Risk Management Solutions Flow to Implement Quantitative Methods as Part of ISO 55000 for Physical Asset Management

by

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Declaration

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Abstract

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Physical asset management has undergone a phenomenal growth period in recent years and is being acknowledged as a value adding activity that is critical to the success of any organization. The recently launched ISO 55000 series has sparked an entirely new course for PAM by introducing specific guidelines for implementing asset management. The purpose of this thesis is to investigate the quantitative requirements in ISO 55000 and how quantitative methods can be applied as part of a PAM program. It further intents to develop a basic Risk Management Solutions Flow framework primarily incorporating quantitative methods. An exhaustive literature study constitutes the first part of the research.

The literature study addresses the background of asset management and the transformation from traditional maintenance to asset management. Risk management is identified as the most important area of concern in asset management and ISO 55000. The focus of the research is therefore placed on the management of risk through quantitative methods. ISO 31000 provides a foundation for risk management and is touched on briefly. Sub-criteria are distinguished to form part of the risk management process including asset life cycle management, optimized decision making, asset criticality, financial management and failure analysis. The first two are incorporated throughout the entire development of the risk management solutions flow and asset criticality, financial management and failure analysis are integrated as independent sections. The literature study also includes a detailed overview of the entire ISO 55000 series and research regarding the various quantitative methods related to identifying critical assets, determining the financial impact and the extent of failure analysis.

The process of conceptualizing the risk management solutions flow commences based on the research executed during the literature study. The end result is a graphical representation of the detailed risk management solutions flow ready for implementation at an organization. In lieu of the developed risk management solutions flow, the framework is applied at an iron ore mine. Data is collected from the maintenance department during July and August 2015. The case study is the final part of the thesis and follows the sequence of the risk management solutions flow. The case study demonstrates the value of the risk management solutions flow to physical asset management and risk management associated with physical assets. Furthermore, the risk management solutions flow is critical in the introduction of ISO 55000 and adherence to the guidelines stipulated in the series. It also enables the organization to incorporate quantitative methods and become more aware of risks associated with the critical assets. Foremost, the risk management solutions flow paves the way for becoming ISO 55000 accredited by adhering to specific guidelines in the documents. Validation of the risk management solutions flow is achieved by applying it to a real world situation with actual data from an iron ore mine.

This thesis comes to a closure by determining that the risk management solutions flow can be used as a framework for implementing quantitative methods regarding risk management and ISO 55000. Future research may expand on the results of this study in order to develop an improved risk management solutions flow framework. The risk management solutions flow can be applied to different organizational types and even on employees as assets. Finally, the reach of the risk management solutions flow can be widened to enable full ISO 55000 accreditation.

Uittreksel

Risiko Bestuur Oplossings Vloei vir die Implementering van Kwantitatiewe Metodes as Deel van ISO 55000 vir Fisiese Bate Bestuur

("Risk Management Solutions Flow to Implement Quantitative Methods as Part of ISO 55000 for Physical Asset Management")

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Fisiese bate bestuur het 'n fenomenale vooruitgang ondervind oor die afgelope paar jaar en word tans beskou as 'n aktiwiteit wat waarde toevoeg en krities is tot die sukses van 'n besigheid. ISO 55000 is onlangs vrygestel en het bate bestuur in 'n nuwe rigting gestuur. ISO 55000 stel nuwe riglyne voor vir die implementering van bate bestuur. Die doel van dié tesis is om navorsing te doen omtrent kwantitatiewe riglyne in ISO 55000 en dus kwantitatiewe metodes toe te pas as deel van 'n bate bestuur program. Die studie streef ook na die ontwikkeling van 'n vereenvoudigde Risiko Bestuur Oplossings Vloei raamwerk wat hoofsaaklik gefokus is op kwantitatiewe metodes. 'n Volledige literatuur studie vorm deel van die navorsing.

Die literatuur studie brei uit op die agtergrond van bate bestuur assok die transformasie proses van tradisionele instandhoudings tegnieke na bate bestuur. Risiko bestuur word geidentifiseer as die mees belangrikste aspek van bate bestuur en ISO

55000. Die fokus van die navorsing word geplaas op die bestuur van risikos gekoppel aan fisiese bates met behulp van kwantitatiewe metodes. ISO 31000 verskaf ook 'n basis vir risiko bestuur en word kortliks bespreek. Spesifieke sub-kriteria word uitgewys as deel van die risiko bestuur proses insluitend bate lewens siklus bestuur, geoptimiseerde besluitneming, kritiese bate besluitneming, finansiële bestuur en falings analise. Die eers genoemdes word betrek deur die hele risiko bestuur oplossings vloei ontwikkeling en kritiese bate besluitneming, finansiële bestuur en falings analise, as los staande seksies. Die literatuurstudie behels ook 'n oorsig van die ISO 55000 series en die navorsing in verband met die kwantitatiewe metodes wat gepaard gaan met die identifisering van kritiese bates, finansiële bestuur en falings analise.

Ontwikkeling van die risiko bestuur oplossings vloei is gebasseer op die navorsing uitgevoer in die literatuurstudie. Die eind resultaat is 'n grafiese voorstelling van die gedetaileerde risiko bestuur oplossings vloei, wat geimplementeer kan word by enige organisasie wat afhanklik is van fisiese bates vir die bestaan en groei van die organisasie. Gepaardgaande met die ontwerp van die risiko bestuur oplossings vloei, word die raamwerk toegepas by 'n ystererts myn. Data is ontvang vanaf die instandhoudings departement in Julie en Augustus 2015. Die gevallestudie is die finale deel van die tesis en word toegepas gelykstaande met die volgorde van die risiko bestuur oplossings vloei. Die gevallestudie demonstreer die waarde van die risiko bestuur oplossings vloei vir FBB en risiko bestuur in verband met fisiese bates. Verder is die risiko bestuur oplossings vloei krities tot die bekendstelling van ISO 55000 en om te voldoen aan die riglyne soos gestipuleer in die reeks. Die risiko bestuur oplossings vloei stel die besigheid in staat om kwantitatiewe metodes te inkorporeer asook die bewusmaking van die risikos geasosieer met die kritiese bates. Die eind doel is om ISO 55000 akkreditasie te ontvang deur te voldoen aan die riglyne in die dokumente. Die akkreditasie proses word voorendag gebring deur die risiko bestuur oplossings vloei. Validasie van die risiko bestuur oplossings vloei is bereik deur dit toe te pas op 'n bestaande situasie met werklike data vanaf 'n ystererts myn.

Hierdie tesis kom tot 'n konklusie deur te bevestig dat die risiko bestuur oplossings vloei wel gebruik kan word as 'n raamwerk vir die implementering van kwantitatiewe metodes in terme van risiko bestuur en ISO 55000. Verdere navorsing kan uitbrei op die resultate van die studie deur die ontwikkeling van 'n verbeterde weergawe van die risiko bestuur oplossings vloei raamwerk. Die risiko bestuur oplossings vloei kan toegepas word op verskillend industrie tipes en selfs op personeel as bates. Die risiko bestuur oplossings vloei kan ook verder ontwikkel word sodat volle ISO 55000 akkreditasie bereik kan word.

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Papers and Publications

(1) Basson, W. and Vlok, P.J. (2014). 'Physical Asset Management Adjustments in line with Mining on the Coastal Regions of Southern Africa.' in *Proceedings of the 9th World Congress on Engineering Management (WCEAM)*, 28-31 October 2014, Pretoria, South Africa [accepted for publication].

(2) Basson, W., Minnaar, J.R. and Vlok, P.J. (2013). Quantitative Methods Required for Implementing PAS 55 or the ISO 55000 Series for Asset Management. *South African Journal of Industrial Engineering*, Vol 24, No 3.

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Acronyms and Abbreviations

AHP	Analytic Hierarchy Process
ALCM	Asset Life Cycle Management
API	American Petroleum Institute
BCR	Benefit-Cost Ratio
BSC	Balance Score Card
BSI	British Standards Institution
CA	Criticality Analysis
CBA	Cost-Benefit Analysis
CBM	Condition Based Maintenance
CE	Cost Effectiveness
CI	Consistency Index
CM	Continuous Miner
CPM	Critical Path Method
CR	Consistency Ratio
EU	Expected Utility
EVA	Economic Value Added
FMEA	Failure Mode Effects Analysis
FMECA	Failure Mode, Effects and Criticality Analysis
FRCA	Failure Root Cause Analysis
HPP	Homogeneous Poisson Process
HRA	Human Reliability Analysis
IAM	The Institute of Asset Management
IBM	International Business Machines
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LCCA	Life Cycle Cost Analysis
MAD	Mean Absolute Deviation
MAT	Maintenance Activity Type
MCCE	Multi-criterion Classification of Critical Equipments
MFOP	Maintenance Free Operating Period
MLD	Master Logic Diagram
MRP	Maintenance Recovery Period
MS	Microsoft
MTBF	Mean Time Between Failure

MTTF	Mean Time To Failure
NHPP	Non-Homogeneous Poisson Process
NOPAT	Net Operating Profit After Tax
NPV	Net Present Value
NQB	Net Quantifiable Benefits
OEE	Overall Equipment Effectiveness
OPE	Overall Process Effectiveness
ORM	Operational Risk Management
PAM	Physical Asset Management
PAS	Publicly Available Standards
PC	Personal Computer
PCNT	Pairwise Comparison Non-parametric
PDCA	Plan, Do, Check, Act
PDF	Probability Density Function
R&D	Research and Development
RA	Reliability Analysis
RCFA	Root-Cause Failure Analysis
RCM	Reliability Centered Maintenance
RCO	Risk-Cost Optimization
RI	Random Consistency Index
RMSF	Risk Management Solutions Flow
ROIC	Return On Invested Capital
RPN	Risk Priority Number
SAMP	Strategic Asset Management Plan
SRC	System Reliability Center
SSE	Sum of Squares Error
SSR	Sum of Squares Regression
SST	Sum of Squares Total
TDI	Toxic Damage Index
TLCAM	Total Life Cycle Asset Management
TPM	Total Productive Maintenance
TQM	Total Quality Management
TTF	Time To Failure
TTR	Time To Repair
UK	United Kingdom
WACC	Weighted Average Cost of Capital
WO	Work Order

Nomenclature

Chapter 4: Quantitative methods for implementing ISO 55000

Failure Mode and Effects (Criticality) Analysis (FME(C)A)

β	Failure Effect Probability
α	Failure Mode Ratio
λ	Part Failure Rate
τ	Operating Time

Risk Priority Number (RPN)

O	Frequency of Occurrence
S	Severity of the Effect
D	Ability to Detect the Failure

Criticality Analysis (CA)

C_m	Criticality Number for the Failure Mode
λ	Part Failure Rate
β	Failure Effect Probability
α	Failure Mode Ratio
d	Probability of Detecting Failure
t_h	Duration of Applicable Operating Hours

Theory of Probability and Bayes Theorem

A and B	Independent Events
P	Probability of
R	Reliability
x	Individual Items

Analytic Hierarchy Process (AHP)

n, i and j	Variables
w_i	Weight given to Criterion i
λ_E	Eigenvalue
R_j	Global Priorities
v_i	Respective Weights
r_{ij}	Scores

Risk Priority Number (RPN) with Fuzzy Logic

Z	Weighted Average Value
μ	Level of Membership in a Class
y	Class

Monte Carlo Simulations

$\hat{R}$	Reliability of the Unit
N_R	Number of Replications

Multi-criterion Classification of Critical Equipments

I_C	Criticality Index
c_i	Criterion
w_i	Weight of Criterion
n	Number of Criterion
l_i	Levels
m	Number of Levels
d	Number of Criticality Degrees
d_i	Criticality Degree of a Certain Equipment

Net Present Value (NPV)

t_y	Year from 0 to N
N_Y	Numbers of Years
r	Discount Rate

Benefit-Cost Ratio (BCR)

PV_{benefits}	Present Value of Benefits
PV_{costs}	Present Value of Costs

Economic Value Added (EVA)

r_{ROIC}	Return On Invested Capital (ROIC)
c_{WACC}	Weighted Average Cost of Capital (WACC)
K	Economical Capital Employed
$NOPAT$	Net Operating Profit after Tax
EV_{PAM}	Economic Value of Physical Asset Management
Otp	Output
Op	Operating
NQB	Net Quantifiable Benefits
$WACC$	Weighted Average Cost of Capital

Overall Equipment Effectiveness (OEE) and Overall Process Effectiveness (OPE)

A	Availability
η	Speed
p_d	Proportion Defective
N_s	Number of Stoppages
ϕ	Repair Rate
T	Loading Time
η_m	Number of Minor Stoppages
ϕ_m	Minor Repair Rate
t_r	Time Lost to Reduced Speed Operation
t_O	Operating Time
η_f	Defectives Made Just After Stoppages
η_c	Defectives Made When the Process was in Control
η_s	Defectives Due to Assignable Quality Control Causes
η	Total Number Units Made
ΔCE	Improvement in Cost-Effectiveness
C_a and C_b	Total Cost of Batch Before (b) and After (a) change in the policy

Laplace Trend Test

r_A	Arrival Times
S	Order Statistics

MTTF, MTBF, MFOP and Weibull Analysis

N_F	Total Number of Failures
x_i	Time Elapsed
i	Failures
$\hat{\theta}$	Mean Time To Failure (MTTF)
n	Number of Items Tested
t_i	Failure Times

t_{mf}	Surviving Units of Time
η	Scale Parameter
β	Shape Parameter
$R(t)$	Reliability

Log-Linear and Power Law Models

α_0 and α_1	Parameters for Log-Linear Model
λ and δ	Parameters for Power Law
t	Continuous Global Time
N_F	Expected Number of Failures

Markov Analysis

t	Time
i and j	States
p_{ij}	Probability of State i at Time t and State j at Time $t+1$
P_{S-F}	Probability of Transition from State S to F
P_{S-F}	Probability of Transition from State F to S

Forecasting Models

$f_{t,1}$	Forecasting Period for the Moving Average Model
N_P	Number of Periods
e_t	Forecast Error
A_t	Smoothed Average of a Time Series
α, β and γ	Smoothing Constants
L_t	Base Level
T_t	Per-Period Trend
c	Number of Periods in the Length of the Seasonal Pattern
s_t	Estimate of Seasonal Multiplicative Factor
ε_i	Error Term
R^2	Coefficient of Determination
s_e	Standard Error of Estimation
n	Number of Observations
r_{xy}	Sample Linear Correlation

Utility Theory

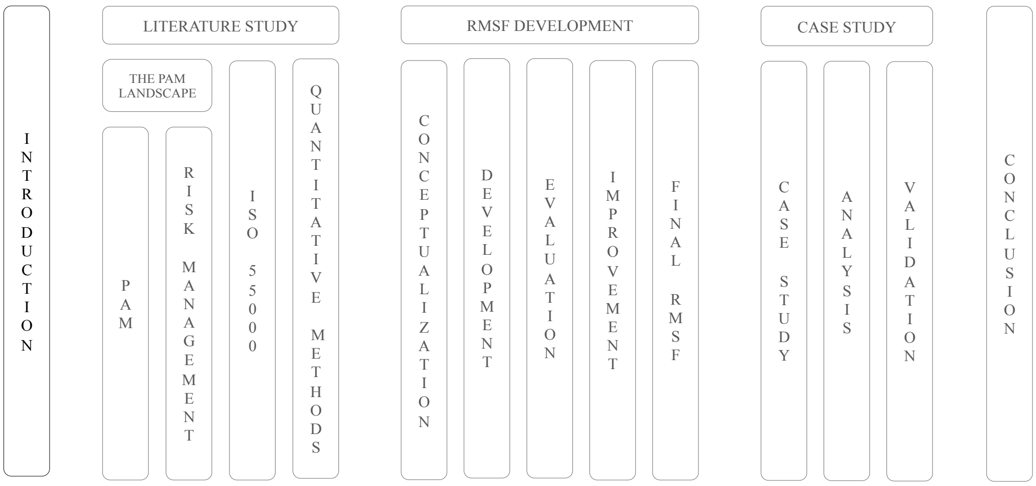
L	Lottery
r_i	Reward Received
p_i	Probability of Reward Received
u	Utility Function
q_i	Utility of the Reward

Chapter 1

Introduction

Chapter Aim:

The aim of this chapter is to introduce the study conducted. Physical Asset Management (PAM) is presented together with the growth the field has seen in recent years. Another important discussion is the importance of implementing a proper PAM program in an organization. Specific areas as part of the asset management landscape and the ISO 55000 series are explored. The move from traditional maintenance to PAM is examined. It goes further in introducing the new International Organization for Standardization (ISO) series known as ISO 55000, a brief look at the Publicly Available Specifications (PAS) 55 and finally risk management.



Chapter Outcomes:

- Introduction to the research landscape i.e. PAM, PAS 55, ISO 55000, Maintenance and Risk Management.
- Presentation of the problem statement and research objectives.
- Development of the research design and methodology.
- Delineation of the structure of this document.

1.1 Introduction

The field of Physical Asset Management (PAM) has undergone a monumental growth process in the last three decades. Ever since organizations realized that traditional maintenance programs were not giving the optimal results as expected, a new approach was needed. Maintenance costs are a critical part of the total operating costs of all production and manufacturing industries. Mobley (2002) gives some interesting facts regarding maintenance costs stating that it can be anything between 15 and 60 percent of the cost of goods produced. Furthermore, one-third of the money spent on maintenance is wasted due to unnecessary or improperly carried out maintenance. In the United States' manufacturing industry, this results in a loss of $60 billion each year. Thus, the need for proper maintenance techniques has become a value adding activity and not just *"a necessary evil"*. Port *et al.* (2011) summarizes the plight for asset management with the following statement:

> *"Today's maintenance and physical asset management managers face great challenges to increase output, to reduce equipment downtime, to lower costs, and to do it all with less risk to safety and the environment.*

Striving towards this balance is the essence of PAM and the full extent of PAM, as it is known today, has grown from a rich history surrounding asset management and maintenance techniques.

The early 1980s saw the introduction of innovative maintenance theories such as Total Productive Maintenance (TPM) and Reliability Centred Maintenance (RCM), which lead to the formation of PAM as a concept on its own. In recent years, the launch of the British Standard Publicly Available Specification 55 (PAS 55) set a new direction for the field of PAM. Research into asset management increased and organizations started adopting and implementing techniques as outlined in PAS 55. PAS 55 however, lacked the accreditation of being a standard for PAM and thus the International Organization for Standardization (ISO) formulated the ISO 55000 series, which is the first standard for and about PAM. ISO 55000 was finally launched at the beginning of 2014.

An important part of the standard was the need for quantitative methods when implementing a PAM program. The standard does not focus on giving complete guidelines in terms of the specific quantitative methods that are applicable to the various areas of the organization, but rather mentions the need for quantitative analysis numerous times in the series. Numbers and figures have always been an important measure of an organizations success and thus an important part of maintenance and asset management.

Another crucial part of the ISO 55000 standard, which is mentioned more than once, is the concept of risk management in the PAM environment. Associating the appropriate quantitative methods with risk management is critical to the success of the asset management process.

The rest of Chapter 1 introduces the key concepts and themes that lead this study and aims to understand the dilemma faced by organizations regarding PAM, maintenance and risk management. Commencing with the primary theme of the research namely Physical Asset Management (PAM).

1.2 Physical Asset Management

Physical Asset Management (PAM) is the management of fixed or non-current assets and therefore it is fundamental to have a firm grasp on certain aspects of asset management to understand the PAM process. These include:

- Background information regarding PAM.
- The definition of a *physical asset* and the description of PAM.
- Changing from traditional maintenance to PAM and Asset Life Cycle Management (ALCM).
- The PAM process and the most important areas associated with PAM.
- The importance of PAM in organizations today.

Subsequently, these aspects are discussed throughout the rest of this chapter. Chapter 1 thus provides the background to the rest of the research.

1.2.1 Background

Asset management as a concept has been used by the financial service sector for more than a century to define the optimum balance between risk and reward. Asset management in the financial industry relates to portfolios consisting of stocks, cash, shares and other investments as described by The Institute of Asset Management (2011) also known as the IAM. However, it required a catastrophic event for asset management to shift towards physical assets and for PAM to gain acknowledgement.

The Piper Alpha disaster of 1988 caused the death of 167 workers when an explosion occurred due to a gas leak as described by the newspaper, The Guardian (2013). The Piper Alpha was a fixed oil production platform about 193 kilometres north-east of Aberdeen. It was later determined that the maintenance and safety procedures were not up to standard. Following the disaster and the crash of the oil price in the 1980s, the North Sea Oil & Gas industry turned to multi-disciplined teams managing each oil platform as an asset by taking the whole life cycle into consideration. Parallel to this change in the management of assets, the public sector in Australia and New Zealand were forced to consider better planning methods as costs rose and service levels went down. These changes inspired the move from maintenance to life cycle management and slowly PAM became more important in the engineering maintenance and asset management industry.

2004 brought the first documented guidelines associated with PAM to the table in the form of PAS 55 (PAS 55 (2010)), the Public Available Specification (PAS) published by the British Standards Institution. Reyes-Picknell (2011) gives a brief introduction to PAS 55. PAS 55 took nine years to be published and only gained recognition in 2006 when the United Kingdom (UK) utilities section acknowledge the document and started implementing the ideas described in PAS 55. Since publication, PAS 55 has become increasingly popular in the world of PAM by giving a framework to establish good management practices. PAS 55 was revised in 2008 and accepted by the International Standards Organization (ISO) as the basis for the ISO 55000 series.

The ISO 55000 series was launched in early 2014 after being developed and reviewed since 2011 as summarized by The Woodhouse Partnership Ltd (2014). It is the first official standard related to PAM. According to Minnaar, Basson and Vlok (2013), the ISO 55000 series:

> *"provide a minimum set of requirements for an effective asset management system, but allow the organization itself to determine how best it should be implemented to suit their needs".*

The above description of the ISO 55000 series is directly related to this thesis as it aims to provide the organization with the right set of quantitative tools to adhere to the quantitative guidelines in the ISO 55000 series. The ISO 55000 series is discussed briefly in this chapter and in detail in Chapter 3. Furthermore, to be able to understand the entirety of the series, it is crucial to understand the definition of physical assets and asset management.

1.2.2 Physical Assets and Asset Management

Distinguishing between assets and physical assets is an important part of understanding PAM. Defining a physical asset sets it apart from the more established financial asset management. A number of sources have created definitions to explain the terms associated with PAM, but the underlying intention boils down to same idea.

Amadi-Echendu (2004) defines an asset as follows:

> *" . . . an asset may be described as an entity which has the capability to create and sustain value while in current use, or that which appreciates in value because of perceived capability to create value in future use"*

ISO 55000 (2014) goes further in identifying a physical assets as *"equipment, inventory and properties owned by the organization".*

Physical assets also include humans i.e. employees of the organization. Amadi-Echendu (2004) adds to the definition of the ISO 55000 series by classifying physical assets in four groups namely plant and equipment, buildings and infrastructure, furniture and fittings and information technology.

PAS 55 (2010) defines five categories of assets: human assets, financial assets, information assets, intangible assets and of course, physical assets. Figure 1.1 shows each category and how they interact and relate to physical assets.

