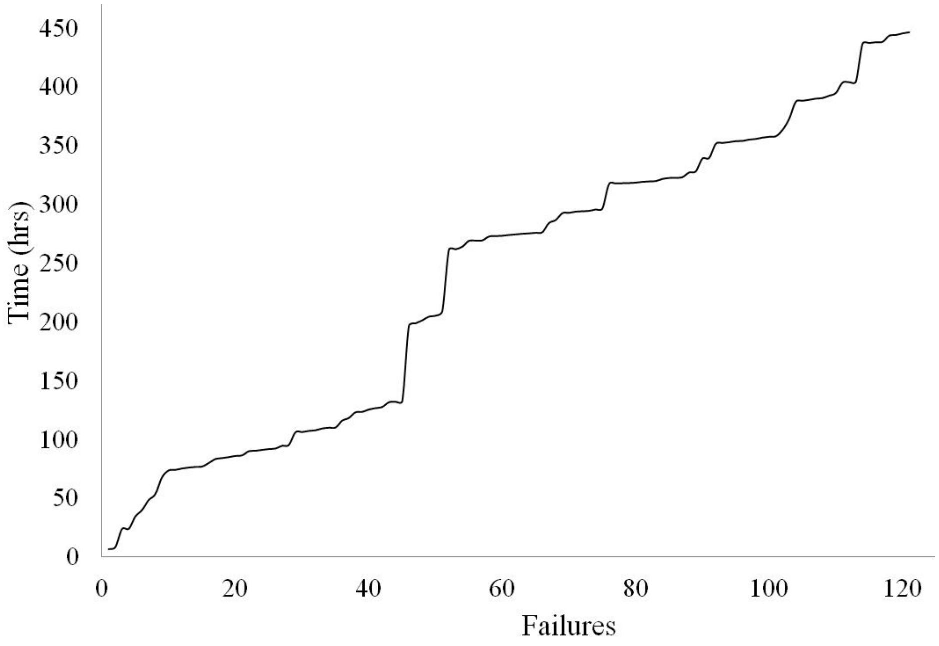


Figure B.5: Tertiary Crusher

(a) Cumulative Time Between Failures



(b) Cumulative Repair Times



Appendix C

THAPP Pairwise Comparison

Table C.1: THAPP Criteria Comparison

Asset	Extremely Strong 0	Very Strong 7	Strong 5	Marginally Strong 3	Equal 1	Marginally Strong 3	Strong 5	Very Strong 7	Extremely Strong 9	Asset
Production			x							Safety
Safety							x			Maintenance Cost
Maintenance Cost				x						Production

Table C.2: THAPP Asset Comparison concerning the *MTBF*

Asset	Extremely Smaller 0	Much Smaller 7	Marginally Smaller 5	Smaller MTBF 3	Equal MTBF 1	Smaller MTBF 3	Marginally Smaller 5	Much Smaller 7	Extremely Smaller 9	Asset
Primary Crusher			x							Primary Screen
Primary Crusher						x				Secondary Crusher 1
Primary Crusher								x		Secondary Crusher 2
Primary Crusher								x		Secondary Crusher 3
Primary Crusher	x									Secondary Screens
Primary Crusher							x			Tertiary Crusher
Primary Crusher		x								Tertiary Screen
Primary Screen							x			Secondary Crusher 1
Primary Screen									x	Secondary Crusher 2
Primary Screen									x	Secondary Crusher 3
Primary Screen				x						Secondary Screens
Primary Screen									x	Tertiary Crusher
Primary Screen					x					Tertiary Screen
Secondary Crusher 1						x				Secondary Crusher 2
Secondary Crusher 1						x				Secondary Crusher 3
Secondary Crusher 1		x								Secondary Screens
Secondary Crusher 1						x				Tertiary Crusher
Secondary Crusher 1		x								Tertiary Screen
Secondary Crusher 2					x					Secondary Crusher 3
Secondary Crusher 2	x									Secondary Screens
Secondary Crusher 2					x					Tertiary Crusher
Secondary Crusher 2	x									Tertiary Screen
Secondary Crusher 3	x									Secondary Screens
Secondary Crusher 3					x					Tertiary Crusher
Secondary Crusher 3			x							Tertiary Screen
Secondary Screens									x	Tertiary Crusher
Secondary Screens						x				Tertiary Screen
Tertiary Crusher		x								Tertiary Screen