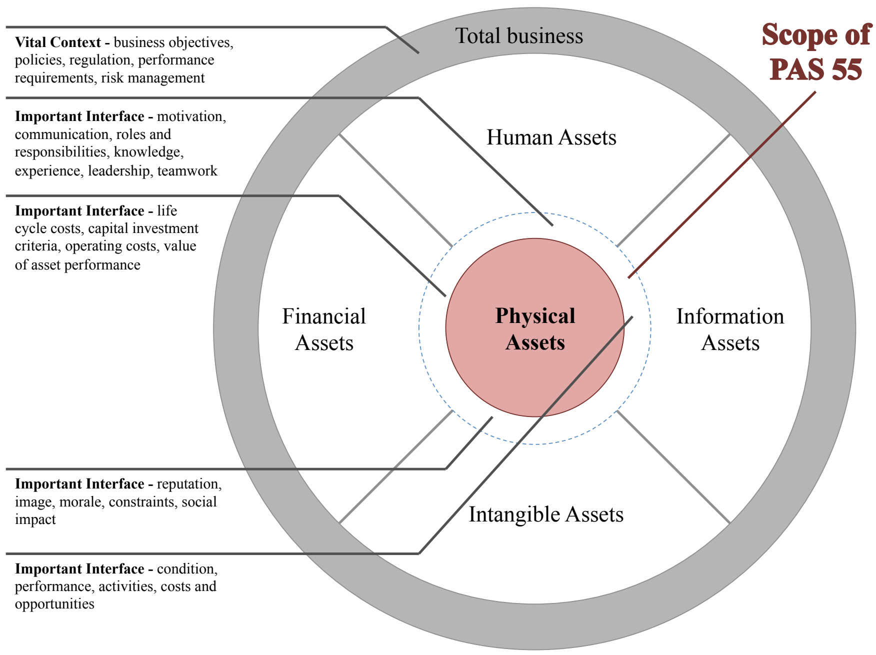


FIGURE 1.1: Types of assets identified by PAS 55.
Adapted from PAS 55 (2010)

To summarize the definitions above, a physical asset is an entity that creates, sustains or has the potential to create value and includes, but is not limited to, equipment, infrastructure, valuables, inventory, information and employees. Having properly defined physical assets, it is now easier to understand the asset management process applied to these assets.

Woodhouse (2001) focus on the *"Whole Life Business Impact"* when defining PAM:

> *"The set of disciplines, methods, procedures and tools to optimize the Whole Life Business Impact of costs, performance and risk exposures (associated with the availability, efficiency, quality, longevity and regulatory/safety/environmental compliance) of the company's physical assets."*

This concept of the *"Whole Life Business Impact"* is further explored in the following description of PAM by The Institute of Asset Management (2011):

> *"It converts the fundamental aims of the organisation into the practical implications for choosing, acquiring (or creating), utilizing and looking after (maintaining) appropriate assets to deliver those aims. And it does so while seeking the best total value approach (the optimal combination of costs, risks, performance and sustainability).*

Another definition of asset management from Pudney (2010) further elaborates on the various elements contributing to PAM:

> *"Asset Management is an organisation's coordinated multi-disciplinary practice that applies human, equipment and financial resources to physical assets over their whole life cycle to achieve defined asset performance and cost objectives at acceptable levels of risk whilst taking account of the relevant governance, geo-political, economic, social, demographic and technological regimes."*

All of these definitions are in their own way complete, but could possible add to the confusion of the PAM environment. However, the most understandable, basic and most descriptive definition of PAM is as described in Schneider *et al.* (2006):

> *"Asset management means operating a group of assets over the whole technical life-cycle guaranteeing a suitable return and ensuring defined service and security standards."*

This definition refers back to the discussion of the *"Whole Life Business Impact"* by Woodhouse (2001).

Finally, asset management is broken down into its most important factors and analyzed in more detail. Ruitenburg *et al.* (2014) gave five criteria that PAM fulfils. PAM is

- a multidisciplinary practice;
- in which the whole life cycle of a physical asset is taken into account;
- with the goal to achieve certain objectives;
- within the limits of risk and relevant regimes; and
- that this should determine the allocation of resources.

The five criteria mentioned above as well as the various definitions of PAM, enable the discussion and understanding of the core values of this research throughout the rest of this chapter. These values include PAM, PAS 55, the ISO 55000 series, risk management and the role of maintenance. These areas are of paramount concern to the research and are a result of the essential role of physical asset management in industry.

1.2.3 The Importance of Asset Management

Over recent decades the importance and value of PAM have been clearly acknowledged. Technology is identified as one of the main reasons for the increase in awareness. Organizations are making use of more machines and automated processes and thus maintenance and asset management are crucial to the success of the company according to Zuashkiani *et al.* (2011).

Organizations relying heavily on their physical assets, assign a large part of their operating budget to maintenance (Tsang *et al.* (1999)). Maintenance is an expense that is often regarded as a necessity and not one that can actually add value to the company. Therefore, maintenance costs can quite easily be one of the items being reduced when an organization needs to make budget cuts. Tsang (2002) found that the UK manufacturing industry spends between 12 and 23 per cent of the total factory operating costs on maintenance. It is thus of critical importance to manage and operate the already existing assets optimally. Four developments are identified by Tsang (2002) that complicates the demand for maintenance. These include:

(1) *Emerging trends of operation strategies.* Many organizations have moved to *"lean manufacturing"*, *"just-in-time production"* and *"six-sigma programs"*. These trends are beneficial to the organization by adjusting the focus from volume to quick response times, eliminating waste and preventing defects. However, these revolutionary techniques have a downside as the need for the right and properly managed equipment increases drastically and thus increase costs.

(2) *Toughening social expectations.* The issues regarding the environment and the health and safety of humans have increased significantly. These problems are often the result of organizations not operating at optimal conditions. Proper maintenance and asset management programs could reduce waste and pollution and lead to less accidents and health hazards.

(3) *Technological changes.* New technology presents a catch-22 situation to the field of maintenance. It creates new methods, software and equipment to implement maintenance techniques and plans. In contrast, it improves areas in the organization that requires further maintenance.

(4) *Changes in the people and organizational systems.* People's requirements regarding their career and work environment, have changed a great deal over recent years. The increase in education and the ability of people to manage themselves have led to a change in the structure of the organization. People

now strive towards quality of life at work. The changing structures of the work environment could also complicate the process of maintenance or in some ways enable excellent progress in terms of moving away from traditional maintenance techniques.

According to Arunraj and Maiti (2007) downtime has always had a severe impact on the productivity of physical assets. Downtime reduces production, increases operating costs and disturbs customer service quality. The effect of just-in-time, as also mentioned by Tsang (2002), aggravates the effects of downtime. Adding to the issues identified by Tsang (2002), the following problems in regards to badly managed maintenance are recognized by Arunraj and Maiti (2007):

- More failures lead to unsatisfactory quality.
- More failures lead to safety and environmental issues.
- Maintenance costs are rising rapidly (in terms of total expenditure). In some industries it is now the second highest or even the highest percentage in regards to operating costs.
- Product quality, plant safety and increasing maintenance costs are responsible for between 15% and 70% of total production costs.

The above listed complications identifies maintenance as a real double-edged sword if not managed properly. Thus, the need for proper maintenance techniques and the identification of PAM as a field on its own, lead to the creation of PAS 55.

1.3 Publicly Available Specifications 55

The Institute of Asset Management (IAM) and the British Standards Institution (BSI) introduced PAS 55 in 2004 due to the increasing demand from industry for a standard regarding asset management. The standard was revised in 2008. According to PAS 55 (2010) this standard:

> *"(It) is applicable to any organization where physical assets are key or a critical factor in achieving its business goals."*

Therefore, PAS 55 is accepted across industries and has been recognized as a valuable contribution to asset intensive organization. Furthermore, PAS 55 is briefly summarized by The Institute of Asset Management (2014) and indicates the following areas of concern:

(1) Definition of terms in asset management.

(2) Requirement specification for good practice.

(3) Guidance for the implementation of such good practice.

Referring back to the definitions of PAM, PAS defines asset management as:

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

PAS, as mentioned earlier in this chapter, describes the five categories of asset types: human assets, information assets, financial assets, intangible assets (for example reputation, morale etc.) and physical assets. Physical assets are undeniable linked to each of the other four categories as seen in Figure 1.1, but PAS 55 deals specifically with physical assets.

Furthermore, PAS discusses the need for an asset management system in a variety of industries. The common denominator is the fact that all of these organizations rely on the function and performance of their physical assets and the return value provided to the organization by their assets.

It is important to remember that PAS only defines what *has* to be done and not *how* to do it. The organization needs to take initiative with the *how*. However, the standard does require the implementation of an asset management system, an asset management policy, an asset management strategy, asset management objectives and asset management plan(s).

PAS 55 Section 4 [1] namely *Asset management system requirements* is subdivided into seven areas of concern:

(1) General requirements

(2) Asset management policy

(3) Asset management strategy, objectives and plans

(4) Asset management enablers and controls

(5) Implementation of asset management plan(s)

(6) Performance assessment and improvement

(7) Management review

Reyes-Picknell (2011) describes PAS 55 as *"a framework outlining good management practices for many asset intensive industries around the world"*.

The Plan-Do-Check-Act (PDCA) cycle, or also known as the Deming Cycle, is *"a systematic series of steps for gaining valuable learning and knowledge for the continual improvement of a product or process"* according to The Deming Institute

[1]To avoid confusion between the sections of this thesis and the sections in PAS 55, the sections in PAS 55 will be referred to as *"PAS 55 Section x"*.

(2015). It involves four steps namely PDCA, and these are repeated continuously throughout the process as part of a never-ending cycle.

Figure 1.2 is a summary of where the different divisions of PAS 55 fit in with the Plan-Do-Check-Act (PDCA). Each section in PAS 55 is linked to a step in the PDCA. For example, PAS 55 Section 4.3 titled *Asset management strategy, objectives and plan* is filed under the *Plan* step.

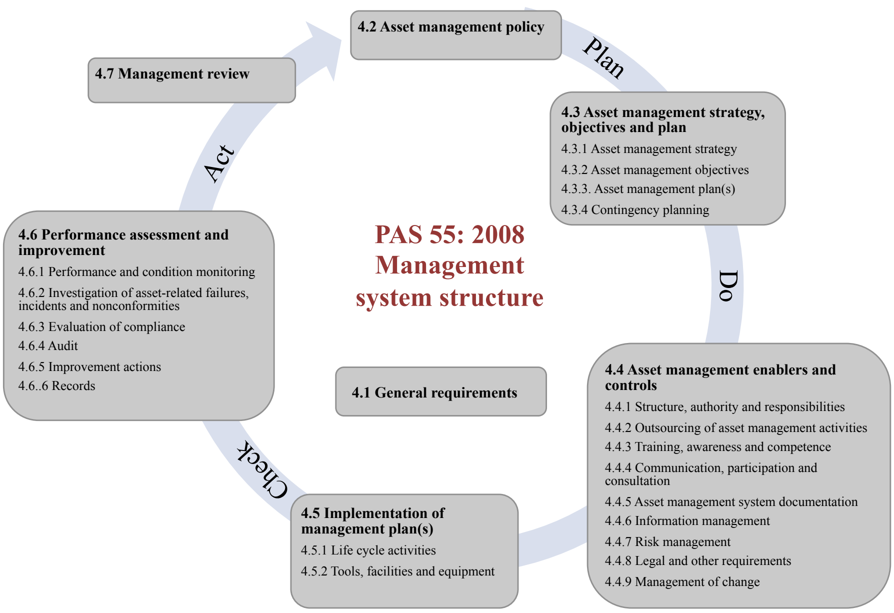


FIGURE 1.2: PAS 55 management system structure.
Adapted from PAS 55 (2010)

The success of PAS 55 led to the further recognition of asset management as an important discipline and evolved to the development of a standard for PAM known as the ISO 55000 series.

1.4 International Organization for Standardization 55000 (ISO 55000)

According to research by Botha (2014), ISO 55000 has many benefits for organizations willing to adopt the standard. These include being recognized internationally, spreading the value of asset management to the boardroom as well as to sections in the organization other than the maintenance department, creating a culture of continuous improvement and also recognizing asset management as a discipline.

Adding to these advantages, Fogel (2012) gives ten reasons why the asset management standard will play a role in the future of asset management. It includes advantages such as top management commitment to asset management strategies, creating alignment and consistency across the entire organization, providing a procedure for organizations who are starting to implement asset management strategies and being internationally recognized. To name but a few. The downside of the ISO 55000 series, as mentioned by Botha (2014), is that the asset management best practices or technical aspects are not covered. The ISO 55000 series includes **Note 2** several times as part of the *Scope* of the document. **Note 2** states that:

> *"This International Standard does not provide financial, accounting and technical guidance for managing specific asset types."*

In a study done by Fogel and Terblanche (2014), more than 50 mines across the globe were surveyed regarding their asset management maturity. The study found that only a few mines are achieving the desired outcomes in comparison to the industry averages. Although the mining industry is not adopting the proper asset management plans, they do realize the value of asset management. Further complicating the adoption of an asset management program is the novelty of the ISO 55000 series resulting in the mining industry struggling to come to terms with the extent of requirements in the standard. These problems are extended to industries above and beyond just the mining industry.

ISO 55000 is discussed in more detail in Chapter 3 as well as the requirements in terms of quantitative methods and risk management. The fundamentals of PAM and the ISO 55000 series are based on the traditional maintenance domain and it is thus significant for this research to build an understanding of this specific field.

1.5 Maintenance

> *"Maintenance plays a key role in an organization's long-term profitability and has increasingly become part of a total performance approach, together with other topics such as productivity, quality, safety and environment.*

These are the views of De Groote (1995) and he goes further to say that maintenance performance is onerous to establish, because one has to dictate quantitative parameters as well as qualitative parameters.

Moubray (1997*a*) reported that over the last few decades, maintenance have undergone noteworthy changes, more so than any other management discipline. Certain factors have promoted these changes according to Hameed *et al.* (2014): an increase in the variety and number of physical assets acquired by an organization, design complexity, novel maintenance philosophies and techniques, the way maintenance in an organization is viewed as well as the responsibilities associated with it.

Today, hundreds of pieces of equipment make up an organization. The difficulty lies in developing and optimizing the maintenance strategy while considering the operations of the entire plant. Hameed *et al.* (2014) proposes a solution to this problem by moving towards a *"risk-based critical component selection"* and using an *"optimized shut-down and maintenance interval"*. They go further to establish that risk, reliability and availability are interlinked.

The development of maintenance techniques has gone through four phases as researched by (Arunraj and Maiti (2007)): first, second, third and recent generations. Types of maintenance techniques have also been identified over the years. It includes preventive maintenance, corrective maintenance, predictive maintenance and proactive maintenance. The four phases of maintenance as well as the four types of maintenance are discussed in detail in Chapter 2. Focusing on the *"risk-based critical component selection"* identified by Hameed *et al.* (2014), the final area of significance to this thesis is that of risk management.

1.6 Risk Management

According to the American Petroleum Institute (API Publication (2002)), risk is *"a combination of the probability of an event and its consequence"*. Bharadwaj *et al.* (2012) summarize the definition of risk as *"a deviation from the normal or expected"* Lai and Lau (2012) states that many unpredictable risk events can affect the operational environment of an organization and interpret risk management as follows:

> *"Risk management is a pro-active approach to identify, analyse, and manage all potential risk faced by a company.*

The potential risk events can occur suddenly and unexpectedly and could have a momentous impact on the short- and long-term performance of the company according to Tang (2006). Thus, these events should be managed precisely to avoid suffering a loss.

The need for more realistic quantification of risk factors is an important part of PAM and currently the lack thereof is still evident. Bharadwaj *et al.* (2012) claims that a risk-based approach to asset management gives organizations more flexibility while still meeting the objectives. The flexibility is due to not keeping to a fixed asset management schedule, but rather basing decisions on specific risk measures. The quantification of risk is depended on the quality of the consequences of the study as well as the estimates of the probability of failure (Khan and Haddara (2003)).

A proper risk management plan can provide many benefits to an organization as listed in ISO 31000 (2009) and will enable the organization to

- achieve their objectives;
- manage pro-actively;
- be aware of the importance of identifying and treating risk throughout the entire organization;

- improve the process to identify opportunities and treats;
- adhere to legal and regulatory requirements as well as international standards;
- enhance reporting – mandatory and voluntary –;
- achieve better governance;
- gain trust and confidence from stakeholders;
- determine a basis for decision-making and planning that is reliable;
- improve controls;
- assign and use resources associated with risk treatment appropriately and effectively;
- improve the effectiveness and efficiency of operations;
- enable the protection of the environment as well as enhancing the health and safety aspect;
- increase loss prevention statistics and manage incidents more effectively;
- reduce losses;
- promote organizational learning; and
- build organizational resilience.

These are just some of the aspects that will improve once an organization starts focusing on proper risk management.

The Aberdeen Group conducted research on the operational risk management strategies for asset intensive industries (Shah and Littlefield (2011)) and identified areas where risk is present. Some of the most important risk areas include employee safety, plant safety, failure of assets, environmental damages, non-compliance and supplier non-conformance or roughly categorized as people, processes and asset risks.

Additionally, Shah and Littlefield (2011) concludes that insufficient resources are the biggest challenge faced by organizations regarding risk management. An organization is also faced with the problem of establishing a risk-based culture and providing decision makers with the appropriate information. It is of fundamental value to provide historical as well as real-time data in terms of assets as well as quantifying risk in terms of financial performance.

Risk Management is discussed in detail in Chapter 2 and the focus is also placed on why risk management is important in the PAM landscape. Concluding the introduction to the research, the dilemma observed is defined, refined and summarized as the Problem Statement.

1.7 Problem Statement

The evolution of maintenance into PAM has caused a stir in many organizations and it has quickly become a necessity when striving to be an industry leader. In response to the growing request for asset management, PAS 55 was launched to guide organizations by providing a standard of what needs to be done in terms of asset management. The continuous growth of PAM resulted in the highly anticipated ISO 55000 series, which was launched in January 2014. This is the first internationally recognized standard for asset management and has replaced the PAS 55 specification as discussed by van den Honert *et al.* (2013). For the first time there is a standard for asset management that could lead to accreditation for the organization. In direct comparison, it also increased the pressure on organizations to become ISO 55000 accredited.

As mentioned, the ISO 55000 series tells organizations what to do and not how to do it according to Minnaar *et al.* (2013). Furthermore, the need for quantitative methods is identified in various sections in the ISO 55000 series. This can create complications for any organization as the question now becomes: *what quantitative methods have to be used to facilitate accreditation?* The need for decision-making criteria is discussed in ISO 55002. ISO 55002 Section 4.2.4 [2] supports the need for quantitative methods with the following statement:

> *"The criteria can be expressed in a number of ways, to support quantitative, semi-quantitative or qualitative decisions."*

Also in ISO 55002 Section 6.2.1.1, the asset management objectives are described as being "*quantitative measurements (e.g. mean time between failure) and qualitative measurements (e.g. customer satisfaction)*".

Minnaar *et al.* (2013) identifies the important areas that require quantitative methods as well as give some examples of methods that can be used to aid the process of asset management and becoming ISO 55000 accredited. In addition, various literature governs the critical areas important to PAM and through a ranking process, which is discussed in Chapter 2, the number one area of concern is discerned as risk management. The need for a practical framework consisting of various quantitative methods focused on risk management to aid the ISO 55000 accreditation process, is currently missing in organizations.

Thus, to formulate the research problem in a concise manner, a quick summary is provided. The most important part of the research regarding the field of asset management is the novelty of the ISO 55000 series and the difficulty organizations experience in understanding the full extent of the requirements. This is further complicated by the need for quantitative methods in terms of which methods to use and how to incorporate them into an asset management program. The main

[2] To avoid confusion between the sections of this thesis and the sections in the ISO 55000 series, the sections in the ISO 55000 series will be referred to as *"ISO 5500y Section x"*.

concern is thus that any organization needs a practical and basic process to start implementing ISO 55000.

This study aims to address this need in a practical and easy to understand manner. The goal is to introduce organizations to the newly launched ISO 55000 series and start the process of becoming accredited. The primary focus is risk management and quantitative methods which are identified as the most critical areas of concern in the ISO 55000 series. It was decided that a user-friendly, risk management framework applicable to any industry to implement quantitative methods that will facilitate the asset management process and lead to ISO 55000 accreditation, is the ultimate solutions. From the problem statement, specific research objectives are developed and lead the research in finding a possible solution.

1.8 Research Objectives

The problem statement guides the development of the objectives of this research study and leads to the execution of the research. The main objective of the research is to provide any industry with a risk management framework in terms of quantitative methods in regards to requirements in ISO 55000 with the end goal of becoming ISO 55000 accredited. An important factor to remember when perusing this thesis, is that it is not an objective to enable an organization to become ISO 55000 accredited, but rather aiding and facilitating the process **towards** accreditation.

Sub-objectives are identified that support the main objective of this thesis and build the foundation of the research study. The first sub-objective is to capture the fundamentals of the critical components that form the research domain of this thesis. An exhaustive literature study in Chapter 2 provides a deeper understanding of the PAM environment and risk management to satisfy the first objective. Secondly, this chapter discusses the important areas of concern in the research regarding PAM, ISO 55000, PAS 55 and those related to quantitative methods.

The research study is further expanded with Chapter 3 to adhere to the next three objectives. A descriptive summary and analysis of the ISO 55000 series is given. The need for quantitative methods in ISO 55000 and the discovery of what it means to become ISO 55000 compliant covers two further objectives respectively.

The final chapter that forms part of the literature study is Chapter 4 and fulfils two research objective. Firstly, the expansive range of quantitative methods related to PAM is investigated and these methods are then grouped according to the areas of concern discerned in Chapter 2.

Chapter 5 pursues the single research objective of constructing a simplified risk management framework or Risk Management Solutions Flow (RMSF). The framework development builds on the findings in the literature review and results in a final descriptive process ready for implementation.

Chapter 6 is responsible for the case study. Two more objectives are met in this chapter by means of the application of the RMSF and the validation of the results obtained. The final research objective is the closure of this thesis in Chapter 7. A conclusion is drawn and the limitations existing throughout the case study are emphasized. Further research opportunities are uncovered and discussed.

Table 1.1 shows the corresponding sequence of research objectives in this thesis. Finally, the problem statement and research objectives drive the thesis to set in motion the methodology and roadmap to attain a possible solution.

TABLE 1.1: Sequence of research objectives.

Chapter 2	
1.	Establish the fundamentals of PAM and risk management.
2.	Single out the most important areas in the research domain.
Chapter 3	
3.	Construct a summary of the ISO 55000 series.
4.	Determine the need for quantitative methods in ISO 55000
5.	Understand what it means to become ISO 55000 compliant.
Chapter 4	
6.	Research the vast collection of quantitative methods related to PAM.
7.	Group the various quantitative methods according to the identified areas.
Chapter 5	
8.	Systematically develop a simplified risk management framework.
Chapter 6	
9.	Apply the constructed risk management framework.
10.	Validate the analysis results.
Chapter 7	
11.	Draw conclusions from the analysis and present limitations and future research opportunities.

1.9 Research Methodology

Traditionally, a distinction was drawn between qualitative and quantitative research. Newman and Benz (1998) suggests that these two techniques are not dichotomies, but rather defines them as:

> *" . . . the two philosophies are neither mutually exclusive (i.e., one need not totally commit to either one or the other) nor interchangeable*

> *(i.e., one cannot merge methodologies with no concern for underlying assumptions). Rather, we present them as interactive places on a methodological and philosophical continuum based on the philosophy of science."*

Furthermore, Newman and Benz (1998) claims that qualitative research methods are the starting point followed up by more quantitative methodologies. Onwuegbuzie and Leech (2005) studied the value of combining quantitative and qualitative research methodologies. They concluded that establishing a divide between these two methodologies is only detrimental to the research conducted and by utilizing both in the same framework results in more *"pragmatic researchers"*. In order to add value to an existing field of research, it is critical to incorporate both qualitative and quantitative methodologies in a thesis.