Table C.3: THAPP Asset Comparison concerning the *Last Event*

Asset	Extremely Strong	Very Strong	Strong	Marginally Strong	Equal	Marginally Strong	Strong	Very Strong	Extremely Strong	Asset
	0	7	5	3	1	3	5	7	9	
Primary Crusher						x				Primary Screen
Primary Crusher								x		Secondary Crusher 1
Primary Crusher									x	Secondary Crusher 2
Primary Crusher						x				Secondary Crusher 3
Primary Crusher					x					Secondary Screens
Primary Crusher				x						Tertiary Crusher
Primary Crusher					x					Tertiary Screen
Primary Screen							x			Secondary Crusher 1
Primary Screen								x		Secondary Crusher 2
Primary Screen					x					Secondary Crusher 3
Primary Screen				x						Secondary Screens
Primary Screen				x						Tertiary Crusher
Primary Screen				x						Tertiary Screen
Secondary Crusher 1							x			Secondary Crusher 2
Secondary Crusher 1			x							Secondary Crusher 3
Secondary Crusher 1		x								Secondary Screens
Secondary Crusher 1		x								Tertiary Crusher
Secondary Crusher 1		x								Tertiary Screen
Secondary Crusher 2	x									Secondary Crusher 3
Secondary Crusher 2	x									Secondary Screens
Secondary Crusher 2	x									Tertiary Crusher
Secondary Crusher 2	x									Tertiary Screen
Secondary Crusher 3					x					Secondary Screens
Secondary Crusher 3				x						Tertiary Crusher
Secondary Crusher 3					x					Tertiary Screen
Secondary Screens				x						Tertiary Crusher
Secondary Screens					x					Tertiary Screen
Tertiary Crusher				x						Tertiary Screen

Table C.4: THAPP Asset Comparison concerning the *Production Impact*

Asset	Extremely Strong	Very Strong	Strong	Marginally Strong	Equal	Marginally Strong	Strong	Very Strong	Extremely Strong	Asset
	0	7	5	3	1	3	5	7	9	
Primary Crusher							x			Primary Screen
Primary Crusher								x		Secondary Crusher 1
Primary Crusher							x			Secondary Crusher 2
Primary Crusher								x		Secondary Crusher 3
Primary Crusher						x				Secondary Screens
Primary Crusher							x			Tertiary Crusher
Primary Crusher				x						Tertiary Screen
Primary Screen							x			Secondary Crusher 1
Primary Screen						x				Secondary Crusher 2
Primary Screen							x			Secondary Crusher 3
Primary Screen					x					Secondary Screens
Primary Screen						x				Tertiary Crusher
Primary Screen					x					Tertiary Screen
Secondary Crusher 1			x							Secondary Crusher 2
Secondary Crusher 1					x					Secondary Crusher 3
Secondary Crusher 1			x							Secondary Screens
Secondary Crusher 1				x						Tertiary Crusher
Secondary Crusher 1		x								Tertiary Screen
Secondary Crusher 2					x					Secondary Crusher 3
Secondary Crusher 2				x						Secondary Screens
Secondary Crusher 2						x				Tertiary Crusher
Secondary Crusher 2				x						Tertiary Screen
Secondary Crusher 3			x							Secondary Screens
Secondary Crusher 3				x						Tertiary Crusher
Secondary Crusher 3				x						Tertiary Screen
Secondary Screens								x		Tertiary Crusher
Secondary Screens					x					Tertiary Screen
Tertiary Crusher			x							Tertiary Screen

Table C.5: THAPP Asset Comparison concerning the *Safety Impact*

Asset	Extremely High 0	High Impact 7	Unsafe 5	Marginal Impact 3	Equal 1	Marginal Impact 3	Unsafe 5	High Impact 7	Extremely High 9	Asset
Primary Crusher			x							Primary Screen
Primary Crusher				x						Secondary Crusher 1
Primary Crusher				x						Secondary Crusher 2
Primary Crusher				x						Secondary Crusher 3
Primary Crusher	x									Secondary Screens
Primary Crusher							x			Tertiary Crusher
Primary Crusher		x								Tertiary Screen
Primary Screen							x			Secondary Crusher 1
Primary Screen							x			Secondary Crusher 2
Primary Screen							x			Secondary Crusher 3
Primary Screen					x					Secondary Screens
Primary Screen								x		Tertiary Crusher
Primary Screen					x					Tertiary Screen
Secondary Crusher 1					x					Secondary Crusher 2
Secondary Crusher 1					x					Secondary Crusher 3
Secondary Crusher 1			x							Secondary Screens
Secondary Crusher 1					x					Tertiary Crusher
Secondary Crusher 1				x						Tertiary Screen
Secondary Crusher 2					x					Secondary Crusher 3
Secondary Crusher 2			x							Secondary Screens
Secondary Crusher 2						x				Tertiary Crusher
Secondary Crusher 2			x							Tertiary Screen
Secondary Crusher 3				x						Secondary Screens
Secondary Crusher 3					x					Tertiary Crusher
Secondary Crusher 3			x							Tertiary Screen
Secondary Screens								x		Tertiary Crusher
Secondary Screens						x				Tertiary Screen
Tertiary Crusher			x							Tertiary Screen

Table C.6: THAPP Asset Comparison concerning the *Maintenance Cost*

Asset	Extremely Expensive	Very High	High Cost	Marginally High	Equal	Marginally High	High Cost	Very High	Extremely Expensive	Asset
	0	7	5	3	1	3	5	7	9	
Primary Crusher		x								Primary Screen
Primary Crusher						x				Secondary Crusher 1
Primary Crusher							x			Secondary Crusher 2
Primary Crusher						x				Secondary Crusher 3
Primary Crusher			x							Secondary Screens
Primary Crusher							x			Tertiary Crusher
Primary Crusher		x								Tertiary Screen
Primary Screen							x			Secondary Crusher 1
Primary Screen								x		Secondary Crusher 2
Primary Screen							x			Secondary Crusher 3
Primary Screen					x					Secondary Screens
Primary Screen								x		Tertiary Crusher
Primary Screen						x				Tertiary Screen
Secondary Crusher 1						x				Secondary Crusher 2
Secondary Crusher 1					x					Secondary Crusher 3
Secondary Crusher 1			x							Secondary Screens
Secondary Crusher 1						x				Tertiary Crusher
Secondary Crusher 1				x						Tertiary Screen
Secondary Crusher 2					x					Secondary Crusher 3
Secondary Crusher 2			x							Secondary Screens
Secondary Crusher 2						x				Tertiary Crusher
Secondary Crusher 2				x						Tertiary Screen
Secondary Crusher 3			x							Secondary Screens
Secondary Crusher 3						x				Tertiary Crusher
Secondary Crusher 3			x							Tertiary Screen
Secondary Screens									x	Tertiary Crusher
Secondary Screens						x				Tertiary Screen
Tertiary Crusher			x							Tertiary Screen