This thesis is based primarily on the quantitative aspect of ISO 55000 and PAM. However, this does not signify that qualitative research methodologies should be ignored entirely. Creswell (2009) explains specifically in his book that the exploratory nature of qualitative methods is beneficial when minor research is conducted. Therefore, an approach of mixed-methods i.e. qualitative and quantitative research philosophies is used in this thesis. The initial research is qualitative in nature with an extensive literature study around PAM, ISO 55000, PAS 55 and Risk Management. Research into the quantitative methods applied to PAM as well as the initial contextualization of the RMSF adds to the qualitative analysis. Concluding the research is a case study based on real life data extracted from a large iron ore mine. The case study follows the course of the RMSF and the need for quantitative research methodologies is key to the development of the end results.

Deductive and inductive reasoning are two methods used as part of a research process. The problem statement and the critical components identified in Chapter 2 classified as important in ISO 55000, PAM, PAS 55, in the general research field and for quantitative methods are part of deductive reasoning and thus *deductively derived*. In contrast, the process of contextualizing the Risk Management Solutions Flow (RMSF), is *inductively derived* and part of inductive reasoning. Consequently, this thesis utilizes both inductive and deductive reasoning.

The penultimate section shows the full project roadmap and the steps taken to conduct the research.

1.10 Project Roadmap

The research methodology is a systematic process guided by the research objectives and the following steps attempts to achieve the desired objectives:

(1) Research the PAM and Risk Management fields and identify critical areas.

(2) Master the ISO 55000 series and identify areas of concern.

(3) Develop a thorough understanding of the quantitative methods that are applicable to the areas of concern identified in the ISO 55000 series.

(4) Understand the process to become ISO 55000 accredited and what this means in regards to quantitative methods associated with risk management.

(5) Research the quantitative methods applicable to PAM and risk management.

(6) Assign specific quantitative methods to the critical areas identified.

(7) Design a user-friendly risk management framework for asset intensive industries that relates quantitative methods to the ISO 55000 series to enable the process of achieving accreditation.

(8) Validate the procedure by implementing and applying the methods identified as part of a case study.

(9) Provide a descriptive closure for the research.

In Figure 1.3 these steps are transformed into a project roadmap for the intended research study.

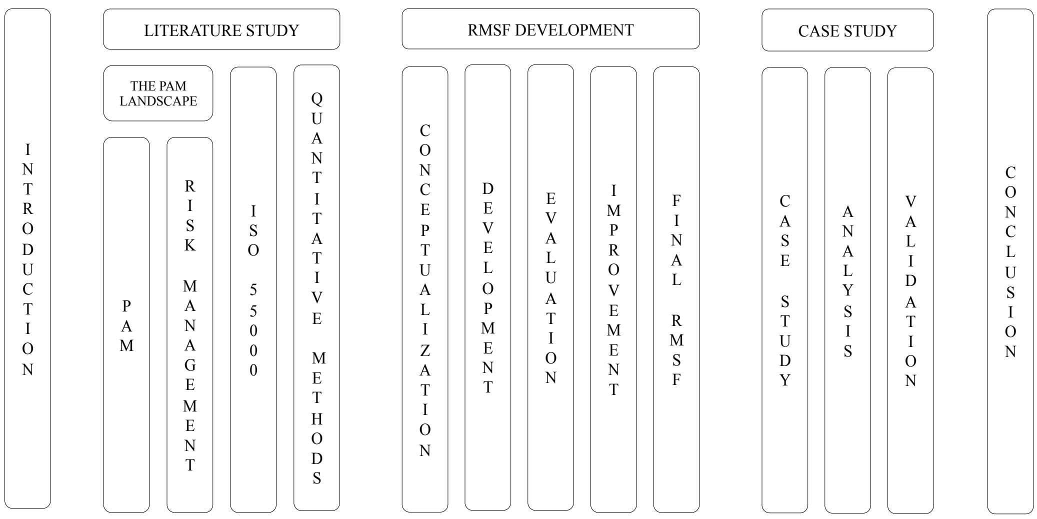


FIGURE 1.3: Project Roadmap.

The roadmap guides the research and is fully illustrated in terms of the full document layout in the final section of Chapter 1.

1.11 Document Structure

In this chapter the PAM environment and the ISO 55000 series are introduced. The problem statement is discussed in detail and motivates the reason for conducting the research study. The research methodology and project roadmap are an extension of the research problem and guide the flow of this thesis. An encapsulation of the thesis as a whole is outlined below.

Chapter 1: Introduction

Chapter 1 is the introductory section. This chapter focuses on the research environment and specifically on Physical Asset Management (PAM), PAS 55 and ISO 55000. The problem statement and research objectives are explored. Finally, the thesis layout is produced and renders a document structure and project roadmap.

Chapter 2: Physical Asset Management

Chapter 2 is a literature study of the PAM landscape. It builds on the introduction made in *Chapter 1*. This chapter includes a review of the PAM domain, traditional maintenance, the important areas associated with PAM and a discussion of these areas, especially risk management, in more detail.

Chapter 3: The ISO 55000 Series

Chapter 3 is an in-depth analysis of the ISO 55000 series and more specifically the areas that require the use of quantitative methods. The ISO 55000 series is outlined and summarized according to the structure of the ISO 55000 series.

Chapter 4: Quantitative Methods for Implementing ISO 55000

Chapter 4 is the literature study of the different quantitative methods available and applicable to the asset management process in becoming ISO 55000 accredited. The various quantitative methods are grouped according to the three areas of concern under risk management. Applicable examples are also provided where needed.

Chapter 5: Risk Management Solutions Flow for ISO 55000 Accreditation

Chapter 5 is the conceptualization of the risk management framework denominated as the Risk Management Solutions Flow or in short the RMSF. It outlines the framework and describes the steps needed to implement the RMSF. The procedure for risk management adheres to the requirements stipulated in the ISO 55000 series and the appropriate quantitative methods are analyzed.

Chapter 6: Case Study

Chapter 6 is the final step of the research. The risk management solutions flow as described in *Chapter 5* is validated by means of a case study conducted in regards to the quantitative methods identified in *Chapter 4*. The entire process and results are depicted in *Chapter 6*.

Chapter 7: Conclusion

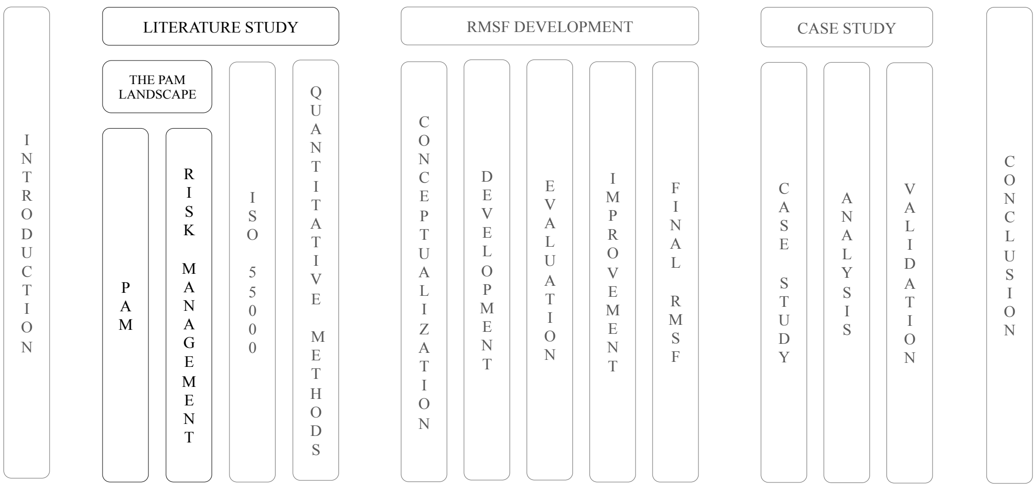
Chapter 7 reflects on the research study and identifies limitations and discrepancies. Finally, a conclusion is drawn and future research opportunities are identified.

Chapter 2

Physical Asset Management

Chapter Aim:

The aim of this chapter is to establish a deeper understanding of the terms and PAM concepts introduced in Chapter 1. The PAM landscape is scrutinized and the important areas associated with PAM are ascertained by means of ranking.



Chapter Outcomes:

- Further analysis of the PAM environment.
- Understanding the role of maintenance as the foundation of PAM.
- Discovery of Risk Management and the ISO 31000 documents.
- Identifying specific critical areas in PAM.

2.1 Physical Asset Management

> *"A physical asset is an entity that creates, sustain or has the potential to create value and includes, but are not limited to, equipment, infrastructure, valuables, inventory, information and employees."*

The above definition of a physical asset is as summarized in Chapter 1 from the numerous definitions for physical assets as gathered through the literature. Thus, the field of Physical Asset Management (PAM) is the management of equipment, inventory and properties owned by the organization.

Even though the field of PAM has been recognized for some time, Lutchman (2006) claims that companies still struggle to distinguish between traditional maintenance and PAM.

According to Port *et al.* (2011) effective asset management strives to achieve the following:

- Maximize uptime.
- Maximize accuracy.
- Minimize cost per unit produced.
- Minimize the risk that productive capacity, quality, or economic production will be lost for unacceptable periods of time.
- Prevent safety hazards to employees, and the public.
- Ensure the lowest possible risk of harming the environment.
- Conform to national and international regulations on due diligence.

The first component paramount to the field of PAM is reliability and is further discussed in the succeeding section.

2.1.1 Reliability

An important part of establishing a maintenance management program is reliability studies. These forms of analysis is becoming a standard practice in any organization. Especially in the mining industry as established in the research by Vagenas *et al.* (1997). Furthermore, reliability is researched by Morad *et al.* (2014) and clarified with the following definition:

> *"Reliability is defined as the probability of the system mission implementation without occurrence of failure at a specified time period"*

Morad *et al.* (2014) also affirms that reliability is a suitable quantitative metric for calculating system survival. Reliability is determined by the failures of the system and *"proper statistical techniques"*. Reliability is directly related to failure analysis and thus an important factor in implementing PAM.

Managing equipment is becoming more and more complex and it is vital to effectively use all resources to achieve high productivity levels. Vagenas *et al.* (1997) also notes that there are two approaches when conducting a maintenance evaluation: a basic maintenance approach and a reliability based approach. The first is just a basic method of determining equipment downtime and the latter more focused on predicting future operating characteristics. Referring to the findings on reliability in this section, it is safe to say that reliability forms the basis for the field of maintenance and further leads to PAM.

2.1.2 Maintenance

> *"Optimal maintenance policies aim to provide optimum system reliability/availability and safety performance at lowest possible maintenance costs*

Pham and Wang (1996) perfectly encapsulates the essence of maintenance and the final goal optimal maintenance policies strive towards. In addition, Jardine and Tsang (2005) describes maintenance as *"an expensive and daunting element of supporting the product life cycle of any given system"* that has been observed for many years. More attention has been paid to maintenance engineering and maintenance management (Coetzee (1999)). High productivity and high capital cost are increasing problems in organizations today. Proper maintenance programs will stifle the growth of many alarming problems, such as the ones mentioned above. Not so long ago, asset and maintenance management were seen as a *"necessary evil"* as discussed by Spires (1996). This was especially true regarding lower and middle management who never considered that the benefits associated with maintenance could out weight the costs associated with it.

According to Spires (1996) the 1990s brought forth the age of technology where information became available at the touch of a button and the personal computer (PC) became smaller and more widely used. Executives were able to analyze areas in their organization that was previously ignored and this lead to asset and maintenance management receiving more attention. In regards to these findings, Coetzee (1999) proposes that a more holistic view of maintenance functions is needed. This is the foundation on which the asset management process is build.

Maintenance techniques have undergone mayor transformation over recent years. Development of these techniques have moved through four phases: first, second, third and recent generations (Arunraj and Maiti (2007)).

The four phases are summarized and graphically presented in Figure 2.1. The figure clearly shows the dated development stages of each of the four phases and the type of maintenance techniques represented in each of the sectors. Furthermore, a detailed description of each phase is provided below.

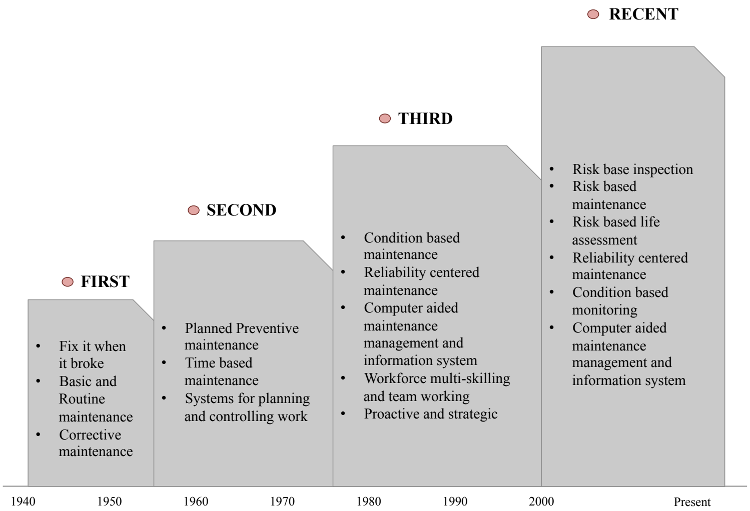


FIGURE 2.1: Development of maintenance philosophies.
Adapted from Arunraj and Maiti (2007)

First Generation
In the period before the First World War, industries were not completely mechanized. There was no clear cut way to predict failures and machines were operated until they failed. The maintenance practices that defined this period were basic and routine maintenance, reactive breakdown service (fix it when it breaks) and corrective maintenance.

Second Generation
After World War Two up until the late 1970s, an increase in complexity in organizations rose and brought forth the *Second Generation.* The dependency on machines increased and thus maintenance cost also increased. Maintenance policies adopted during this period were planned preventative maintenance, time based maintenance and system for planning and controlling work.

Third Generation
Third Generation policies existed between 1980 and 2000. This period was defined by further growth in plant complexity, accelerating use of automation, just in time production systems, rising demand for standard of product and service quality and more tight legislation on service quality. The rise of Condition Based Maintenance (CBM), Reliability Centered Maintenance (RCM) and computer aided maintenance management were seen during this generation.

Recent Generation
During the late 1990s and beyond 2000, risk-based inspection and maintenance methods were introduced and quickly grew in popularity. The goal of this maintenance process is to increase profitability and optimize total life cycle costs while keeping safety and environmental issues in mind.

As the maintenance world grew and evolved, more research was done into the value of maintenance and asset management. This lead to the creation of techniques and processes to facilitate PAM. Márquez *et al.* (2009) proposes a maintenance management framework that is divided into eight phases. Each phase is associated with respective techniques and further grouped into effectiveness (*Phase 1*, *2* and *3*), efficiency (*Phase 4* and *5*), assessment (*Phase 6* and *7*) and improvement (*Phase 8*). The entire framework can be seen in Figure 2.2.

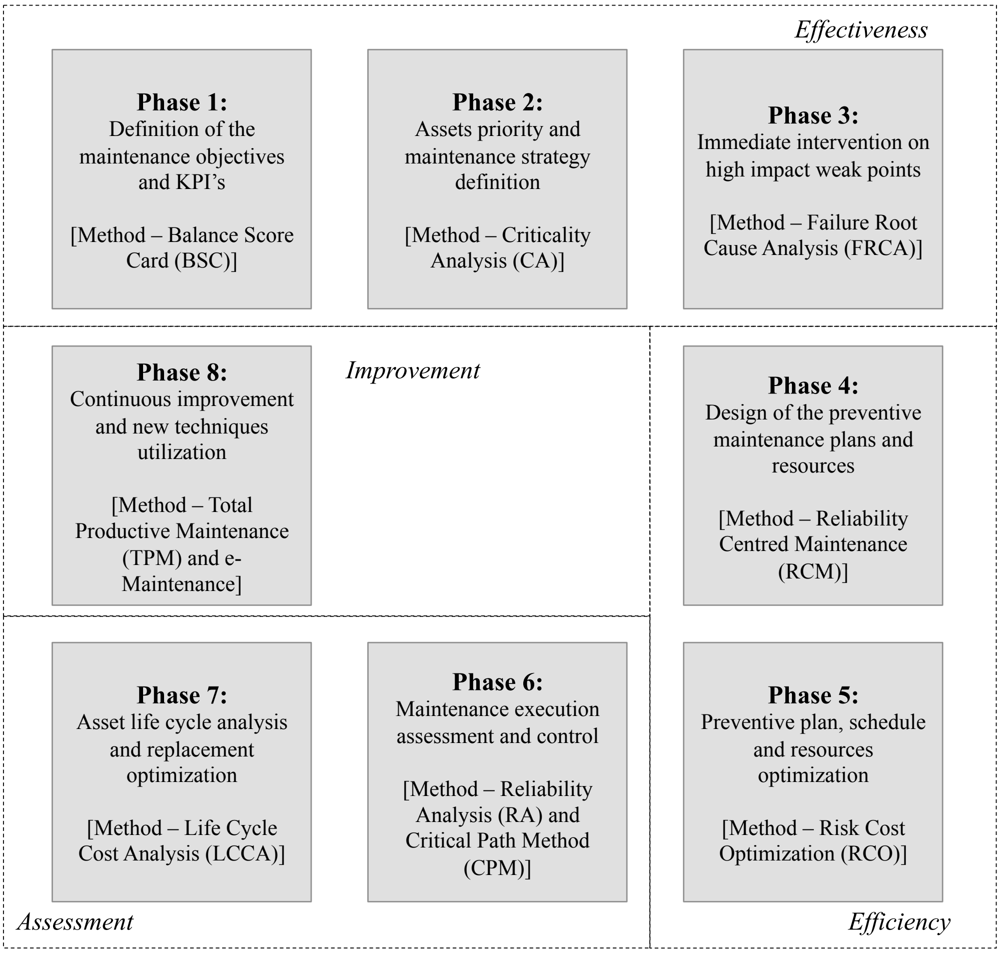


FIGURE 2.2: Maintenance management framework.
Adapted from Márquez et al. *(2009)*

In their research, definitions for both effectiveness and efficiency are provided to demonstrate the difference between these terms:

> *"**Effectiveness** concentrates then on the correctness of the process and whether the process produces the required results"*

> *"**Efficiency** is acting or producing with minimum waste, expense, or unnecessary effort. Efficiency is then understood as providing the same or better maintenance for the same cost."*

In *Phase 1*, the Balance Score Card (BSC) method can be used to align the maintenance objectives and Key Performance Indicators (KPI's) with the overall business strategy. The BSC is specifically designed for the organization and focus on achieving performance targets. Once the BSC is completed and the objectives and strategy of the business and maintenance are aligned, *Phase 2* is initialized.

Phase 2 determines which assets are most important and should be prioritize for maintenance management. A number of quantitative and qualitative methods exist to enable the process. For the purpose of this research, only the quantitative methods will be considered and will be discussed in detail in Chapter 4. Risk assessment techniques are used here to determine the critical assets. The process, as depicted in Márquez *et al.* (2009), is as follows:

(1) Define the purpose and the scope of the analysis.

(2) Establish the risk factors and also the relative importance of these factors.

(3) Decide the number of levels of risk criticality.

(4) Determine the process for identifying and prioritizing the critical assets.

Assets are analyzed according to the impact they have on the environment, safety, quality, working time, delivery, reliability and maintainability. Categories are created to group assets according to importance and each category is assigned certain maintenance strategies. *Phase 3* focus on high priority items and tries to eliminate, if possible, the causes of these failures. The Root-Cause Failure Analysis (RCFA) is one of the most popular methods to use to find out why a particular problem exists.

During *Phase 4* the preventive maintenance plan for a system is designed by identifying the functions of the system and how they may fail. RCM is one method to conduct this analysis. Moving to *Phase 5*, the optimization of the maintenance planning and scheduling is important to increase the effectiveness and efficiency of the maintenance policies. Once the maintenance activities are designed and implemented, it is important to constantly monitor and assess for any deviations from the business targets established previously during *Phase 6*.

Phase 7 is responsible for the Life Cycle Cost Analysis (LCCA). This is typically the cost of an asset for its entire life from planning, Research and Development

(R&D), and production to operations, maintenance and disposal. Finally, *Phase 8* is the continuous improvement of maintenance management made possible by the evolving techniques and technologies.

Four types of maintenance were introduced in Chapter 1 and Sharma *et al.* (2011) describe three types of maintenance as

(1) preventive maintenance;

(2) corrective maintenance; and

(3) predictive maintenance.

Mobley (2002) also discusses types of maintenance management methods and summarizes them as

(1) run-to-failure management;

(2) preventive maintenance;

(3) predictive Maintenance;

(4) Total Productive Maintenance (TPM); and

(5) RCM.

Proactive maintenance is the collective term for preventive and predictive maintenance as defined in Kothamasu *et al.* (2009). Corrective maintenance, preventive maintenance, predictive maintenance and RCM is identified as applicable to this study and researched further.

2.1.2.1 Corrective Maintenance

Corrective Maintenance or Run-To-Failure Management is also known as breakdown maintenance. This is a reactive approach as maintenance is only done once the equipment or system has failed as presented by Tsang (1995).

Wang *et al.* (2014) claims that corrective maintenance is still implemented extensively in engineering practice and defines corrective maintenance as follows:

> *"Corrective maintenance is a maintenance task performed to identify and rectify the cause failures for a failed system.*

This *"if it ain't broke, don't fix it"* maintenance management plan seems to be the perfect solution as the organizations only spends money once a machine or system has broken down according to Mobley (2002). But, it is the most expensive maintenance method due to the high costs once a breakdown is observed. Mainly due to the fact that once a machine breaks down, chances are that the entire production process will stop and lead to a loss in time, products produced and therefore a loss in profit. On top of these cost, the cost of fixing the failure is generally high.

2.1.2.2 Preventive Maintenance

Preventive maintenance is a time-driven management program. Maintenance tasks are thus performed on a set time schedule.

Another relatively new branch of preventive maintenance is CBM discussed in Prajapati *et al.* (2012) and defined as maintenance done according to the monitored condition of the asset. CBM was initially known as preventive maintenance and was conceptualized in the 1940s by the Rio Grande Railway Company. It was quickly adopted by different industries and was deemed a great success in terms of reducing the impact of unscheduled failures.

2.1.2.3 Predictive Maintenance

Predictive maintenance is based on the monitoring of specific operating indicators such as mechanical condition and operating efficiency as mentioned in Mobley (2002). This direction of maintenance management ensures that the appropriate data is provided to determine the maximum interval between repairs as well as minimizing the number and cost of unscheduled breakdowns.

2.1.2.4 Reliability Centered Maintenance

Moubray (1997*b*) describes RCM as

> *"A process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating context."*

Smith and Hinchcliffe (2004) gives four features associated with RCM:

(1) Preserve functions.

(2) Identify failure modes that can defeat the functions.

(3) Prioritize function need (via failure modes).

(4) Select applicable and effective preventive maintenance tasks for the high priority failure modes.

A short description of each of the four features follows:

Feature 1: Preserve functions
Preserving the function of the system is the most important feature and the primary task of RCM. It enables a systematic process and ensures that the right function(s) are related to the appropriate equipment. *Feature 1* supports the organization to *"not assume a priori that every item of equipment is equally important"*.

Feature 2: Identify failure modes that can defeat the functions
Feature 2 concentrate on the failure modes that have the potential to result in redundant functional failures. Identifying these failures is not an easy task and thus all the "in-between states" of functional failures should be considered.