Appendix D

Criteria for SMART Prioritization

Table D.1: Production Impact Criteria for SMART Prioritization

Failure Mode	Production Impact Rating Scale					
	1	2	4	6	8	10
		Limit operational excellence for..	Limit operational excellence for..	Limit operational excellence for..	No production for..	No production for..
Crusher	Production is only aware of the problem, no direct influence.					
Choked		<0.34 hours	<0.67 hours	<1.01 hours	<1.01 hours	>1.01 hours
High spider bearing temperature		<2.55 hours	<5.09 hours	<7.63 hours	<7.63 hours	>7.63 hours
Hydroset fault		<1.67 hours	<3.34 hours	<5.01 hours	<5.01 hours	>5.01 hours
Low spider bearing temperature		<1.67 hours	<3.34 hours	<5.01 hours	<5.01 hours	>5.01 hours
Tighten bolts on top shell		<1.5 hours	<3 hours	<4.5 hours	<4.5 hours	>4.5 hours
Unhealthy speed switch		<3.24 hours	<6.48 hours	<9.72 hours	<9.72 hours	>9.72 hours
Feedback Fault						
Crusher overload		<0.33 hours	<0.66 hours	<0.99 hours	<0.99 hours	>0.99 hours
Thermal Overload		<0.28 hours	<0.56 hours	<0.84 hours	<0.84 hours	>0.84 hours
Tripped		<3.71 hours	<7.41 hours	<11.11 hours	<11.11 hours	>11.11 hours
Lubrication System						
High oil temperature		<0.96 hours	<1.92 hours	<2.88 hours	<2.88 hours	>2.88 hours
High pressure before filters		<1.63 hours	<3.26 hours	<4.89 hours	<4.89 hours	>4.89 hours
Leaking grease pipe		<2.09 hours	<4.17 hours	<6.25 hours	<6.25 hours	>6.25 hours
Low oil pressure before filter		<2.45 hours	<4.89 hours	<7.34 hours	<7.34 hours	>7.34 hours
Low oil temperature		<0.33 hours	<0.66 hours	<0.99 hours	<0.99 hours	>0.99 hours
Lube pump tripped		<0.56 hours	<1.12 hours	<1.67 hours	<1.67 hours	>1.67 hours
Oil flow low		<1.2 hours	<2.39 hours	<3.58 hours	<3.58 hours	>3.58 hours
Oil pipe leak		<8.92 hours	<17.84 hours	<26.76 hours	<26.76 hours	>26.76 hours
Unhealthy flow switch		<13.29 hours	<26.57 hours	<39.85 hours	<39.85 hours	>39.85 hours
Other						
Blocked chute		<0.34 hours	<0.67 hours	<1.01 hours	<1.01 hours	>1.01 hours
Comms failure		<1.12 hours	<2.23 hours	<3.34 hours	<3.34 hours	>3.34 hours
Controller not controlling		<1.83 hours	<3.66 hours	<5.49 hours	<5.49 hours	>5.49 hours
Power						
Power dip		<1.25 hours	<2.5 hours	<3.75 hours	<3.75 hours	>3.75 hours

Table D.2: Maintenance Cost Criteria for SMART Prioritization

Failure Mode	Production Impact Rating Scale					
	1 Average repair cost is	2 Average repair cost is	4 Average repair cost is	6 Average repair cost is	8 Average repair cost is	10 Average repair cost is
Crusher						
Choked	> R 33.30	> R 66.60	> R 133.20	> R 199.80	> R 266.40	> R 333.00
High spider bearing temperature	> R 210.90	> R 421.80	> R 843.6	> R 1265.4	> R 1687.2	> R 2109.00
Hydroset fault	> R 94.60	> R 189.20	> R 378.40	> R 567.60	> R 756.80	> R 946.00
Low spider bearing temperature	> R 365.00	> R 730.00	> R 1460.00	> R 2190.00	> R 2920.00	> R 3650.00
Tighten bolts on top shell	> R 170.90	> R 341.80	> R 683.60	> R 1025.40	> R 1367.20	> R 1709.00
Unhealthy speed switch	> R 463.30	> R 926.60	> R 1853.20	> R 2779.80	> R 3706.40	> R 4633.00
Feedback Fault						
Crusher overload	> R 67.80	> R 135.60	> R 271.20	> R 406.80	> R 542.40	> R 678.00
Thermal Overload	> R 15.50	> R 31.00	> R 62.00	> R 93.00	> R 124.00	> R 155.00
Tripped	> R 476.50	> R 953.00	> R 1906.00	> R 2859.00	> R 3812.00	> R 4765.00
Lubrication System						
High oil temperature	> R 40.20	> R 80.40	> R 160.80	> R 241.20	> R 321.60	> R 402.00
High pressure before filters	> R 18.90	> R 37.80	> R 75.60	> R 113.40	> R 151.20	> R 189.00
Leaking grease pipe	> R 317.00	> R 634.00	> R 1268.00	> R 1902.00	> R 2536.00	> R 3170.00
Low oil pressure before filter	> R 13.10	> R 26.20	> R 52.40	> R 78.60	> R 104.80	> R 131.00
quad Low oil temperature	> R 10.50	> R 21.00	> R 63.40	> R 54.60	> R 72.80	> R 91.00
Lube pump tripped	> R 23.90	> R 47.80	> R 95.60	> R 143.40	> R 191.20	> R 239.00
Oil flow low	> R 20.10	> R 40.20	> R 80.40	> R 120.60	> R 140.80	> R 161.00
Oil pipe leak	> R 190.10	> R 380.20	> R 760.40	> R 1140.60	> R 1520.80	> R 1901.00
Unhealthy flow switch	> R 22.90	> R 45.80	> R 91.60	> R 137.40	> R 183.20	> R 229.00
Other						
Blocked chute	> R 13.20	> R 26.40	> R 52.80	> R 79.20	> R 105.60	> R 132.00
Comms failure	> R 30.80	> R 61.60	> R 123.20	> R 184.80	> R 246.40	> R 308.00
Controller not controlling	> R 13.5	> R 27.00	> R 54.00	> R 81.00	> R 108.00	> R 135.00
Power						
Power dip	> R 7.60	> R 15.20	> R 30.40	> R 45.60	> R 60.80	> R 76.00