Feature 3: Prioritize function need
The priority assigned to the functional failures and the failure modes associated with them is significant in RCM. Ranking the failure modes allows the organization to determine how and where budgets and resources should be allocated.

Feature 4: Select applicable and effective preventive maintenance tasks for the high priority failure modes
The final feature of RCM is concluded if each potential preventive maintenance task is *applicable* and *effective*. *Applicability* determines if the task will adhere to one of three reasons for conducting preventive maintenance known as mitigate or prevent failure, detect the inception of a failure and unearth a concealed failure. *Effectiveness* is the organizations willingness to allocate resources and money to complete the task.

Figure 2.3 shows the costs advantages of each of the maintenance types identified. As the *Effectiveness* increases the **Cost** of the maintenance technique decreases. From the graph, Proactive Maintenance and Reliability Driven Maintenance are the ultimate goals of an organization.

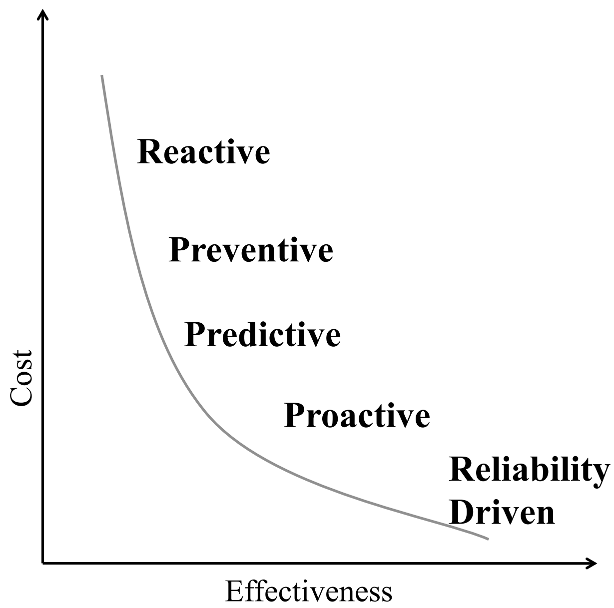


Figure 2.3: Cost advantages of maintenance types.
Adapted from Mitchell (2007)

2.2 Important Areas in Physical Asset Management

Critical areas in the field of PAM need to be identified to emphasize the focus of the research. Minnaar *et al.* (2013) identifies six areas of concern where numerical methods are needed in regards to PAM and PAS 55. These six areas include data analysis, life cycle management, asset criticality, risk management, statistical failure analysis and sustainable development.

Considering the many definitions of PAM in this chapter, the following areas are clearly important and mentioned in some way in all of the different definitions:

- Asset Life Cycle Management (ALCM)
- Risk Management
- Financial Management

PAS 55 (2010) also identifies six key principles and attributes of asset management: systematic, systems-oriented, risk-based, optimal, sustainable and holistic. All six elements are integrated and part of the development of good asset management techniques and shown in Figure 2.4.

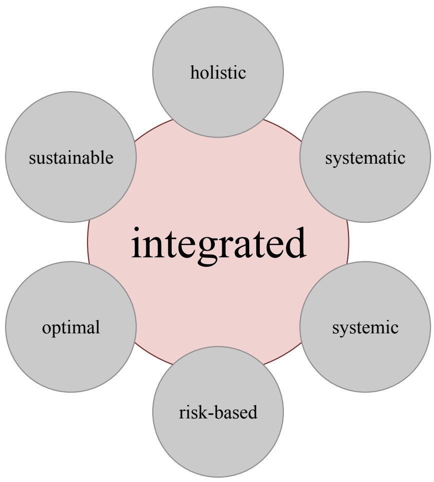


FIGURE 2.4: Key Principles and attributes of asset management.
Adapted from PAS 55 (2010)

Jooste (2014) included the asset management characteristics most cited by scholars in his research:

- Multi-disciplinary
- Organizational alignment
- Value realization

- Optimized decision-making
- Total life cycle management
- Integration
- Strong leadership

Furthermore, Rao Tummala and Leung (1996) proposes an expanded risk management framework that includes six phases. This risk management framework is seen in Figure 2.5.

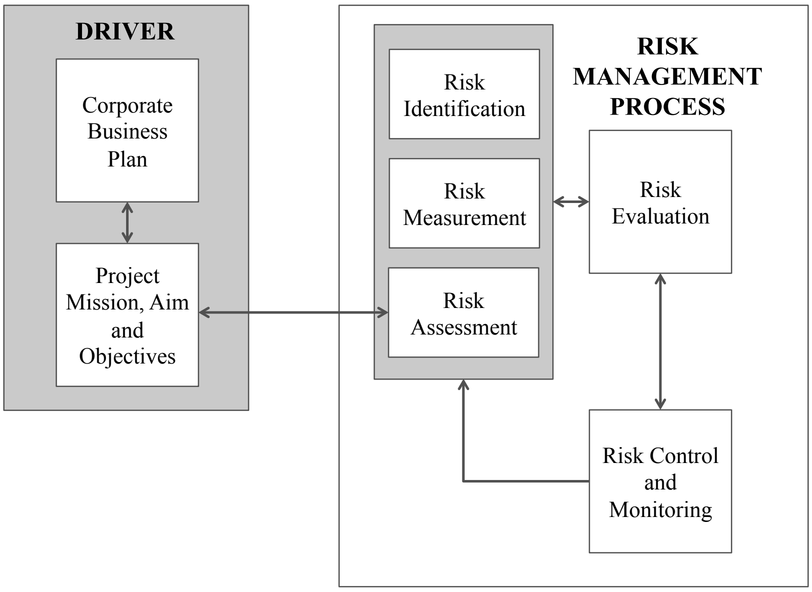


FIGURE 2.5: Risk management process.
Adapted from Rao Tummala and Leung (1996)

The six phases mentioned regarding the risk management framework as designed by Rao Tummala and Leung (1996), include:

(1) Identification of hazard or risk
(2) Analysis of system hazard
(3) Ranking of hazard
(4) Development of action plans
(5) Evaluation of risk
(6) Controlling and monitoring of risk

Considering all the definitions by various sources regarding PAM and the important elements associated with PAM, a comparison was needed to determine the importance of each area in regards to PAM, ISO 55000, PAS 55, the research in general and the importance of quantitative methods for that specific element. This step is crucial to the development of the thesis, as it will enable the research to focus on the most important areas.

Table 2.1 is a summary and ranking of the importance of the various areas as mentioned above. Every area of concern is given a rating between 1 and 3. 1 being *Not Important*, 2 being *Moderately Important* and 3 being *Very Important* as determined by the research. The rating was given according to the value of each element.

Table 2.1: Importance of quantitative methods.

	Important in PAM	Important in PAS 55	Important in ISO 55000	Important in Research	Important for Quantitative Methods	**Total**
Data Analysis	2	1	1	2	3	**9**
Life Cycle Management	3	3	3	3	2	**14**
Statistical Failure Analysis	2	2	2	2	3	**11**
Asset Criticality	2	2	2	2	3	**11**
Risk Management	3	3	3	3	3	**15**
Sustainable Development	2	3	2	2	1	**10**
Financial Management	2	3	3	2	3	**13**
Multi-Disciplinary	2	2	2	3	1	**10**
Health, Safety and Environmental	3	2	2	3	1	**11**
Organizational Alignment	2	2	3	2	1	**10**
Value Realization	2	1	1	3	1	**8**
Optimized Decision-Making	3	2	2	3	3	**13**
Integration	2	3	2	2	1	**10**
Strong Leadership	3	2	2	2	1	**10**
Systematic	1	3	1	1	1	**7**
Systems Oriented	1	3	1	1	1	**7**
Optimal	3	3	3	3	2	**14**
Holistic	2	3	2	2	1	**10**
Systemic	1	3	1	1	1	**7**

It is clear from the table, that the most important aspect is **Risk Management**. Closely followed by Life Cycle Management and Optimal. Other important areas especially for quantitative methods are Asset Criticality, Financial Management, Optimized Decision Making, Health, Safety and Environmental and Statistical Failure Analysis. These areas will be discussed in more detail as well as how they relate to PAM. An important decision was made up front with regards to Health, Safety and Environmental Impact. Although this is an important element to this research, it was determined that it constitutes a much larger field that this thesis can accommodate. It is therefore excluded from the study.

2.2.1 Risk Management

To understand the concept of risk management, it is important to understand what risk is and how it is defined.

ISO 31000 (2009) defines risk as the:

> *"effect of uncertainty on objectives"*

The standard also goes further in defining the concept of risk with five important notes quoted directly from the ISO 31000 document:

> ***"Note 1****: An effect is a deviation from the expected – positive and/or negative.*
>
> ***Note 2****: Objectives can have different aspects (such as financial, health and safety, and environmental goals) and can apply at different levels (such as strategic, organization-wide, project, product and process).*
>
> ***Note 3****: Risk is often characterized by reference to potential events and consequences, or a combination of these.*
>
> ***Note 4****: Risk is often expressed in terms of a combination of the consequences of an event (including changes in circumstances) and the associated likelihood of occurrence.*
>
> ***Note 5****: Uncertainty is the state, even partial, of deficiency of information related to, understanding or knowledge of an event, its consequences, or likelihood."*

Khan and Haddara (2003) defines risk analysis as follows:

> *"Risk analysis is a technique for identifying, characterizing, quantifying, and evaluating the loss from an event. Risk analysis . . . attempts to answer the following questions:*
>
> – *What can go wrong that could lead to a system failure?*
> – *How can it go wrong?*
> – *How likely is its occurrence?*
> – *What would be the consequences if it happens?"*

Furthermore, risk can be defined quantitatively as follows:

$$Risk = probability\ of\ failure \times consequence\ of\ the\ failure$$

Risk management is the process of identifying the significant risks and taking the appropriate actions to minimize these risks as discussed by Sanders (2011). It is important to balance risk control strategies, the effectiveness and costs of these strategies and the requirements and needs of the stakeholders. Six steps define the risk management process:

(1) Initiation

(2) Preliminary analysis

(3) Risk estimation

(4) Risk evaluation

(5) Risk control

(6) Action/monitoring

Communication between stakeholders and the risk team is also of great importance. Shah and Littlefield (2011) describes four key performance criteria to determine the Best-In-Class organizations: Overall Equipment Effectiveness (OEE), unscheduled asset downtime, return on assets and maintenance costs. The concept of Operational Risk Management (ORM) is also introduced and defined as follows:

> *"The concept of ORM is about creating a framework across the organization that will enable executives and plant floor employees to understand the top risks impacting organization, establish business processes to effectively address these risks and implement procedures for corrective and preventive actions"*

A comprehensive review was done by Raz and Hillson (2005) on the standards available regarding risk management. They picked nine national and international standards and compared the similarities and differences between all of them. The idea was to determine if a worldwide agreement on the process of risk management is possible. Although different terminology is used, the standards all agree on the basic steps of risk management: planning, identification, analysis, treatment and control. These steps, however, also varies for the different standards, but provides a good basis for the research of this study.

Although this thesis is focused on ISO 55000, it was decided to evaluate ISO 31000. This series focus on risk management and provide a background and strong foundation for the research.

2.2.1.1 ISO 31000: Risk management – Principles and guidelines

The International Organization for Standardization created the ISO 31000 for managing risk in an organization. According to ISO 31000 (2009), this standard *"describes the systematic and logical process in detail"*. The standard also defines a range of principles that an organization should apply to ensure effective risk management. As ISO 55000 clearly states a dire need for risk management, it is valuable to also take into account the ISO 31000 series. Once again, it is necessary to put emphasis on the fact that this thesis is focused on PAM and thus, the ISO 31000 series acts as an introduction to Risk Management.

The International Standard advise organizations to do the following:

> *"This International Standard recommends that organizations develop, implement and continuously improve a framework whose purpose is to integrate the process for managing risk in the organization's overall governance, strategy and planning, management, reporting processes, policies, values and culture."*

The standard is also applicable to any organization in any industry. ISO 31000 defines the risk management process as shown in Figure 2.6 and discussed in detail below.

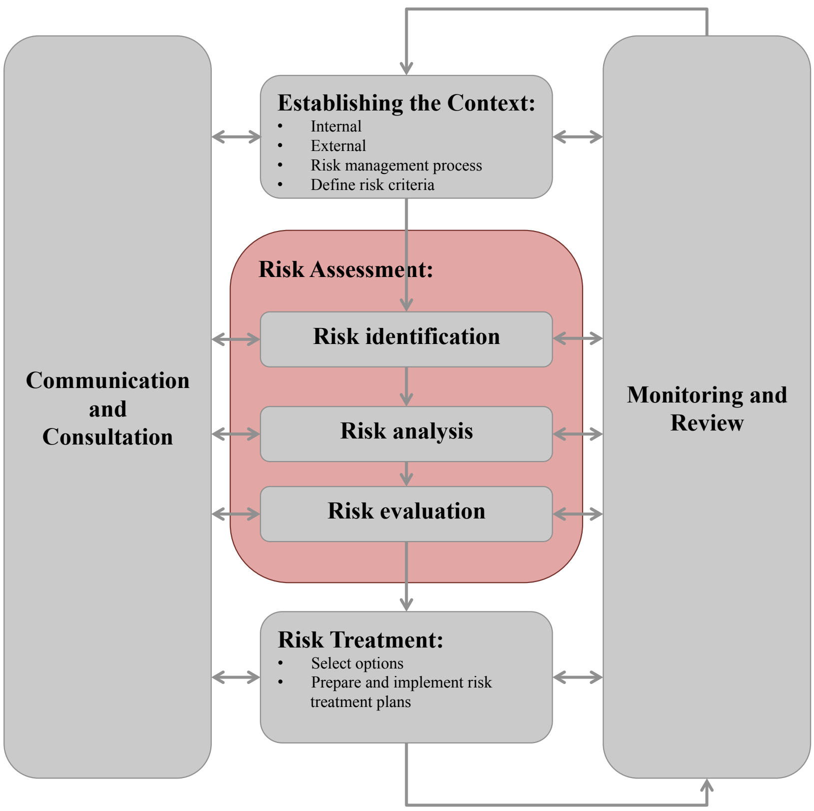


FIGURE 2.6: Risk management process.
Adapted from ISO 31000 (2009)

The first part of the process is *Communication and Consultation*. This stage integrates with all other stages during the process. Communication takes place with internal and external stakeholders.

Establishing the Context stage is responsible for defining the internal environment (i.e. the organization's policies, objectives, governance, structures, etc.) and external environment (i.e. social environment, culture, legal requirements, key drivers, etc.), establishing the risk management process context and defining the risk criteria.

Risk Assessment is the next logical step. This includes identifying the risk, analyzing the risk and evaluating the risk.

Risk Treatment is the penultimate step. The treatment options are selected, prepared and implement.

Finally, *Monitoring and Review* of the entire process is very important to be able to improve and ensure that the process is effective and efficient.

Another important part of the risk management process is to constantly and continuously record the entire process. This enables ongoing evaluation and improvement of the risk management process.

2.2.1.2 ISO 31010: Risk management – Risk assessment techniques

ISO 31010 is the second part of the International Standard dedicated to risk management. This standard proposes risk assessment techniques.

Table A.1 and Table A.2 in ISO 31010 (2009) proposes risk assessment tools and also analyses these tools according to their relevance of influence in terms of resources and capability, nature and degree of uncertainty and complexity. For the purpose of this research, the methods, with quantitative components are focused on in Table 2.2.

TABLE 2.2: Quantitative risk assessment tools as proposed by ISO 31010.

Tools and Techniques	Relevance of influence		
	Resources and capability	Nature and degree of uncertainty	Complexity
Human reliability analysis (HRA)	Medium	Medium	Medium
Toxicological risk assessment	High	High	Medium
Fault tree analysis	High	High	Medium
Event tree analysis	Medium	Medium	Medium
Cause/consequence analysis	High	Medium	High
Failure, Mode and Effect Analysis (FMEA) and Failure, Mode, Effect and Criticality Analysis (FMECA)	Medium	Medium	Medium
Reliability-centred maintenance	Medium	Medium	Medium
Layers of protection analysis	Medium	Medium	Medium
Bow tie analysis	Medium	High	Medium
Markov analysis	High	Low	High
Monte-Carlo analysis	High	Low	High
Bayesian analysis	High	Low	High

As described in the problem statement, the goal of this research is to initialize the process of becoming ISO 55000 and understanding the quantitative requirements as stipulated by the document by designing a simple and easy-to-use risk management framework. It is thus important to keep this view in mind when deciding on the quantitative methods to use. Specific methods identified in Table 2.2 that could add value to this thesis are:

- Failure, Mode and Effect Analysis (FMEA) and Failure, Mode, Effect and Criticality Analysis (FMECA)
- Monte-Carlo Analysis
- Markov Analysis
- Reliability-centred Maintenance
- Event Tree Analysis
- Bayesian Analysis

These methods can relate to PAM and risk management and are familiar in most organizations.

2.2.1.3 Risk-based Maintenance

Risk-based maintenance is an important part of PAM and Khan and Haddara (2003) researched the risk-based maintenance framework consisting of two phases: risk assessment and maintenance planning based on risk. Figure 2.7 is the full risk-based maintenance framework.

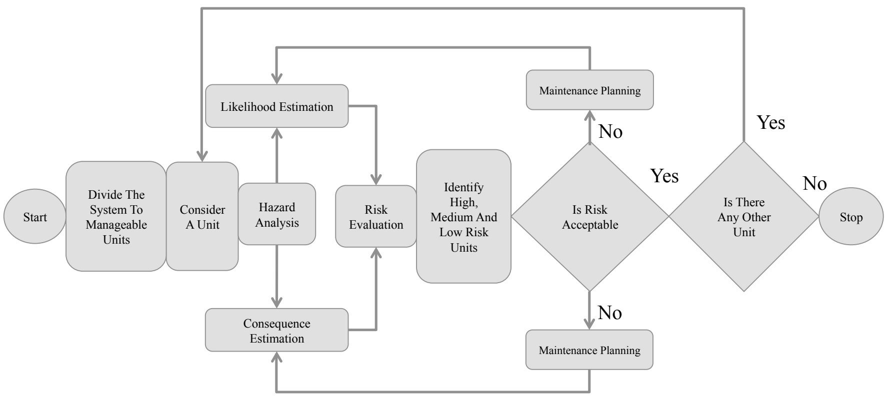


FIGURE 2.7: General risk-based maintenance approach.
Adapted from Khan and Haddara (2003)

The risk-based maintenance framework starts with the *Hazard Analysis*. During this phase the failure scenario is identified and developed based on physical conditions of operations, geometry, operational characteristics of the system and safety requirements. The second phase is the *Likelihood Assessment* with the goal to calculate the occurrence of the undesired event i.e. the failure probability or frequency for a specific time period. *Consequence assessment* is the next phase. Here the potential consequences of the credible future scenario are calculated and quantified. The consequences are asset, production, environmental, health and safety losses. *Risk Estimation and Acceptance* are next in the framework. The risk associated with each unit is estimated based on the consequence analysis and probabilistic failure analysis. The calculated risk is then analyzed against the acceptance criteria defined. If it does not adhere to the criteria, the need for maintenance is identified. Finally, *Maintenance Planning* is accepted as the solution to risk reduction.

Asset Life Cycle Management (ALCM) is also considered as being fundamental to PAM and is identified in ISO 55000 as beneficial to the process of adhering to the guidelines as stipulated in the ISO 55000 series.

2.2.2 Asset Life Cycle Management (ALCM)

Asset Life Cycle Management (ALCM) is regarded as a sub-discipline of PAM (Ruitenburg *et al.* (2014)). The concept of ALCM is defined by Haffejee and Brent (2008) and the detailed ALCM model is presented in Figure 2.8:

> *"ALCM refers to the management of assets over their complete life cycle, from before acquisition to disposal, taking into account economic, environmental, social and technical factors and performances"*

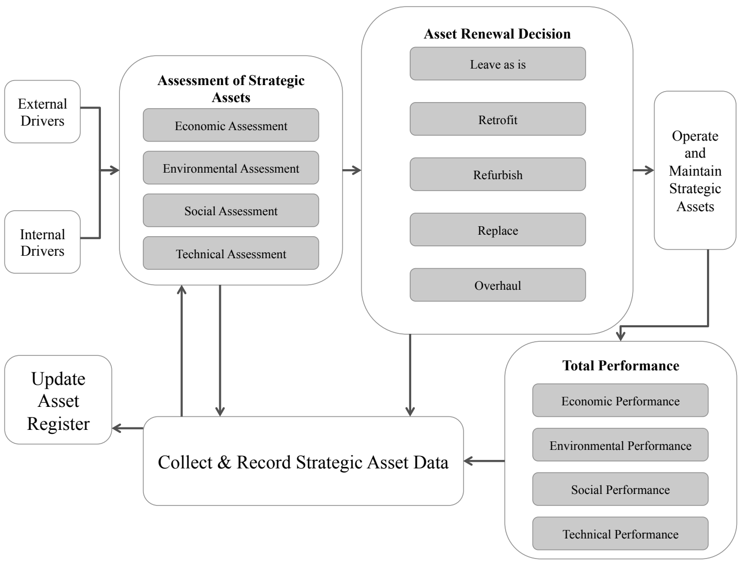


FIGURE 2.8: ALCM model.
Adapted from Haffejee and Brent (2008)

The model is modified from a previous model and focus on the water utility sector, but Haffejee and Brent (2008) concluded that the model is adaptable to any industry where strategic asset management is of importance. The elements contributing to the ALCM model is outlined.

External drivers of change are factors from outside the organization that results in changes in the organization for example competition, social concerns, cost of electricity, etc.

Internal drivers of change are factors from within the organization that results in changes in the same organization for example loss of skilled personnel, high maintenance costs, process efficiency, etc.

Assessment of strategic assets allows the performance assessments to be done in terms of the four areas of concern: economic, environmental, social and technical. For example life cycle costing, disasters affecting people, efficiency, etc.

Asset renewal decisions are being made regarding the future of the asset. These include: leave as is (run to failure or operate and maintain as usual), retrofit, refurbishment, replacement of component parts, overhaul or replacement.

Operate and maintain strategic assets are predetermined guidelines, specifications or standards that determines how the assets are operated and maintained.

Total performance of assets are predetermined standards and specifications that determines how the asset is monitored and managed in terms of economic, environmental, social and technical performance.

Collect and record asset data is the phase where data is collected, verified, validated and recorded. The data is verified against design performance parameters.

Update asset register. The asset database is kept and updated regularly. Identifies the asset, where it is located, technical ratings, design life, total cost of ownership, etc.

McGlynn and Knowlton (2011) gives the Total Life Cycle Asset Management (TLCAM) framework as adopted by The International Business Machines Corporation (IBM). The framework consists of eight phases with two supporting structures namely:

(1) Asset Strategy

(2) Plan

(3) Evaluate and Design

(4) Create and Procure

(5) Operate

(6) Maintain

(7) Modify

(8) Dispose

(9) Financial Management

(10) Technology

Figure 2.9 shows the TLCAM framework consisting of the eight phases and the supporting structures as *Financial Management* and *Technology*.