Appendix E

TOPSIS Maintenance Tactic Selection

Table E.1: TOPSIS Maintenance Tactic Rates

Maintenance Tactic	Failure Mode	Condition	Time	Cost	Failure Mode	Condition	Time	Cost	Failure Mode	Condition	Time	Cost
Corrective	FM11	7	6	6	FM01	10	6	10	FM18	6	6	6
Preventive		8	6	7		8	6	10		6	8	8
Predictive		8	7	5		8	6	10		8	8	8
Design-out		10	3	2		8	6	10		8	8	8
Corrective	FM08	8	6	6	FM03	8	6	8	FM12	6	6	6
Preventive		8	8	8		8	8	8		6	8	6
Predictive		8	8	10		10	7	8		8	8	8
Design-out		10	10	10		10	6	6		8	7	5
Corrective	FM13	8	8	8	FM14	8	7	8	FM16	7	6	6
Preventive		9	10	7		9	8	8		8	7	7
Predictive		10	8	7		9	8	7		8	7	6
Design-out		10	5	7		10	6	7		10	3	2
Corrective	FM17	8	8	8	FM19	8	7	8	FM15	8	8	9
Preventive		8	8	8		8	7	7		8	8	8
Predictive		9	8	9		8	8	6		8	7	7
Design-out		10	4	5		10	6	5		10	6	6
Corrective	FM4	6	6	6	FM02	7	6	6	FM20	8	6	8
Preventive		8	8	8		8	8	7		8	8	8
Predictive		9	6	5		9	6	6		8	8	10
Design-out		10	6	4		10	6	4		10	10	10
Corrective	FM05	10	6	10	FM09	8	6	8	FM06	6	6	6
Preventive		8	6	10		8	8	8		6	8	6
Predictive		8	6	10		10	7	8		8	8	8
Design-out		8	6	10		10	6	6		8	7	5
Corrective	FM07	8	6	7	FM10	7	7	7				
Preventive		8	6	6		10	8	7				
Predictive		8	7	5		10	6	5				
Design-out		10	3	2		10	5	4				

Table E.2: TOPSIS Relative Closeness

		Relative Closeness			
Failure Mode		**Corrective**	**Preventive**	**Predictive**	**Design-out**
High pressure before filters	FM11	0.5762	0.6953	0.6573	0.3429
Choked	FM01	1.0000	0.0000	0.0000	0.0000
Unhealthy flow switch	FM18	0.1565	0.6627	0.6549	0.6252
Thermal Overload	FM08	0.0000	0.3978	0.4937	1.0000
Hydroset fault	FM03	0.2976	0.5215	0.7290	0.4785
Leaking grease pipe	FM12	0.1522	0.3953	0.7992	0.6047
Low oil pressure before filter	FM13	0.4962	0.7840	0.6436	0.3235
Low oil temperature	FM14	0.3224	0.6746	0.6330	0.5242
Oil flow low	FM16	0.5665	0.7360	0.7044	0.3535
Oil pipe leak	FM17	0.4737	0.6635	0.8172	0.3147
Blocked chute	FM19	0.4877	0.4011	0.4321	0.4417
Lube pump tripped	FM15	0.5355	0.4856	0.2881	0.4645
Low spider bearing temperature	FM04	0.2314	0.6573	0.5154	0.5500
High spider bearing temperature	FM02	0.2844	0.5978	0.5285	0.5173
Comms failure	FM20	0.0000	0.3978	0.4937	1.0000
Tighten bolts on top shell	FM05	1.0000	0.0000	0.0000	0.0000
Tripped	FM09	0.6481	0.5853	0.5853	0.4147
Unhealthy speed switch	FM06	0.1565	0.6627	0.6549	0.6252
Crusher overload	FM07	0.6962	0.6553	0.6566	0.2525
High oil temperature	FM10	0.4910	1.0000	0.5646	0.4437