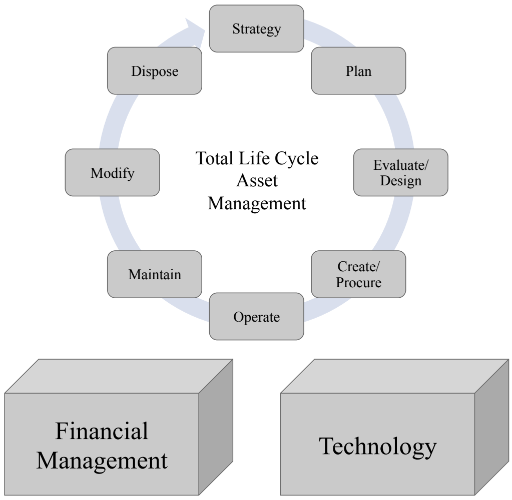


FIGURE 2.9: TLCAM framework.
Adapted from McGlynn and Knowlton (2011)

The TLCAM consists of eight life cycle phases and is supported by technology and financial management. All eight phases are delineated and described below. It is the organization's prerogative to analyze their asset register and manage their asset over the entire asset life cycle.

Asset Strategy

Setting an *Asset Strategy* is the first step of the TLCAM framework. It could include activities such as analyzing the practices associated with asset management, developing the asset management strategy as well as measuring and monitoring techniques such as introducing appropriate KPI's. The most important to remember during this phase is that the asset strategy should be applicable to the company's asset class and business requirements. This resonates with the requirements set in the ISO 55000 series.

Plan

During this phase the company needs to plan across the entire portfolio of assets. Companies should define targets, standards, policies and procedures leading to the execution of the asset management strategy.

Evaluate and Design

Assets being purchased should be evaluated and those that need to be created should be designed. Activities include the development of a *"capital program assessment model"*, which aids the process of decision making when acquiring assets.

Create and Procure
The *Create and Procure* phase is where the most money is spent in regards to asset management. Creating, building or procuring of assets leads this phase.

Operate
Standards, policies and procedures will enable the organization to manage operations of assets as dictated by the asset management strategy. During this phase, performance is of importance.

Maintain
Again, the assets should be maintained according to the asset management strategy and goals as set out by the standards, policies and procedures. Maintenance costs could have a significant impact on total costs.

Modify
Modifying assets are important to extend the life of assets and should again adhere to the strategy, policy and procedures.

Dispose
Finally, disposal of assets needs to be managed. Disposing of assets is not an easy feat with the current emphasize on green practices and operations. The financial implications are also role players.

Financial Management
Each phase impacts the cost of the TLCAM. Attention should be paid to the *Create-and-Procure*, *Disposal*, *Operate* and *Maintain* phases as the cost in these phases are the most significant.

Technology
Technology is a great support system to the TLCAM framework. Each phase can draw from technological tools to improve the asset management process.

2.2.3 Optimized Decision Making

Burnett (2013) places a great burden on decision making by describing it as a *"primary function of management"* and demands that *"the importance thereof should not be underestimated"*. Proper decision making is a crucial part of managing an organization and for it to function effectively and efficiently. Al-Tarawneh (2012) supports these claims by defining decision making as *"the most critical core managerial function"*. Furthermore, Al-Tarawneh (2012) provides the following definition for decision making:

> *"Decision making is the process of identifying and selecting from among possible solutions to a problem according to the demands of the situation. For example, decision making in the area of vendor contracting might address how to deliver a service, which bidder gets a contract, how to ensure that a contractor meets its obligations, or whether to pay the contractor in large or small bills.*

Important decisions regarding the research include:

- What are the critical assets of the organization?
- What quantitative methods are available?
- What areas are of concern regarding PAM and risk management?
- What is the probability of failure?
- What are the financial risk implications?
- When will a specific asset fail?

Above mentioned decisions are just a few of the numerous decisions applicable to this thesis. The areas of concern identified from Table 2.1 are

- asset criticality;
- financial management; and
- failure analysis.

The three areas of concern are chosen due to the fact that they are rated as most critical in terms of ISO 55000, PAS 55, PAM, research regarding PAM and the need for quantitative methods. Certain aspects were also rated as critical in these fields and include Life Cycle Management, Optimal and Optimized Decision Making. The reason these three were not chosen as alone standing aspects, is because they should be incorporated in to the entire asset management process and thus into the entire risk management framework. The three domains listed above, namely asset criticality, financial management [1] and failure analysis, are examined and defined to enable the understanding of the research and case study.

2.2.4 Asset Criticality

The consequences an organization experience due to the failure of an asset determine the criticality of the asset (Sanders (2011)). This is an important part of risk management as it determines where the focus should be placed in terms of the assets in the organization. An important factor to remember is that asset criticality differs from industry to industry and organization to organization. Talking to the employees and people who know the organization is critical to the success of the plan. Thus, the methods should be customized to the organization in question when an asset management plan is established. The following criticality measures are important across all organizations:

[1] Financial management will henceforth be referred to as *Financial Risk Impact*.

- Asset performance (reliability, availability and maintainability);
- Cost (direct maintenance and engineering costs, indirect costs of loss of production);
- Safety (lost time incidents, lost time accidents, disabling injuries, fatalities); and
- Environment (number of environmental incidences, cost of environmental clean-up, environmental compliance).

Determining the critical assets in an organization helps the process of focusing on the appropriate assets and applying financial risk impact and failure analysis only to these assets.

2.2.5 Financial Risk Impact

Risk management has been a critical part of good engineering practice as confirmed by Hughes *et al.* (2009). However, the ability to relate asset replacement and risk management strategies to senior management relies heavily on conveying engineering decisions with regards to financial costs or benefits.

Any project has financial risks associated with it as discussed in Brookefield and Boussabaine (2009) due to the fact that project or asset failure will always have a financial consequence. Financial analysis is a very important measure as "making money" is primarily the goal of any company.

The financial risk impact can be related to the failure analysis and the possibility of an overlap is very real.

2.2.6 Failure Analysis

Blischke and Prabhakar Murthy (2003) defines failure analysis as

> *" . . . analysis of the underlying causes of failure, the mechanisms of failure, and its consequences.*

Overstress and excessive wear are generally the main causes of failure. Failure analysis is confined to quantitative methods in the context of this thesis. Failure analysis is at the heart of risk management and PAM and paves the way for proactive maintenance. Vlok (2011) puts forth the challenges faced by traditional maintenance techniques with the following statement:

> *"The maintenance fraternity has realized that the use of formalized maintenance models and tactics alone are not necessarily the optimal way to maintain equipment. One aspect of formal maintenance that needs optimization is decision making in life-limiting maintenance strategies*

> *i.e. preventive maintenance, because of enormous losses industries are suffering due to waste of residual life of equipment.*

Failure analysis attempts to predict the time period associated with failures. More than one quantitative method exists to aid the process of determining when and how equipment will fail and these methods are tackled in Chapter 4.

2.3 Chapter Summary

Chapter 2 concludes the literature study of the field of Physical Asset Management (PAM) and broadens on the introduction made in Chapter 1. The significance of maintenance techniques, as the foundation to PAM, is established. Different maintenance techniques including corrective maintenance, preventive maintenance, predictive maintenance and RCM are discussed. These four maintenance techniques are identified as the most relevant and recent methods in the industry and directly applicable to this research of PAM and risk management.

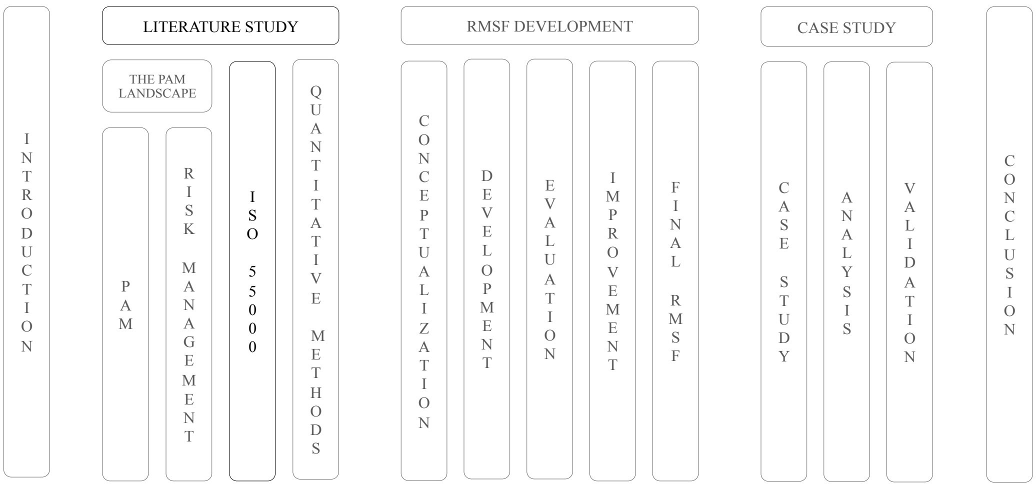
The second part of Chapter 2 is the identification of the critical areas in the various documents and research fields applicable to the thesis. Table 2.1 is the analysis of the critical areas. Through the analysis, specific areas are rated as more important than others. These include risk management, asset life cycle management, optimized decision making, asset criticality, financial risk impact and failure analysis. Through careful consideration, it was decided to focus on Asset Criticality, Financial Risk Impact and Failure Analysis as part of the all incorporating landscape of risk management and asset management. Each of these areas is explored in more detail. Chapter 2 instigates the development of the RMSF framework and sparks further research into ISO 55000 and the quantitative methods applicable. Furthermore, Chapter 2 accomplishes objective one and two as listed in Chapter 1.

Chapter 3

ISO 55000 Series

Chapter Aim:

This chapter presents a summary of the ISO 55000 Series. The three documents namely ISO 55000, ISO 55001 and ISO 55002, represents the ISO 55000 series and are discussed in conjunction with their various subsections. The analysis of each of the documents leads to the emphasis on the need of quantitative methods as part of the asset management program. The figure below indicates how this chapter forms part of the literature study.



Chapter Outcomes:

- Comprehension of the ISO 55000 series.
- Analysis and summary of the subsections in the ISO 55000 documents consisting of ISO 55000, ISO 55001 and ISO 55002.
- Understanding the need for and focus on quantitative methods in the ISO 55000 series.

3.1 The ISO 55000 Series

The International Organization for Standardization (ISO) is a federation of national standards bodies that operates worldwide. The purpose of the ISO 55000 series is to provide an overview of asset management and asset management systems. Common practices are identified that can be applied to a broad range of assets, organizations and cultures as described in ISO 55000 (2014). The series consists of three documents namely:

(1) ISO 55000: Asset management – Overview, principles and terminology

(2) ISO 55001: Asset management – Management systems – Requirements

(3) ISO 55002: Asset management – Management systems – Guidelines for the application of ISO 55001

ISO 55000 provides the context for ISO 55001 and ISO 55002. All three documents can be used together with other asset management standards or technical specifications. The ISO 55000 series is aimed at organizations looking to implement an asset management system or improve the existing asset management system while extracting the optimum value from their assets. An organization willing to adopt the ISO 55000 series will surely benefit in the long term by managing its assets effectively and efficiently. Organizations will also benefit financially.

This chapter acts as a summary of the ISO 55000 series and is not complete in all aspects of the series, but rather a focus on the more important aspects of the documents. For a deeper understanding of the ISO 55000 series, perusal of ISO 55000 is needed.

3.1.1 ISO 55000

The first part of the ISO 55000 series is titled *Asset Management – Overview, principles and terminology* and stipulates the general idea and overview of asset management and asset management systems. It also provides the context for the documents that follow, ISO 55001 and ISO 55002.

ISO 55000 is subdivided into three sections namely *Scope*, *Asset Management* and *Terms and Definitions*.

3.1.1.1 Scope

The *Scope* of the document is set out in the first section. An overview of asset management, the principles and the terminology is given as well as some expected benefits from adopting the standards regarding asset management.

Three very important facts to take into consideration that stretch across all three documents are the following:

> ***"Note 1:*** *The ISO 55000 series is specifically focused on managing physical assets, but can be adopted for other asset types as well.*
>
> ***Note 2:*** *The ISO 55000 series does not discuss financial, accounting and technical guidance. This research will however incorporate guidelines regarding these three aspects.*
>
> ***Note 3:*** *ISO 55000 refers to the term "asset management system" which is used to signify a management system for asset management."*

The ISO 55000 standard can be applied to all types of assets and by various types of asset intensive organizations.

3.1.1.2 Asset management

The *Asset Management* section discusses the benefits of asset management, the definition of an assets, the overview of asset management, the overview of the asset management system and the integrated management system approach. These five sections are discussed individually to gain an overview of the context of ISO 55000.

A crucial part of the asset management system is to identify the factors that influence how the assets are managed. These include the nature and purpose of the organization, the operating context, the financial barriers, regulatory requirements, and the needs and expectations of the organization and its stakeholders.

(i) Benefits of asset management
A list of benefits obtained regarding the implementation of asset management is also examined. Benefits include improved financial performance, informed asset investment decisions, risk management, improved services and outputs, social responsibility and compliance demonstration, superior reputation, improved organizational sustainability and improved efficiency and effectiveness.

(ii) Assets
An asset is defined by ISO 55000 (2014) with the following statement:

> *"An asset is an item, thing or entity that has potential or actual value to an organization. The value will vary between different organizations and their stakeholders, and can be tangible or intangible, financial or non-financial."*

This section also discuss the asset life and questions whether to manage assets individually or as a group.

(iii) Overview of asset management

Asset management is defined by ISO 55000 as:

> *"Asset management involves the balancing of costs, opportunities and risks against the desired performance of assets to achieve the organizational objectives."*

Asset management is based on a set of fundamentals that include:

- The value provided to the organization or stakeholders.
- The alignment of organizational objectives with technical and financial decisions, plans and activities.
- The leadership and commitment to the successful implementation of asset management.
- The assurance given by asset management that the asset will fulfil its role and give value to the organization.

The asset management system is used to direct, coordinate and control the asset management activities. Figure 3.1 shows the relationship between the key asset management terms. The *Asset portfolio* forms part of the *Asset management system*, which in return forms part of *Asset management* and finally, all three forms part of *Managing of the organization*.

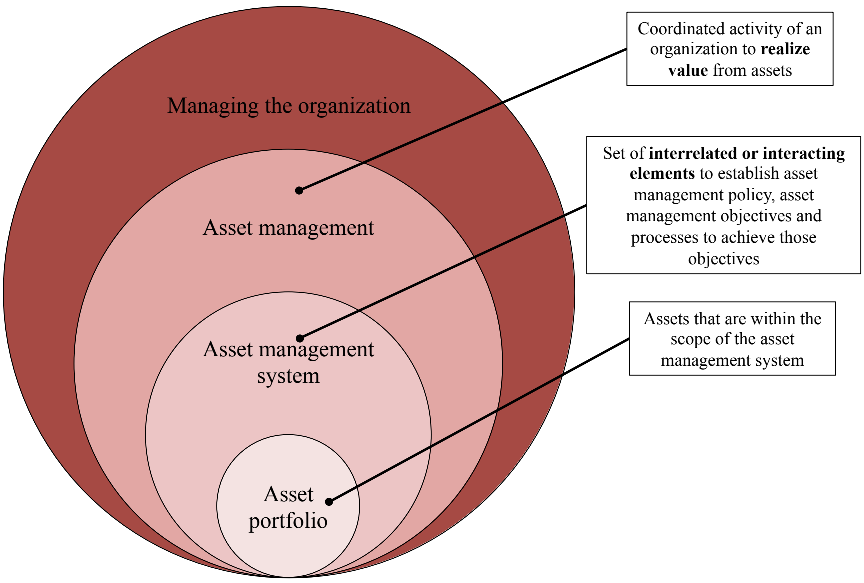


FIGURE 3.1: Relationship between key terms.
Adapted from ISO 55000 (2014)

ISO 55000 establish a definition for asset management system as follows:

> *"An asset management system is a set of interrelated and interacting elements of an organization, whose function is to establish the asset management policy and asset management objectives, and the processes, needed to achieve those objectives."*

An asset management system is bigger than just an information system. It draws from and provides supports for all functions in the organization.

(iv) Overview of the asset management system

The asset management system is a structured plan to establish or improve asset management techniques in an organization.

Providing various benefits for the organization is one of the key roles of the asset management system. Benefits include introducing new technology and processes that stimulate work ethic, providing new perspective in various section of the organization, motivating top management towards cross-functional integration and acquiring financial benefits.

An asset management system will be beneficial to different sectors of the organization. These sectors include human resource management, control system, employees, suppliers and contracted service providers. The asset management system also drives creativity and innovation.

Implementing a proper asset management system requires an understanding of and focus on each of its most important elements. Critical elements are

- the context of the organization;
- leadership;
- planning;
- support;
- operation;
- performance evaluation; and
- improvement.

The internal and external contexts of the organization are both vital to the asset management system. An internal context constitutes of the culture, the environment, the mission, the vision and the values of the organization whereas the external context involves the social, cultural, economic and physical environments. Regulatory and financial constraints also play a role in the external context. Finally, the stakeholders should be considered as part of the context of the organization.

During the process of implementing or improving the asset management system in an organization, it is very important for management at all levels to get actively involved and support the process. Top management and leaders should provide the right resources, dissolve conflict and improve communication between the different sections and people in the organization.

Organizational objectives provide the foundation for planning the asset management activities. Interfacing between the different areas of the planning process is shown in Figure 3.2.

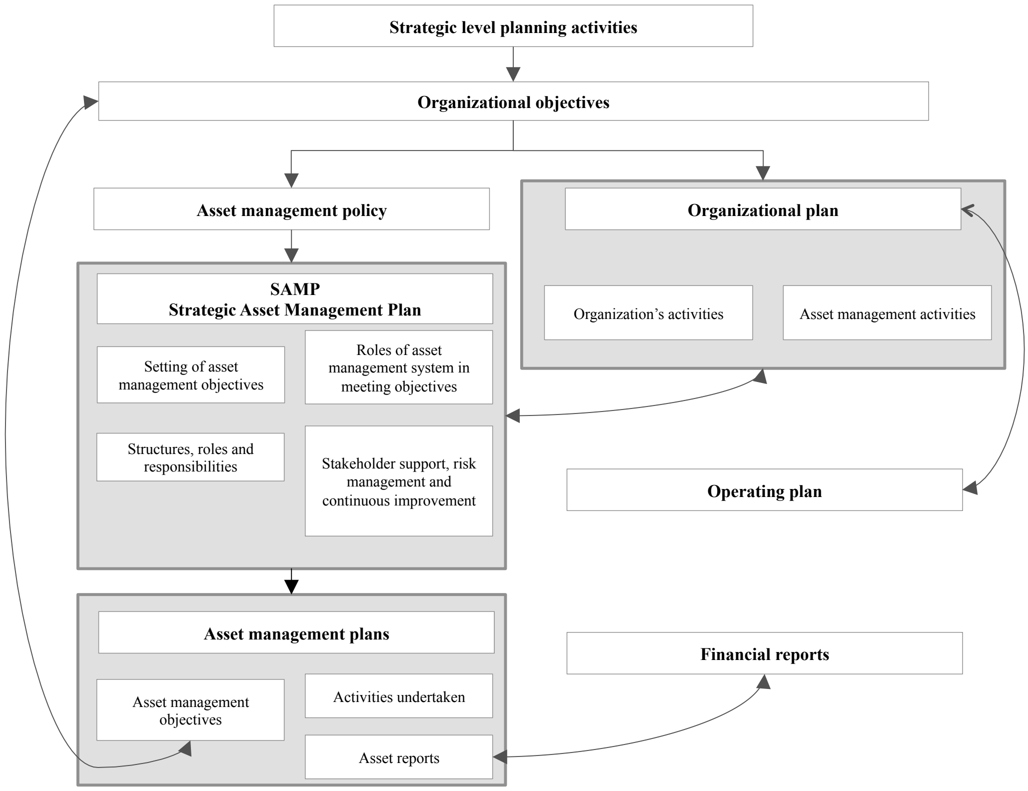


FIGURE 3.2: Interactions between different sections of the planning process.

Support from various parts of the organization for the asset management system is critical to the effectiveness and efficiency of the program. Collaboration between these departments is important for sharing resources and emphasizing the asset management objectives throughout the entire organization. The asset management system and the human resource management system should support each other.

Design and operation of the asset management systems should be based on the asset management plans. Once the asset management system is operating, the initial plan is highly likely to undergo changes. These changes could introduce new risks and should be dealt with accordingly. Asset management activities that are outsourced should always be kept in the control of the organization.

The assets, asset management and asset management system of the organization should be scrutinized to continuous evaluation and improvement. Financial or non-financial performance measures are of value and can be direct or indirect.

Asset management performance should be evaluated against the predetermined asset management objectives. The organization should determine if the asset management objectives have been satisfied and the reason behind failures and successes. Performance evaluations should be done on assets managed by the organization as well as assets that are outsourced. Evaluations determine if the asset management system is effective and efficient and should be further used for management reviews.

Through performance evaluations, management reviews and internal and external audits, nonconformities or potential nonconformities can be identified and focused on.

It is important to pay close attention to emergency situations related to assets as well as conducting risk assessments before implementing changes.

(v) Integrated management systems approach

The *Integrated Management system approach* allows the asset management system to gain support from the organization's existing systems including health and safety, risk, quality and environmental management. This approach shortens the time needed to implement the asset management system as well as improving collaboration between different departments and disciplines in the organization.

3.1.1.3 Terms and definitions

Terms and definitions defines the most important terminologies used in the ISO 55000 series. It builds the basis for the ISO 55001 and ISO 55002 and should be referred back to if and when needed during and after the implementation of the ISO 55000 guidelines.

3.1.2 ISO 55001 and ISO 55002

ISO 55001 is titled *Asset management – Management systems – Requirements* and is the main standard specifying the requirements for an asset management system. It discusses specific areas that an organization needs to comply to in order to be certified. These areas include

- context of the organization;
- leadership;
- planning;
- support;
- operation;

– performance evaluation; and
– improvement.

ISO 55002 is titled *Asset management – Management systems – Guidelines for the application of ISO 55001* and details specific, technical requirements as well as guidelines for implementing and interpreting ISO 55001. The same sections discussed in ISO 55001 are used in ISO 55002.

A brief account of each section is summarized in this research study. The most important areas that requires quantitative methods in the ISO 55001 and ISO 55002 documents are furthermore identified.

3.1.2.1 Context of the organization

The *Context of the organization* is subdivided into understanding the organization and its context, understanding the needs and the expectations of stakeholders, determining the scope of the asset management system and asset management system.

Internal and external issues of the organization should be considered and the asset management and organizational objectives should be aligned. Relevant stakeholders, their requirements, expectations and criteria regarding asset management should be determined. The stakeholders' requirements for recording information are also of importance.

Above mentioned criteria should be considered when establishing the scope as well as establishing, implementing, maintaining and continually improving the asset management system.

3.1.2.2 Leadership

Leadership is subdivided into leadership and commitment, policy, and organizational roles, responsibilities and authorities.

This section gives guidelines on how leadership and commitment shall be demonstrated with regards to asset management. It also focuses on establishing an asset management policy and the responsibilities and authorities that need to be assigned regarding management of the organization.

3.1.2.3 Planning

Planning is subdivided into actions to address risks and opportunities for the asset management system and asset management objectives and planning to achieve them.

The planning section identifies areas that are affected by risks and opportunities. Qualities of the asset management objectives are discussed and also the planning associated with achieving these objectives.

3.1.2.4 Support

Support is subdivided into resources, competence, awareness, communication, information requirements documented information.

Resources required to achieve asset management in the organization and the competence of the persons or employees required to facilitate the asset management process are discussed. Furthermore, what they need to be aware of to be able to succeed is established in conjunction with the communication and information requirements. Finally, how this information shall be documented, updated and controlled is examined in this section.

3.1.2.5 Operation

Operation is subdivided into operational planning and control, management of change and outsourcing.

Here, planning, implementation and control of the processes required to adhere to requirements set in previous sections are listed. The management of changes in operations and outsourcing are also considered.

3.1.2.6 Performance evaluation

Performance evaluation is subdivided into monitoring, measurement, analysis and evaluation, internal audit and management review.

Performance evaluation reports on the importance of monitoring, measuring, analyzing and evaluating the asset management process. The value of an internal audit and a management review are also considered and the specific requirements associated with each.

3.1.2.7 Improvement

Improvement is subdivided into nonconformity and corrective action, preventive action and continual improvement.

The final section titled *Improvement* puts forth necessities for dealing with nonconformities, corrective actions, preventive actions and continual improvement.

3.2 Risk Management Requirements in ISO 55000

Risk management is an integral part of the ISO 55000 series. Section 6.1 in both ISO 550001 and ISO 550002 is entirely focused on risk management and titled *Actions to address risks and opportunities for the asset management system*. In ISO 55001, three paramount ideas are prioritized that are a result of addressing the risk and opportunities. These include a guarantee that the asset management system can adhere to its preconceived outcome(s), prevention, or decrease of undesired consequences and attaining continual improvement. Furthermore, the section place focus on what the organization shall plan in terms of risks and opportunities. The organization is responsible for planning actions to address the risks and opportunities identified and consider the change they can undergo over time. Consideration should also include how the organization shall amalgamate and implement the mentioned actions into the asset management system processes and finally assess the effectiveness.

ISO 550002, as mentioned in Section 3.1.2, *"details specific, technical requirements as well as guidelines for implementing and interpreting ISO 55001"*. Thus, ISO 55002 Section 6.1 stipulates guiding principles on implementing the same section in ISO 55001 and the following summarizes the intention of risk management:

> *"The overall purpose is to understand the cause, effect and likelihood of adverse events occurring to manage such risks to an acceptable level, and to provide an audit trail for the management of risks. The intent is for the organization to ensure that the asset management system achieves its objectives, prevents or reduces undesired effects, identifies opportunities, and achieves continual improvement."*

Specific standards mentioned in ISO 55002 Section 6.1 are condensed to the following list:

– The risk assessment criteria should be defined and could be determined by means of a risk matrix.

– Managing risk associated with the asset management process should be aligned with the risk management plan as used by the organization. This could include business continuity and contingency planning.

– Actions and resources should be identified regarding asset management system risks and should further be incorporated in the implementation plan.

– Effectiveness of the actions should be demonstrated by the organization.

The objectives mentioned regarding risk management in the ISO 55000 series form the core of the research and lead to the identification of quantitative requirements in ISO 55000.

3.3 Quantitative Requirements in ISO 55000

The ISO 55000 series acts as the minimum set of requirements for managing an organization's assets. This is beneficial to the organization in the sense that they have the power to decide how to implement the requirements to best suit their needs. ISO 55002 (2014) clearly states the following in Section 4.4:

> *"Compliance with all the requirements of the ISO 55001 should be considered as achieving only the minimum starting point for an effective asset management system and should not be seen as the final goal."*

Thus, any organization should not strive to only become ISO 55000 accredited, but rather to continuously improve their asset management strategy and strive to be industry leaders in the field of PAM.

Furthermore, the option of using quantitative methods is specifically mentioned in the ISO 55000 series. ISO 55001 Section 6.2 states:

> *"The asset management objectives shall:*
>
> – *be measurable (if practicable);*
>
> – *be monitored;"*

Another important part in this section gives the following requirement:

> *"When planning how to achieve its asset management objectives, the organizations shall determine and document:*
>
> *a) the method and criteria for decision making and prioritizing of the activities and resources to achieve its asset management plan(s) and asset management objectives;*
>
> *b) the processes and methods to be employed in managing assets over their life cycles;"*

The entire Section 9.1 in ISO 55001 and ISO 55002 is labelled *Monitoring, measurement, analysis and evaluation.* These sections require the organization to determine when and what needs to be monitored and measured as well as the methods applicable.

ISO 55002 also notes the need for quantitative methods in a number of sections. ISO 55002 Section 4.2.4 states:

> *"The criteria can be expressed in a number of ways, to support **quantitative**, semi-quantitative or qualitative decisions. The processes to establish the decision-making criteria that guide asset management should be clear and documented."*

In ISO 55002 Section 6.2.1.1, the requirements related to asset management objectives are discussed and gives the following:

> *"They can be both **quantitative** (e.g. mean time between failure) and qualitative measurement (e.g. customer satisfaction)."*

The ISO 55000 series is a detailed standard, thus for the benefit of this research study a conclusive description of the standard is important, but more so the identification of the specific areas that require quantitative methods to aid the process of asset management.

Chapter 2 identified important areas mentioned in the PAM literature, the ISO 55000 series, PAS 55 and in the research in general. Risk management was identified as the number one area of concern.

The ability to manage an organization's risks is one of the most mentioned terms in the ISO 55000 series. In ISO 55000 the need for risk management is emphasized to realize the value of assets and to balance cost, risk and performance. It also mentions the use of a risk framework and a risk based approach to asset management. ISO 55000 Section 2.5.3.6 specifically states that:

> *Risk management and control in the context of managing change is an important consideration in operating an asset management system."*

Risk and risk management as concepts are referenced a number of times in ISO 55001. Listed below are the sections identified in ISO 55001 related to risk and risk management:

– Section 5.1 refers to risk management in terms of aligning the organization's risk management strategy with that of the asset management risk strategy.

– Section 6.1 is dedicated to planning the actions to address risk.

– Section 6.2.2 (k) also focus on the documentation of the actions implemented to address the issue of risk.

– Section 7.3 describes the awareness of the risks associated with the work activities of the respective employees.

– Section 7.5 (a) emphasize the need for information regarding the significance of certain risks.

– Section 8.1 refers back to Section 6.2.2 in the treatment and monitoring of risks.

– Section 8.2 is mostly focused on risk as a whole and is concerned with the risk associated with activities that bring forth change in the organization.

– Section 8.3 concerns the risks associated with outsourcing.

– Section 9.1 and 9.3 (f) also makes note of risk.

To summarize, risk management and the occurrence of risk related situations are mentioned in the following sections in ISO 55002: Section 4.1.2.3 (j), 4.2.4, 4.4, 5.1 (i) and (k), 5.2, 5.2 (d), 6.1, 6.2.1.2 (a), 6.2.2.3, 6.2.2.4, 7.3.1 (d), 7.5.2 (h), 7.5.3 (b) and (g), 8.1.1, 8.1.4, 8.2.3, 8.3.4, 9.1.2.1, 9.1.2.2 (g), 9.1.2.5, 9.1.2.6, 9.2.2, 9.3.2 (f), 10.1.1 (b) and (c), 10.1.3 and 10.3.4 (d).

One section that is very informative and descriptive in the concept of risk management is ISO 55002 Section 6.1 and ISO 55002 Section 6.2.2.3. Section 6.1 gives a description of the actions to address risks for the asset management system. Section 6.1, mentioned previously, gives an example of identifying, analyzing and evaluating risk with the following steps:

(1) Classify assets and define the scope

(2) Identify risks

(3) Identify risk controls that exist

(4) Analyze risks using the appropriate process

(5) Evaluate the level of risk

(6) Evaluate the level of risk over time

(7) Evaluate the tolerability of the risks

(8) Determine the treatment of the risks

To grasp the full extent of the need for quantitative methods in ISO 55000, four critical areas are discussed below including *Monitor, Measure, Analysis and Evaluation*, *Asset Criticality*, *Failure Analysis* and *Financial Risk Impact*. Specific sections are noted that requires each of these areas. The reason these concepts are chosen is due to the fact that asset criticality, financial risk management and failure analysis were chosen in Chapter 2 as the critical areas related to PAM and risk management. *Monitor, Measure, Analysis and Evaluation* is directly related to the concept of quantitative methods and analysis.

3.3.1 Monitor, Measure, Analysis and Evaluation

One of the benefits mentioned in ISO 55000 is the improved efficiency and effectiveness in the organization due to *"reviewing and improving processes, procedures and asset performance"*. It is important to make use of new tools and methods to monitor, measure, analyze and evaluate the data available. Quantitative methods will aid the process of using data in the appropriate way.

ISO 55001 address the monitor, measure, analysis and evaluation of data and actions regarding asset management activities. Specific sections are once again identified dealing with measure, analysis and evaluation in ISO 55001:

- Section 6.1 (b) is associated with the planning of asset management activities and states that the implemented actions should be evaluated.
- Section 6.2.1 also identifies the need for measurable and monitored asset management objectives.
- Section 7.5 is labelled *Information requirements* and this directly relates to the management of data as well as Section 7.6 labelled *Documented information*.

- The most important section is Section 9.1 titled *Monitoring, measurement, analysis and evaluation*. This section gives clear guidelines on how this process should take place. The rest of Section 9 continues to emphasize the need of performance evaluation.
- Section 10 also touch on the need for evaluating and improving.

In ISO 55002 Section 9.1 is titled *Monitoring, measurement, analysis and evaluation* and is thus the most important section regarding this area. The monitor, measure, analyze and evaluate process is also applied to risk management in ISO 55002 Section 6.2.2.3. The same process of establish, implement and maintain process(es) is followed in Section 10 for nonconformity and corrective action (Section 10.1), preventive action (Section 10.2) and continual improvement (Section 10.3). This relates to the idea of monitor, measure, analyze and evaluate data. The following sections also includes reference to this area: Section 5.1 (g), 6.2.1.1, 6.2.1.4, 6.2.2.1, 6.2.2.3, 8.2.3, 8.3.2 (c), (d) and (e), 9.2.1, 9.3.2 (c) 2 and 9.3.5.

3.3.2 Asset Criticality

Asset Criticality ties closely to risk management. Reason being that the organization needs to know what assets are critical to the organization and what assets could cause potential risky situations. This is a continuous process as the value of the asset can change over time as stated in ISO 55000. Emphasis is also placed on monitoring the performance of the assets and this will enable the organization to establish their critical assets.

In ISO 55001 Section 9.1 (a) the problem of what needs to be monitored is addressed. This basically comes down to the critical assets. Also in Section 9.1, the organization is required to measure asset performance enabling the critical assets to be identified.

The need for identifying the critical assets in an organization is emphasized in the following sections in ISO 55002: Section 4.4, 6.2.1.2 (b), 6.2.1.3 (d), 6.2.2.1, 6.2.2.2 (e), 6.2.2.3 (a), 7.1, 7.2, 7.5.1, 7.5.2, 7.6, 9.1.2.1, 9.1.2.6, 9.2.1 and 9.3.2 (c) 2 (ii).

3.3.3 Statistical Failure Analysis

According to Minnaar *et al.* (2013), *Statistical Failure Analysis* is the process of predicting when a machine will fail and directly relates to continual improvement and preventative action. ISO 55000 also includes the importance of asset-related incidents or emergency situations

ISO 55001 Section 10 is titled *Improvement* and relates to statistical failure analysis. It emphasizes the process that needs to be followed in the case of a nonconformity and the need for corrective and preventive action and continual improvement.

ISO 55002 Section 9 and 10 are very important regarding the need for statistical failure analysis. Section 9 discusses the need for performance evaluation and specifically states the monitoring of failures. Section 10 describes the need for improvement by means of corrective and preventive action and continual improvement. Predicting when an asset will fail enables an organization to put these measures into place. The following sections also make note of statistical failure analysis in ISO 55001 and ISO 55002: Section 6.2.1.3 (c) and (d), 7.5.2, 8.1.3

3.3.4 Financial Risk Impact

Although it is clearly stated in ISO 55000 that the standard does not provide financial guidance for managing assets, it is identified throughout the standard as an important part of managing assets. Improved financial performance is listed as one of the benefits of asset management in ISO 55000 Section 2.2. The fact that the value of an asset can be tangible or intangible, financial or non-financial is mentioned more than once throughout the ISO 55000 series. The integration of asset management with the finance section of an organization is important and can only be done efficiently if the asset management program incorporates financial management.

ISO 55001 also refers to financial management and documentation in a variety of sections. Section 4.2 concerns the stakeholders' need for financial information and documentation regarding asset management. Section 6.2.1 and 6.2.2 also includes the need to adhere to financial requirements. Section 6.2.2 (i) indicates the importance of identifying and documenting financial implications of asset management. Section 7.5 (d) and (e) and Section 9.1 also mentions the need for financial management.

The following sections discuss the need for financial reporting in ISO 55002: Section 4.1.2.2, 4.2.3 (f) and (g), 5.1 (d), 6.2.1.3 (a), (b), (c) and (d), 6.2.2.1, 6.2.2.2 (f), 6.2.2.4, 7.4 (more specifically 7.5.2 (g), 7.5.3 (g) and (i)), 9.1.1.2 (a) and (f), 9.1.1.3, 9.1.2.5, 9.1.2.6 including (b) and (c), 9.2.3 (c), 9.3.4 (d), 10.3.4 (c). Section 7.4 is important as it is titled *Communication* and one of the best ways to communicate the impact of asset management to the stakeholders is through financial information.

3.3.5 Chapter Summary

Objective three, four and five as established in Chapter 1, are dealt with in this chapter. The review of ISO 55000 addresses the key concepts that are essential to the development of this thesis and solving the stated problem. Chapter 3 is a broad summary of the three documents bringing together the ISO 55000 series. The first section in this chapter dives into ISO 55000, ISO 55001 and ISO 55002 and their respective ISO 55000 sections. Risk management requirements in ISO 55000 are also identified and furthermore, the need for quantitative methods. To summarize the call for quantitative methods, the list below is provided:

(1) Risks and opportunities that need to be addressed.

(2) Objectives measurable and monitored.

(3) What needs to be monitored and measured.

(4) Methods for monitoring, measurement, analysis and evaluation.

(5) When monitoring and measuring shall be performed.

(6) When the results from monitoring and measurement shall be analyzed and evaluated.

(7) Evaluate and report on asset performance.

(8) Evaluate and report on asset management performance – financial and non-financial.

(9) Evaluate and report the effectiveness of the asset management system.

(10) Evaluate and report on the effectiveness of the process for managing risks and opportunities.

(11) React to non-conformity or incident.

(12) Take action to control and correct it.

(13) Deal with the consequences of it.

(14) Evaluate the need for action to eliminate the causes of the nonconformity or incident in order that it does not occur or recur elsewhere by:

   - reviewing the nonconformity or incident.
   - determining the cause of the nonconformity or incident.
   - determining if similar non-conformities exist or could potentially occur.

(15) Establish process to pro-actively identify potential failures in asset performance and evaluate the need for preventive action.

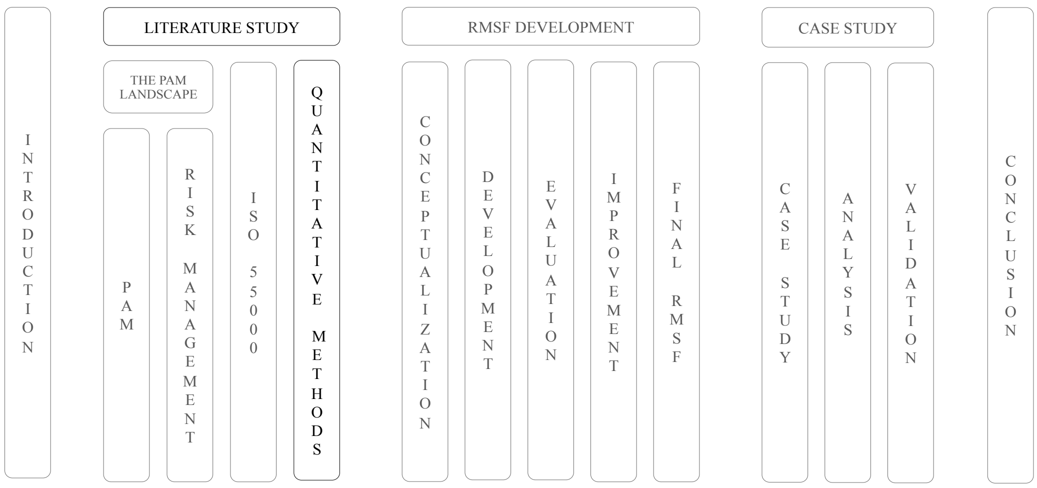
The chapter concludes with the four important areas in ISO 55000: *Monitor, Measure, Analysis and Evaluation*, *Asset Criticality*, *Statistical Failure Analysis* and *Financial Risk Impact*. Each area is identified specifically in ISO 55000 with regards to specific ISO 55000 sections and yields the focus of the solution of this research.

Chapter 4

Quantitative Methods for Implementing ISO 55000

Chapter Aim:

Previously, it was determined that there is a dire need for the use of quantitative methods in asset management as stipulated in the ISO 55000 series. The aim of this chapter is to identify specific quantitative methods related to ISO 55000 that are applicable to asset management and more specifically risk management and the four critical areas.



Chapter Outcomes:

- Identification, description and comprehension of existing quantitative methods applicable to PAM and Risk Management.
- Grouping different quantitative methods into the four important areas.
- Understanding where quantitative methods fit into PAM, Risk Management and ISO 55000.
- Examples associated with the quantitative methods applicable to PAM where needed.

4.1 Quantitative Methods related to PAM and ISO 55000

Chapter 2 provided background information regarding the PAM environment and identified certain critical areas of concern. Thus, for this chapter it was necessary to group the quantitative methods into specific sets to facilitate the evolution of Chapter 5 and the progression of the solutions flow. The sets identified are:

- Criticality Analysis
- Financial Risk Impact
- Failure Analysis

Another two critical areas were identified in the preceding chapters namely *Monitor, Measure, Analysis and Evaluation* and *Health, Safety and Environmental Impact*. Two reasons exist for not incorporating them as alone standing fields. Firstly, it was concluded that *Monitor, Measure, Analysis and Evaluation* encompass the entirety of this research and therefore, it is not important on its own, but rather throughout the entire thesis. Secondly, *Health, Safety and Environmental Impact* is essential in risk management, but it would result in an immense study. Most organizations are heavily focused on *Health and Safety* already, and thus it goes beyond the scope of this research.

4.2 Identify Critical Assets

The first step of the quantitative analysis is to determine what the critical assets in the organization are to be able to focus on these specific assets. Criticality Analysis is defined by the following methods:

(1) Failure Mode and Effects (Criticality) Analysis (FME(C)A)

(2) Criticality Analysis (CA)

(3) Theory of Probability and Bayes Theorem

(4) Reliability

(5) Multi-attribute Technique i.e. Analytic Hierarchy Process (AHP)

(6) Risk Priority Number (RPN)

(7) Fuzzy Logic RPN

(8) Monte Carlo Simulations

(9) Multi-criterion Classification of Critical Equipment (MCCE)

These methods are discussed further and applicable examples are given where needed. It is paramount to remember that these are not the only quantitative methods available to conduct this analysis, but they are the most well-known and valuable methods according to the research conducted during this study.

4.2.1 Failure Mode and Effects (Criticality) Analysis (FME(C)A)

Failure Mode and Effects Analysis (FMEA) is a powerful method for reliability analysis and is widely used in many industries. It is inductive in nature and could be used for all aspects of system failure. Ranging from conception to implementation to disposal (Modarres *et al.* (1999)). It is described as a *"bottom-up approach starting with components and using a single-point failure approach to progressively work up to the top level"* by Dyadem Press (2003).

FMEA is described by Marshall (2012) as:

> *" . . . a step-by-step approach for identifying all possible failures in a design, a manufacturing or assembly process, or a product or service".*

This research will primarily be concerned with FMEA conducted on the risks associated with assets. In the 1960s, FMEA was developed by the aerospace industry as a formal design methodology as discussed in Bowles and Peláez (1995). Since then it has become a popular method to assure the safety and reliability of products. A more quantitative extension of FMEA, is referred to as Failure Mode and Effects Criticality Analysis (FMECA). FMECA is thus more appropriate for this specific research study. FMECA starts by identifying every possible failure mode of all the system components and then eliminates or mitigates the associated effects.

Modarres *et al.* (1999) provides a step-by-step explanation of the FMECA process:

Step 1: Define the system in need of analysis. This includes the identification of

- the system decomposition;
- internal and interface system functions;
- restrains; and
- failure definitions.

Step 2: Construct a block diagram of the system, taking in to consideration the following diagrams (depending on system complexity):

- Structural
- Functional
- Combined
- Master Logic Diagram (MLD)

Step 3: Identify the potential failure modes associated with all items and define the effect they may have on the immediate function, item, system or mission.

Step 4: Evaluate the failure mode identified and assign a severity classification category to each depending on the potential consequences.

Step 5: Identify failure detection methods and provide compensation for each.

Step 6: Identify corrective actions or design to reduce, control or eliminate the risk.

Step 7: Document the analysis and identify the problems that could not be repaired.

The criticality of the component is based on the probability of the failure mode of the item and the severity of its effects. Thus, the priority items can easily be identified. Bowles and Peláez (1995) goes further to describe the two different criticality assessments used to perform FMEA namely calculating a criticality number for each item or developing a Risk Priority Number (RPN). The *failure modes* allude to the specific way failure takes place and the *severity of its effects* relates to the consequences of the mentioned failures.

The criticality number calculation categorizes the severity of the failure mode effect and then determines the probability of a failure with that severity. It is also referred to as a *"criticality ranking"*. In determining the *"criticality ranking"*, the following variables needs to be determined:

- The failure effect probability (β)
- The failure mode ratio (α)
- The part failure rate (λ)
- The operating time (τ)

This method uses three rankings to finally give the RPN. These include the probability of the failure-mode occurrence, the severity of its failure effect and the probability of the failure being detected. All three are measured on a numerical scale for example, from 1 to 10 and then multiplied with one another to get the RPN. Thus, a high RPN is associated with a high risk.

FMECA is an effective tool as it enables a process of identifying root failure causes, facilitates the implementation of corrective action and identifies reliability or safety critical components. It also acts as a proper foundation to conduct additional maintainability, safety, test-ability and logistical analyses.

When conducting a FMECA analysis it is important to list certain specifications in the header before starting the process including

- all assumptions;
- product or part names and numbers;

– team members associated with the areas analyzed; and

– the revision date.

A typical FMECA worksheet is shown in Table 4.1.

TABLE 4.1: Example of a FMECA worksheet.

Item Function	Potential Failure Mode	Potential Effects of Failure	SEV	Potential Cause(s) of Failure	OCC	Current Controls	DET	RPN	Recommended Actions	Responsibility & Target Dates	Action Results				
											Actions Taken	SEV	OCC	DET	RPN

The different sections to be completed in the FMECA worksheet is discussed below. An example of a completed FMECA sheet is provided in Appendix 1 to fully understand the FMECA process. Modarres *et al.* (1999), Dyadem Press (2003) and Marshall (2012) provides a descriptive explanation of the FMECA table.

Item Function

The *Item Function* is the function of the item considered for analysis and which has the possibility of failure. It should be detailed, descriptive and specific to remove any misconceptions or misinterpretations. A measurable metric should also be included. Some tables include columns for identification number and functional identification (nomenclature), but these could just be incorporated under the *Item Function* column if needed.

Potential Failure Mode

A *Potential Failure Mode* is the manner in which a failure can occur. Marshall (2012) identifies five modes of failure: complete failure, partial failure, intermittent failure, function out of specification and unintended failure. Again it is important to be precise and specific when writing the failure modes. There can be more than one and all should be listed. Depending on the system, the environment and other factors, only certain failure modes may apply. For example, electronic components may experience corrosion, short, drifting, etc.

Potential Effect(s) of Failure

The potential outcome of the failure on the system, design, process or service is known as the *Potential Effects of Failure*. The consequences of each failure mode should be analyzed and recorded as a potential effect(s) of failure. The effects should be written as per the view of the customer. Effects should include the safety or regulatory body, the end user and the internal customers such as manufacturing, assembly and service. Modarres *et al.* (1999) distinguish between three levels of failure: local, next higher abstraction level and end effect. Some worksheets also add *Failure Detection Mode* and *Compensating Provision*. The first is a description of how the failure was identified by using previously known symptoms, for example.

The latter, describes how the failure is corrected so that it does not propagate to the entire system. A short description of each follows in Table 4.2.

TABLE 4.2: Three levels of failure associated with the FMECA process.

Failure Level	Failure Name	Failure Description
1	Local Effect	Impact and consequences of the postulated failure mode on the function and operation of the item considered. It is possible that no local effect can be noticed apart from the failure mode itself.
2	Next Higher Abstraction	Consequences of each postulated failure on the output of the item.
3	End Effect	Effect of postulated failure on the operation, function and status of the next higher abstraction level and ultimately on the system itself. Could be the result of multiple failures.

Severity Classification

The *Severity Classification* is the seriousness of the effects of the failure and a measurement (relatively scaled from 1 to 10) that is qualitative in its nature and depicts the worst case scenario and the consequences from the item or function failing. According to the Mil-Std-1629A there are four severity levels of failure shown in Table 4.3.

TABLE 4.3: The four severity levels of failure as developed by Mil-Std-1628.

Category	Effect	Criteria
I	Catastrophic	A failure mode that could cause complete mission or system loss or even death.
II	Critical	A failure mode that could cause property damage, system degradation or injury of severe levels. It will lead to a reduction in mission performance.
III	Marginal	A failure that could cause property damage, system damage or injuries that are minor. It will lead to delay or loss of availability or even mission or system degradation.
IV	Minor	A non-serious failure that would not cause property damage, system degradation or injury. It will, however, lead to unscheduled maintenance or repair and system failure.

Severity could be based upon internally defined criteria or a specific standard, but rating tables should then be included in the FMECA for further reference and explanation.

Potential Cause(s)/Mechanisms of Failure

Causes should be related to design concerns and must be identified for a failure mode and not an individual effect. There will probably be more than one cause of failure for each failure mode. It focuses on the root cause of potential failure modes, not the symptoms.

Occurrence Classification

The *Occurrence Classification* can be seen in Table 4.4 and is defined as the frequency of failure.

Table 4.4: Occurrence classification.

	Description
10	$\geq$ 50 % (1 in two)
9	$\geq$ 25 % (1 in four)
8	$\geq$ 10 % (1 in ten)
7	$\geq$ 5 % (1 in 20)
6	$\geq$ 2 % (1 in 50)
5	$\geq$ 1 % (1 in 100)
4	$\geq$ 0.1 % (1 in 1, 000)
3	$\geq$ 0.01 % (1 in 10,000)
2	$\geq$ 0.001 % (1 in 100,000)
1	Almost Never

If internally defined criteria are established, it must be included in the FMECA to refer to and explain further. It is also important that the occurrence with a value of 1 must have objective data to provide justification. Data or the source of data must be identified in the *Recommended Actions* column. The occurrence rating for a design FMECA is based on the likelihood of cause occurring, past failures or performance of similar systems in similar applications.

Current Design Controls

The *Current Design Controls* are safeguarding measures that strive to eliminate causes of failure, identify or detect failure and reduce the impact of failure. This section is divided into preventive and detective controls. Preventive controls enable the reduction of likelihood that a failure mode or cause will occur and detective controls find faults that have been designed into the product.

Detection

Table 4.5 shows the ranking of the probability that the failure mode will be identified.

Table 4.5: Detection classification.

	Description
10	Absolute uncertainty
9	Very remote
8	Remote
7	Very low
6	Low
5	Moderate
4	Moderately high
3	High
2	Very high
1	Almost certain

These values should also correspond with specific standards and if internally defined criteria are used, these must be included in the FMECA for further reference and explanation. The value assigned to the detective controls is known as detection and if a value of one is found, the potential of failures must be eliminated due to design.

Risk Priority Number (RPN)
The *Risk Priority Number (RPN)* is used to rate the risks relatively to each other. This is done by Equation 4.2.1.

$$\text{RPN} = O \times S \times D \tag{4.2.1}$$

where O is the frequency of occurrence of the cause of the failure, S is the severity of the effect and D is the ability to detect the failure or the effect. The RPN is discussed in more detail in the next section.

Recommended Actions
Recommended Actions should be allocated to each of the critical characteristics. These actions should eliminate the failure mode or mitigate the cause of failure. It also intends to reduce the RPN.

Responsibility & Target Completion Date
A person should be allocated to each of the recommended actions. This person should be part of the team (listed in the header) and is responsible for implementing the action. There must be a completion date assigned to each of the actions.

Action Results
Finally, the actions taken and the results of these actions taken are documented. It must be done by the target completion date. *Severity*, *Occurrence* and *Detection* cannot be lowered or changed based on the results. If these three ratings are not improved, additional recommended actions should be made.

Example:

An example of the FMECA sheet is included in Appendix 1.

4.2.2 Criticality Analysis (CA)

The previous section discussed the FMECA process. The quantitative Criticality Analysis (CA) forms part of the FMECA. It is the combination of a probabilistic determination of a failure mode occurrence and the impact it has on the success of the system mission (Modarres *et al.* (1999)). The *Failure Mode Criticality Number* forms part of the FMECA process as described by Jones (2010) and is calculated with Equation 4.2.2.

$$C_m = \lambda \beta \alpha d t_h \tag{4.2.2}$$

where C_m is the criticality number for the failure mode, λ is the part failure rate, β is the failure effect probability or conditional probability that the failure mode results in the listed end effect, α is the failure mode ratio, d is the probability that the failure mode will be detected by the operator or other means and t_h is the duration of applicable operating hours or cycles in hours.

C_m is used to rank each potential failure mode based on its occurrence and consequences of its effect. β, in complex systems is difficult to determine, thus it is estimated in many cases by the analyst in relation to her prior experience. Table 4.6 gives an indication of determining β. λ can be estimated from test or field data or even generic sources of failure rates.

TABLE 4.6: Failure effect probabilities β for various failure effects.

Failure Effect	β Value
Actual loss	1.00
Probable loss	$0.1 < \beta \leq 1.00$
Possible loss	$0 < \beta \leq 0.1$
No effect	0

Adapted from Jones (2010)

During the criticality analysis, the entire system is analyzed and thus all the assets should be included in the calculations. The critical assets are determined and are an important part of asset management. This tells the organization the specific assets that could cause problems for the organization and thus require their undivided attention Criticality Analysis demands the availability of failure data in regards to the assets.

Example:

The system under consideration runs seven days a week and 24 hours a day. The system also consists of five assets with failure data available. Calculations are shown for the first asset.

Asset A has a 7.3% chance of failing and fails at a rate of 0.08 fails per million hours. The duration of operating time of the five assets are 168 hours and the probability of a failure effect is 60%. There is a 90% probability that the operator will detect the failure before it happens Thus:

$$\lambda = 0.08$$

$$\beta = 0.6$$

$$\alpha = 0.073$$

$$d = 0.9$$

$$t_h = 168$$

and the calculation is as follows:

$$C_m = \lambda\beta\alpha d t_h = (0.08)(0.6)(0.073)(0.9)(168) = 0.5298$$

Table 4.7 shows the results for the entire system as well as the priority ranking of the assets.

TABLE 4.7: Criticality analysis example.

Asset	Part Failure Rate (λ)	Failure Effect Probability (β)	Failure Mode Ratio (α)	Detection Probability (d)	Time Period (t_h)	Criticality (C_m)	Priority
Asset A	0.08	0.60	0.073	0.90	168	0.5298	2
Asset B	0.65	0.00	0.08	0.20	168	0	5
Asset C	0.88	0.04	0.065	0.45	168	0.1730	4
Asset D	0.03	1.00	0.09	0.50	168	0.2268	3
Asset E	0.045	0.90	0.098	0.95	168	0.6335	1

It is thus clear that Asset E is the critical asset with Asset A also being considered as highly critical.

4.2.3 Theory of Probability and Bayes Theorem

Bayes (1764) Theorem is usually used to " *. . . update the probability of an event from newly acquired data . . .* " as summarized by Blaine (2012). The Theorem is derived from the basic rules of probability where A_j and B are independent events. The union of event A_j and B is written as $A_j \cup B$ and the intersection of the two is written as $A_j \cap B$. Furthermore, the **union** of events is described as the part of the sample space occupied by the events considered. The **intersection** of events is the part of the sample space occupied by both the events together. For example, if we have a sample space consisting of $A_1, A_2, A_3, \ldots A_n$, their union is the sample space and they are mutually exclusive if they constitute a partition of the sample space. Bayes Theorem is described in Blaine (2012) and Modarres *et al.* (1999).

The probability of the union of all the A_j events with event B is given by Equation 4.2.3.

$$P(A_j \cup B) = P(A_j) + P(B) - P(A_j \cap B) \tag{4.2.3}$$

The intersection between A_j and B is 0, because they are independent and there is no sample space.

$$A_j \cap B = \phi \text{ and so } P(A_j \cap B) = 0$$

it follows then that

$$P(A_j \cup B) = P(A_j) + P(B) \tag{4.2.4}$$

Furthermore, the probability that event B will occur given that event A_j has occurred is defined as the conditional probability of B and is denoted as $P(B|A_j)$. Equation 4.2.5 shows the calculation for the conditional probability of B.

$$P(B|A_j) = \frac{P(A_j \cap B)}{P(A_j)} \tag{4.2.5}$$

This leads to Equation 4.2.6 and 4.2.7.

$$P(A_j \cap B) = P(A_j) \bullet P(B|A_j) \tag{4.2.6}$$

$$P(B \cap A_j) = P(B) \bullet P(A_j|B) \tag{4.2.7}$$

Because A_j and B are independent, the following is true

$$P(A_j|B) = P(A_j) \text{ and } P(B|A_j) = P(B)$$

This leads to Equation 4.2.8.

$$P(A_j \cap B) = P(A_j) \bullet P(B) = P(B \cap A_j) \tag{4.2.8}$$

The law of probability gives Equation 4.2.9.

$$P(B) = \sum_{j=1}^{n} P(B|A_j) \bullet P(A_j) \tag{4.2.9}$$

Finally, Bayes' Theorem is depicted in Equation 4.2.10.

$$P(A_j|B) = \frac{P(B|A_j) \bullet P(A_j)}{\sum_{j=1}^{n} P(B|A_j) \bullet P(A_j)} \tag{4.2.10}$$

To conclude:

$P(A_j)$ is referred to as the **prior probability**.

$P(A_j|B)$ is known as the **posterior probability**.

Event B is the observation.

$P(B|A_j)$ is called the likelihood function, thus the probability of the observation given that A_j is true.

Example:

Consider the question of whether the oil pressure of a continuous miner is too high. Suppose that the oil pressure is too high 1% of the time. The pressure gage can have a reading that is too high or a reading that is as it should be. When the oil pressure is too high, 95% of the time the oil pressure gage will give a too high reading. When the oil pressure is as it should be, 1% of the time the oil pressure gage will give a too high reading. Given that a reading is observed and the oil pressure gage shows a reading of too high, what is the probability that the oil pressure is too high?

The first step is to indicate the different probabilities given. The states of the world are:

A_1 = oil pressure is too high

A_2 = oil pressure is as it should be

The possible experimental outcomes are:

B_1 = too high reading

B_2 = not too high reading

The prior probabilities are given as $P(A_1) = 0.01$ and $P(A_2) = 0.99$ and the likelihoods $P(B_1|A_1) = 0.95$, $P(B_1|A_2) = 0.01$, $P(B_2|A_1) = 0.05$ and $P(B_2|A_2) = 0.99$. The probability of $P(A_1|B_1)$ needs to be determined. Thus

$$\begin{aligned} P(A_1|B_1) &= \frac{P(B_1|A_1)P(A_1)}{P(B_1|A_1)P(A_1) + P(B_1|A_2)P(A_2)} \\ &= \frac{0.95(0.01)}{0.95(0.01) + 0.01(0.99)} = \frac{95}{194} \\ &= 0.49 \end{aligned}$$

Thus the oil pressure gage will be correct 49% of the time when the reading is too high. This calculation enables the employee to establish if more tests are needed or if the probability of a correct reading is acceptable.

4.2.4 Reliability

Reliability determines the dependability or trustworthiness of an asset or the extent to which the asset is available at its predetermined capacity (Hall and Daneshmend (2003)). The definition of reliability is provided by the System Reliability Center (SRC (2001)) as follows:

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

Simplifying this definition, Vlok (2011) describes reliability as *" . . . the probability of failure"* and notes two different cases that exists in regards to reliability. This includes when the failure of one item in the system influence the survival or failure of the other items (Case 1) and independent failures (Case 2). Reliability analysis can be quantitative or qualitative according to Blischke and Prabhakar Murthy (2003). The quantitative reliability analysis, which is applicable to this research, uses real failure data together with the appropriate mathematical models to enable quantitative estimates of the reliability of the system. A failure can happen at any point in time and therefore it is important to determine the appropriate time scales to measure the lifetime of assets.

Figure 4.1 shows X_i to be the inter-arrival time or local time between failure $(i-1)$ and failure i of the system. x_i is the real variable and measures the time elapsed since the most recent event. The time measured to the i^{th} event or the arrival time of failure i, beginning at 0, is noted as T_i or global time.

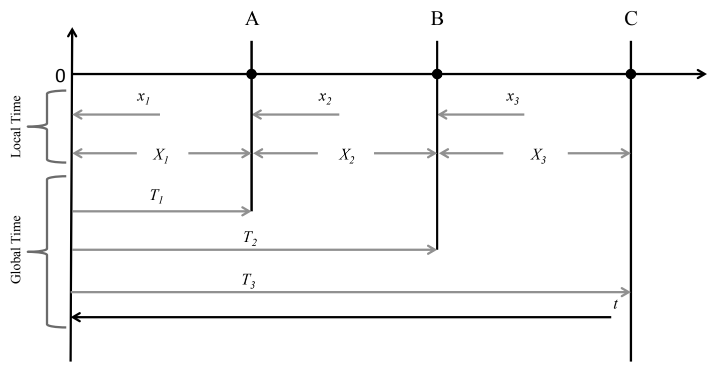


FIGURE 4.1: Failure process.
Adapted from Vlok (2011)

When discussing failure related to reliability and the lifetime of a population, it is important to understand the bathtub curve shown in Figure 4.2.

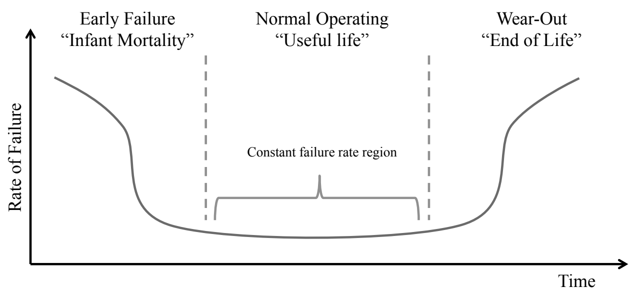


FIGURE 4.2: The Bathtub Curve: Hypothetical failure rate vs. time.
Adapted from Wilkins (2002)

This curve has three distinct periods according to Wilkins (2002): an infant mortality period with decreasing failure rate, a normal life period with a low and constant failure rate and a wear-out period with an increasing failure rate. The bathtub curve does not represent a single item's failure rate, but rather that of an entire population.

Case 1 and Case 2, mentioned previously, is defined by two sets of equations for items in series. Case 1 is given by,

$$\begin{aligned} \mathrm{R} &= \mathrm{P}(A_1 \cap A_2 \cap \ldots \cap A_w) \\ &= \mathrm{P}(A_1)\mathrm{P}(A_2|A_1)\mathrm{P}(A_3|A_1A_2)\ldots\mathrm{P}(A_w|A_1A_2\ldots A_{w-1}) \end{aligned} \tag{4.2.11}$$

In Equation 4.2.11, the reliability (R) is equal to the probability (P) of the intersection of the events (A) related to the individual items (x).

For Case 2, Equation 4.2.11 is reduced to,

$$\begin{aligned} \mathrm{R} &= \mathrm{P}(A_1 \cap A_2 \cap \ldots \cap A_w) \\ &= \prod_{i=1}^{w} \mathrm{P}(A_i) \\ &= \prod_{i=1}^{w} R_i \end{aligned} \tag{4.2.12}$$

Equation 4.2.12 thus shows that the reliability of the system is equal to the product of the reliabilities of the different items. For items in parallel, Equation 4.2.11 and 4.2.12 determines the unreliability of the system (F) and since $F = 1 - R$, the overall reliability of the system is given by,

$$R = 1 - \prod_{i=1}^{w} (1 - R_i) \tag{4.2.13}$$

Hall and Daneshmend (2003) also discusses the reliability growth rate and defines it as follows:

> *"Reliability growth is defined as the positive improvement in a reliability parameter over a period of time."*

Reliability growth is influenced by product design and/or manufacturing process and/or maintenance practice. Equation 4.2.14 is one way to calculate the reliability growth rate.

$$\text{Reliability Growth Rate} = \frac{\text{Final Failure Rate}}{\text{Initial Failure Rate}} = \frac{\text{Initial MTBF}}{\text{Final MTBF}} \tag{4.2.14}$$

Mean Time Before Failure (MTBF) is discussed further in this chapter.

4.2.5 Analytic Hierarchy Process (AHP)

Dr. Thomas L. Saaty developed the Analytic Hierarchy Process (AHP) in 1980 and according to his research (Saaty (1990)), the AHP is defined as follows:

> *"In the Analytic Hierarchy Process we arrange these factors, once selected, in a hierarchic structure descending from an overall goal to criteria, sub-criteria and alternatives in successive levels."*

Zaim *et al.* (2012) describes it as a "*. . . powerful tool in solving complex decision problems"*. The important aspects of the problem are structured into a hierarchical form and enable the breakdown of the problem into sub-problems. Saaty (1990) agrees that these sub-problems can be more easily evaluated and understood. Evaluations are subjective and are converted into quantitative values and ranked according to each alternative on a numerical scale. The process of reducing complex decisions to simple comparisons and rankings and synthesizing the results, enables the decision maker to make the best decision and also provides evidence for the choice made (Zaim *et al.* (2012)).

Bhushan and Rai (2004) contributes to the research and explains that the AHP is divided into a hierarchy of goal, sub-criteria and alternatives. Figure 4.3 is the generic hierarchic structure and shows the relationships between the elements through line connectors. The top goal branches down into attributes and alternatives. The criteria could possibly have sub-criteria and the alternatives are connected to the main goal through the criteria and sub-criteria.

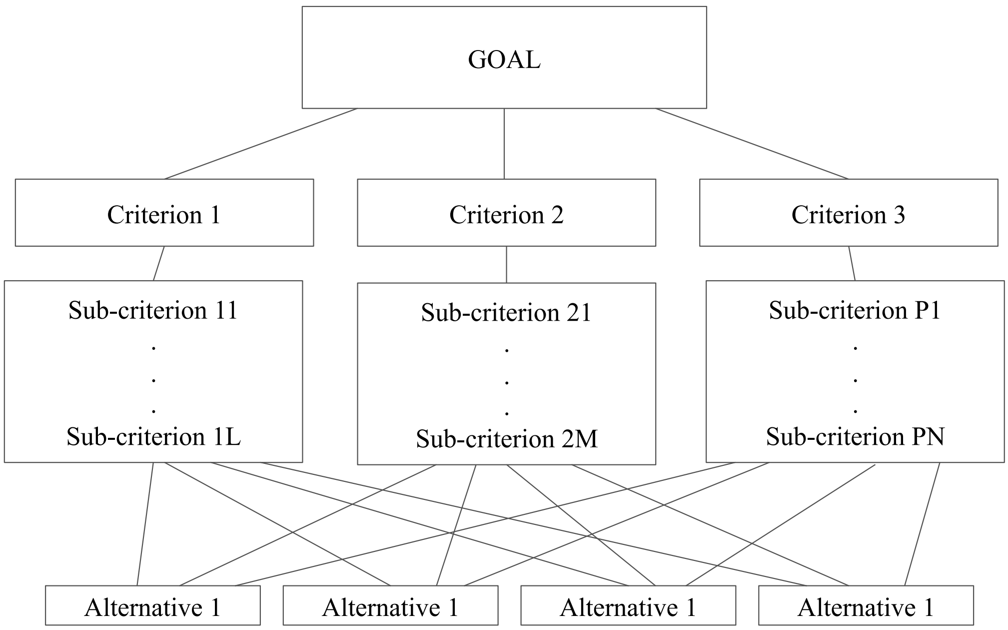


FIGURE 4.3: Generic hierarchic structure.
Adapted from Bhushan and Rai (2004)

Corresponding to the hierarchic structure, a pairwise comparison of the alternatives is conducted and attributed to a specific number as seen in Table 4.8. The alternatives are compared to one another with respect to the attribute.

TABLE 4.8: Rating scale for quantitative comparison of alternatives.

Score	Judgement	Explanation
1	Equal	Two attributes have equal value regarding the criteria
3	Moderate	One attribute is slightly more important than the other due to experience and judgement.
5	Strong	One attribute is strongly favoured over the other due to experience and judgement.
7	Very strong	One attribute is strongly favoured over the other and its dominance is demonstrated in practice.
9	Extreme	The evidence favouring one attribute over another are of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate values	For example, a value of 8 means one attribute is midway between strongly and absolutely more important than the other.

Adapted from Winston (2004)

A square or $n \times n$ matrix is used to organize the criteria as established. The criterion in the ith row is better than the criterion in the jth column if the value of the element $(i{,}j)$ is more than 1. And vice versa.

Comparing each level in the hierarchy creates a comparison matrix as described in Winston (2004). The comparison matrix is created as seen below where w_i is the weight given to the criterion.

$$A = \begin{array}{c} \\ A_1 \\ A_2 \\ \cdot \\ \cdot \\ \cdot \\ A_n \end{array} \begin{array}{c} \begin{array}{ccccc} A_1 & A_2 & \cdot\ \cdot\ \cdot & A_n \end{array} \\ \begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdot\ \cdot\ \cdot & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdot\ \cdot\ \cdot & w_2/w_n \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot \\ w_n/w_1 & w_n/w_2 & \cdot\ \cdot\ \cdot & w_n/w_n \end{bmatrix} \end{array} \begin{bmatrix} w_1 \\ w_2 \\ \cdot \\ \cdot \\ \cdot \\ w_n \end{bmatrix}$$

Once the comparison matrix is established it is important to extract the vector $\mathbf{w} = [w_1 w_2 w_3 \ldots w_n]$. This leads to the system of n equations

$$A\mathbf{w}^T = \Delta\mathbf{w}^T \tag{4.2.15}$$

or

$$= n \begin{bmatrix} w_1 \\ w_2 \\ . \\ . \\ . \\ w_n \end{bmatrix} \tag{4.2.16}$$

Furthermore, Δ is an unknown number and $\mathbf{w}^T$ is an unknown n-dimensional column vector. For any number Δ, Equation 4.2.15 has the trivial solution $\mathbf{w} = [000\ldots0]$. The decision maker is not consistent, thus Δ_{max} is the largest number for which the pairwise comparison matrix has a non-trivial solution ($\mathbf{w}_{\text{max}}$). Δ_{max} is close to n and $\mathbf{w}_{\text{max}}$ close to $\mathbf{w}$. Approximating $\mathbf{w}_{\text{max}}$ and Δ_{max}, a two-step procedure is used:

Step 1: Determine A_{norm} by dividing each entry in column i of the pairwise comparison matrix by the sum of the entries in column i.

Step 2: Find an approximate $\mathbf{w}_{\text{max}}$ by averaging the entries in row i of A_{norm}.

Winston (2004) also suggests that the consistency of the decision maker's comparisons should be checked. This is done by calculating $A\mathbf{w}^T$ and then

$$\frac{1}{n}\sum_{i=1}^{i=n} \frac{i\text{th entry in } A\mathbf{w}^T}{i\text{th entry in } \mathbf{w}^T}$$

Escobar *et al.* (2004) describes the Consistent Index (CI) to measure the consistency of the decision maker to ensure the comparison remains consisted. The CI is calculated with Equation 4.2.17 and is used to calculate the Consistency Ratio (CR) as shown in Equation 4.2.18. The Random Consistency Index (RI) is also used to calculate CR. CR is required to be below 0.1 to make the judgement viable.

$$\text{CI} = \frac{\lambda_E - n}{n - 1} \tag{4.2.17}$$

$$\text{CR} = \frac{\text{CI}}{\text{RI}} \tag{4.2.18}$$

with λ_E being the eigenvalue or the sum-product of the columns.

The eigenvector of the decision matrix and RI is determined through Table 4.9 proposed by Saaty (1987).

TABLE 4.9: AHP Random Consistency Index.

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.51

Adapted from Saaty (1987)

Zaim *et al.* (2012) suggests eight steps to conduct a proper AHP with regards to maintenance strategy selection and their research should be considered for further perusal. The eight steps include:

Step 1: *Form a focus group or project team that consists of engineers and key managers.* Usually some experts and managers from production, planning and control are involved.

Step 2: *Evaluate the problems.* Issues regarding maintenance are identified as well as the selection criteria and sub-criteria for the different maintenance techniques.

Step 3: *Determine the alternative strategies.* The strategies chosen is entirely based on the needs of the industry and organization.

Step 4: *Construct a hierarchical model.* An example was shown in Figure 4.3.

Step 5: *Pairwise comparison among criteria and sub-criteria.* The pairwise comparison is done according to the scale as suggested by Saaty.

Step 6: *Applying AHP algorithms.* The weights of the criteria and the scores of the alternatives are considered. The global priorities are calculated with Equation 4.2.19:

$$R_j = \sum_i v_i \cdot r_{ij} \tag{4.2.19}$$

with v_i the respective weights and r_{ij} the scores.

Step 7: *Prioritization.* Alternatives are listed in descending order regarding their weights.

Step 8: *Compare the results and make the decision.*

Example:

Consider a maintenance problem of a continuous miner. Various maintenance plans exist and a manager needs to choose an option by determining how well each meets the following four objectives:

Objective 1: Low cost (LC)

Objective 2: Output quality (OQ)

Objective 3: Applicability (A)

Objective 4: Flexibility (F)

Three maintenance plans exist and the manager needs to choose the best one. For the ith objective ($i = 1, 2, 3, 4$) the AHP generates a weight w_i for the ith objective. The pairwise comparison matrix is constructed:

$$\begin{array}{c c} & \begin{array}{cccc} LC & OQ & A & F \end{array} \\ \begin{array}{c} LC \\ OQ \\ A \\ F \end{array} & \begin{bmatrix} 1 & 5 & 2 & 4 \\ \frac{1}{5} & 1 & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & 2 & 1 & 2 \\ \frac{1}{4} & 2 & \frac{1}{2} & 1 \end{bmatrix} \end{array}$$

The pairwise comparisons are inconsistent in this example. For example, LC is twice as important as A and A is twice as important as OQ. Thus LC should be 2(2) = 4 times as important as OQ, but it is 5 times as important. Before approaching the problem of inconsistencies, the A_{norm} is calculated by dividing each entry by the sum of the values in that column. For example, column 2 is calculated as

$$\text{Sum of Column 2} = 5 + 1 + 2 + 2 = 10$$

thus in column 2 they A_{norm} value for the entry in row two will be 1/10. The averages of the entries in row i (w_i) is also calculated:

$$A_{\text{norm}} = \begin{bmatrix} 0.5128 & 0.5000 & 0.5000 & 0.5333 \\ 0.1026 & 0.1000 & 0.1250 & 0.0667 \\ 0.2564 & 0.2000 & 0.2250 & 0.2667 \\ 0.1282 & 0.2000 & 0.1250 & 0.1333 \end{bmatrix}$$

$w_1 = \frac{0.5128+0.5000+0.5000+0.5333}{4} = 0.5115$

$w_2 = 0.0986$

$w_3 = 0.2433$

$w_4 = 0.1466$

These weights indicate that *Low cost* is the most important objective, followed by *Applicability*, *Flexibility* and *Output quality*. the manager now has to determine how well each maintenance plan scores. To determine which maintenance plan the manager must choose, the overall score for each of the plans can be calculated if each plan is scored on each objective. This is done with the following equation:

$$\sum_{i=1}^{i=4} w_i(\text{maintenance plan } j\text{'s on objective } i)$$

Table 4.10 shows the scores assigned by the manager to each objective for each maintenance program.

TABLE 4.10: Manager's Score for Each Job and Objective.

Objective	Job 1	Job 2	Job 3
Low cost	0.571	0.286	0.143
Output quality	0.159	0.252	0.589
Applicability	0.088	0.669	0.243
Flexibility	0.069	0.426	0.506

The overall plan score is then calculated as

Plan 1 = 0.339

Plan 2 = 0.396

Plan 3 = 0.265

Thus, the manager should choose Plan 2. Furthermore, the consistency should also be checked.

$$A\mathbf{w}^T = \begin{bmatrix} 1 & 5 & 2 & 4 \\ \frac{1}{5} & 1 & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & 2 & 1 & 2 \\ \frac{1}{4} & 2 & \frac{1}{2} & 1 \end{bmatrix} \begin{bmatrix} 0.5115 \\ 0.0986 \\ 0.2433 \\ 0.1466 \end{bmatrix} = \begin{bmatrix} 2.0775 \\ 0.3959 \\ 0.9894 \\ 0.5933 \end{bmatrix}$$

$$\begin{aligned} &\frac{1}{n}\sum_{i=1}^{i=n} \frac{i\text{th entry in } A\mathbf{w}^T}{i\text{th entry in } \mathbf{w}^T} \\ &= \left(\frac{1}{4}\right)\left(\frac{2.0775}{0.5115} + \frac{0.3959}{0.0986} + \frac{0.9894}{0.2433} + \frac{0.5933}{0.1466}\right) \\ &= 4.05 \end{aligned}$$

CI is calculated as

$$\begin{aligned}\text{CI} &= \frac{4.05 - 4}{3}\\ &= 0.017\end{aligned}$$

CR is also calculated from Table 4.9

$$\begin{aligned}\text{CR} &= \frac{0.017}{0.9}\\ &= 0.019\end{aligned}$$

which is below 0.10 and no serious inconsistencies are noted.

4.2.6 Risk Priority Number (RPN)

The prioritization of the failure modes is done by means of the Risk Priority Number (RPN). This forms part of the FMEA process and is represented by

$$\text{RPN} = O \times S \times D \tag{4.2.20}$$

where O is the probability of failure, S is the severity of failure and D is the probability of not detecting the failure. Table 4.11, 4.12 and 4.13 shows the 10-point scale on which each risk factor could be evaluated.

TABLE 4.11: Suggested ratings for the occurrence of a failure mode.

Probability of failure	Possible failure rates	Rank
Extremely high: failure almost inevitable	$\geq$ 1 in 2	10
Very high	1 in 3	9
Repeated failures	1 in 8	8
High	1 in 20	7
Moderately high	1 in 80	6
Moderate	1 in 400	5
Relatively low	1 in 2000	4
Low	1 in 15,000	3
Remote	1 in 150,000	2
Nearly impossible	$\leq$ 1 in 150,000	1

Adapted from Liu et al. *(2013)*

TABLE 4.12: Suggested ratings for the severity of a failure mode.

Effect	Criteria: severity of effect	Rank
Hazardous	Failure is hazardous, and occurs without warning. It suspends operation of the system and/or involves noncompliance with government regulations	10
Serious	Failure involves hazardous outcomes and/or noncompliance with government regulations or standards	9
Extreme	Product is inoperable with loss of primary function. The system is inoperable	8
Major	Product performance is severely affected but functions. The system may not operate	7
Significant	Product performance is degraded. Certain functions may not operate	6
Moderate	Moderate effect on product performance. The product requires repair	5
Low	Small effect on product performance. The product does not require repair	4
Minor	Minor effect on product or system performance	3
Very minor	Very minor effect on product or system performance	2
None	No effect	1

Adapted from (Liu et al.*, 2013)*

TABLE 4.13: Suggested ratings for the detection of a failure mode.

Detection	**Criteria: likelihood of detection by design control**	**Rank**
Absolute uncertainty	Design control does not detect a potential cause of failure or subsequent failure mode. Or there is no design control	10
Very remote	Very remote chance the design control will detect a potential cause of failure or subsequent failure mode	9
Remote	Remote chance the design control will detect a potential cause of failure or subsequent failure mode	8
Very low	Very low chance the design control will detect a potential cause of failure or subsequent failure mode	7
Low	Low chance the design control will detect a potential cause of failure or subsequent failure mode	6
Moderate	Moderate chance the design control will detect a potential cause of failure or subsequent failure mode	5
Moderately high	Moderately high chance the design control will detect a potential cause of failure or subsequent failure mode	4
High	High chance the design control will detect a potential cause of failure or subsequent failure mode	3
Very high	Very high chance the design control will detect a potential cause of failure or subsequent failure mode	2
Almost certain	Design control will almost certainly detect a potential cause of failure or subsequent failure mode	1

Adapted from Liu et al. *(2013)*

4.2.6.1 RPN based on Fuzzy Logic

The problem with the RPN method is that different levels of risk can be presented by the same RPN value. For example, a state with $S = 9$, $O = 2$ and $D = 2$, the RPN value is calculated as 54. In contrast with a state with $S = 4$, $O = 5$ and $D = 6$, and a RPN value of 120. The second state has a much higher risk associated with it than the first state, although the first state has a high severity of failure rating. This results in the second state being treated as a priority case with corrective measures with no regard for the severity of the consequences of failure in the first case.

Petrović *et al.* (2014) proposes a method that makes use of fuzzy logic and fuzzy set theory. The proposed numerical values of S, O and D are depicted in Table 4.14, 4.15 and 4.16. It is based on a range of 1 – 7. Table 4.17 shows the five risk levels and the measures to be taken to reduce the level of risk. The fuzzy sets for the *Severity*, *Occurrence* and *Detection* are shown in Figure 4.4, 4.5 and 4.6. Finally, the risk fuzzy sets are done on expert opinion by analysis and presented in Figure 4.7.

In assessing the risk level of failure, it is necessary to synthesize failure indicators. The min-max compositions is shown to deliver the best results and the fuzzy sets of risk indicators are presented through a set of membership functions as follows:

$$\begin{aligned} \mu_S = (\mu_S^1, \mu_S^2, \ldots, \mu_S^i), \mu_O = (\mu_O^1, \mu_O^2, \ldots, \mu_O^i), \\ \mu_D = (\mu_D^1, \mu_D^2, \ldots, \mu_D^i), \end{aligned} \tag{4.2.21}$$

The following steps show the min-max process:

(1) Determine the maximum number of combinations of membership functions for the given three fuzzy sets. The number of possible combinations is $C = i^3$.

(2) Only those combinations with the values of membership functions different from 0, i.e. $\mu_{S,O,D}^{i=1,\ldots,7}$ are taken for analysis. The outcome of these combinations are calculated with the following formula:

$$\Omega = \frac{\sum_{S,O,D} i}{3} \tag{4.2.22}$$

(3) The maximum value of the combination $\mu_{S,O,D}$ is then determined for the obtained combinations.

(4) The last step is to classify the combinations according to the outcomes where, for each of the outcomes, the minimum value of the predetermined maximum is obtained.

The level of risk is determined for each variant through the min-max composition of assessed risk indicators. The weighted mean of the maximum is then calculated to defuzzyfy and obtain the value of the class. The weighted average value is calculated with the following formula:

$$Z = \frac{\sum_{i=1}^{7} \mu_i y_i}{\sum_{i=1}^{7} \mu_i} \tag{4.2.23}$$

with μ_i being the level of membership in a certain set or class and y_i the class.

TABLE 4.14: Severity of failure.

Effect	Damage impact	Rank
Extreme	Equipment not functioning/unknown cause	6, 7
High	Equipment not functioning/cause known and uncontrollable	4, 5
Moderate	Equipment not functioning/ cause known and controllable	3
Low	Equipment functioning/low impact on operating	2
Very Low	Equipment functioning/insignificant impact on operating	1

TABLE 4.15: Frequency of failure occurrence.

Effect	The frequency of failure occurrence	Rank
Very high	Few times per month	6, 7
High	2–3 times per year	4, 5
Moderate	Once a year	3
Low	Once in three years	2
Rare	Once in five years	1

TABLE 4.16: Detectability of potential failure.

Effect	Detection of failures by regular equipment check	Rank
Very Low	No possibility for error detection	6, 7
Low	Control will hardly detect irregularities	4, 5
Moderate	Possible to detect irregularities	3
High	Errors noticeable by a check	2
Very high	Control is likely to find the shortcomings	1

TABLE 4.17: Measures to reduce the level of risk.

Risk level	Measures	RPN
Extreme	Reduce the risk to an acceptable level	151–343
High	Reduce the risk to an acceptable level	61–150
Moderate	Monitor the system and reduce the risk to an acceptable level	31–60
Low	Monitor the system changes	16–30
Insignificant	Maintain the risk level on this risk	1–15

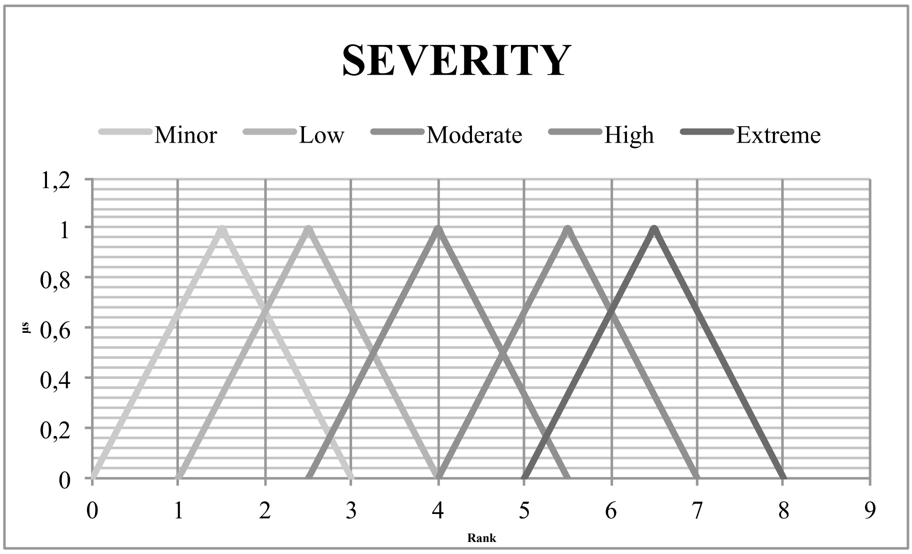


FIGURE 4.4: Severity fuzzy set.
Adapted from Petrović et al. *(2014)*

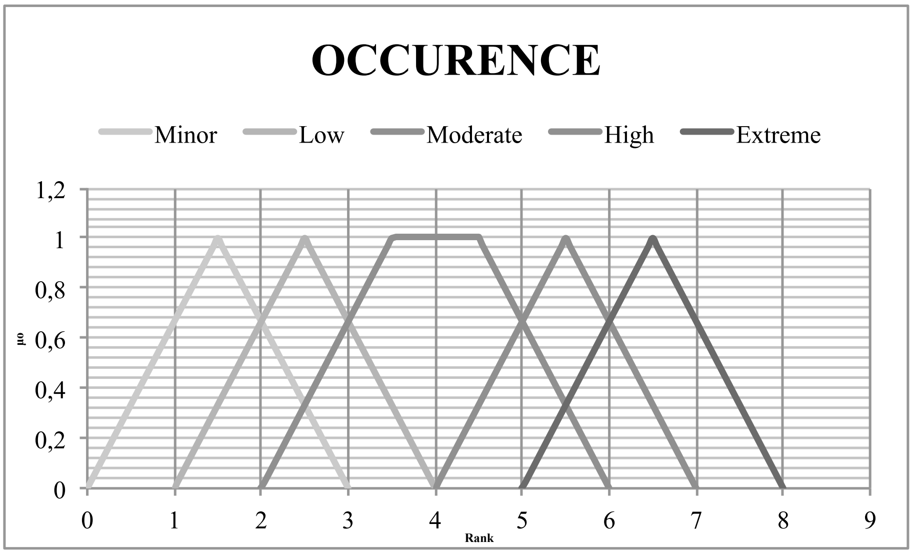


FIGURE 4.5: Occurrence fuzzy set.
Adapted from Petrović et al. *(2014)*

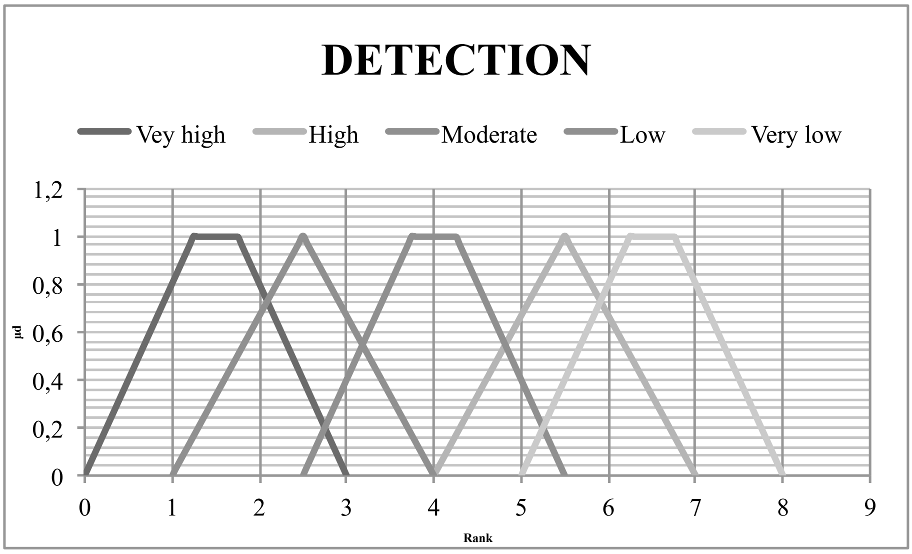


FIGURE 4.6: Detectability fuzzy set.
Adapted from Petrović et al. *(2014)*

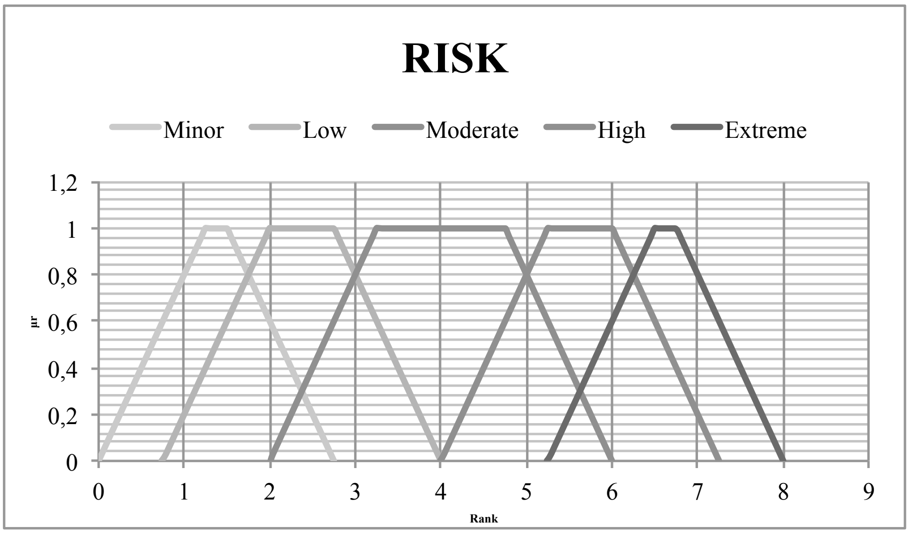


FIGURE 4.7: Risk fuzzy set.
Adapted from Petrović et al. *(2014)*

Example:

A Continuous Miner (CM) is considered for risk analysis. The analysis is performed on the electric motor of the continuous miner and the fuzzy logic theory and RPN calculations are applied. The results from the RPN calculations are shown in Table 4.18. These should be compared to the values in Table 4.17, which shows that the risk level should be reduced.

Table 4.18: RPN values for the electric motor of the Continuous Miner.

No.	CM-parts	Function	Possible errors, causes	Failure description	Effects	S	O	D	RPN
1	Electric Motor	Energy converter	Bad installation	Electric parts, shaft, bearings	Coal transport interruption	3	4	5	60

The fuzzy logic based assessment is then conducted by means of the min-max composition. Determining the maximum number of combinations of membership functions for the three fuzzy sets is the first step. The fuzzy sets are:

$$\mu_S = (0, 0, 0.335, 1, 0.335, 0, 0), \text{moderate}; \ \mu_O = (0, 0, 0, 0, 0.675, 0.675, 0), \text{high};$$
$$\mu_D = (0, 0, 0, 0, 0.8, 0.4, 0), \text{high}$$

The number of possible combinations is $C = i^3$ combination with $i = 7$. Calculating this gives a total of $C_3 = 7^3 = 343$ combinations. All combinations with membership functions $\mu_{S,O,D}^{i=1,\ldots,7} \neq 0$ are taken for analysis.

Table 4.19 shows the various combinations. For example, the combination of $(\mu_S 3, \mu_O 5, \mu_D 5) = (0.335, 0.675, 0.8)$ is calculated as:

$$\Omega = \frac{\Sigma_{S,O,D} i}{3} = \frac{3+5+6}{3} = 4$$

Table 4.19: Non-zero membership functions with their maximum and outcomes.

μ_S	μ_O	μ_D	Ω	MAX
0.335	0.675	0.8	4	0.8
0.335	0.675	0.4	5	0.675
0.335	0.675	0.8	5	0.8
0.335	0.675	0.4	5	0.675
1	0.675	0.8	5	1
1	0.675	0.4	5	1
1	0.675	0.8	5	1
1	0.675	0.4	5	1
0.335	0.675	0.8	5	0.8
0.335	0.675	0.4	5	0.675
0.335	0.675	0.8	5	0.8
0.335	0.675	0.4	6	0.675

The maximum value is then determined. Again for $(\mu_S 3, \mu_O 5, \mu_D 5) = (0.335, 0.675, 0.8)$, MAX $= 0.675$. The next step is to group the combinations according to the outcome values where, for each of the outcomes, the minimum value of the predetermined maximum values is determined as seen in Table 4.20.

TABLE 4.20: Minimum values per outcome.

μ_S	μ_O	μ_D	MAX	Ω	MIN
0.335	0.675	0.8	0.8	4	0.8
0.335	0.675	0.4	0.675	5	0.675
0.335	0.675	0.8	0.8		
0.335	0.675	0.4	0.675		
1	0.675	0.8	1		
1	0.675	0.4	1		
1	0.675	0.8	1		
1	0.675	0.4	1		
0.335	0.675	0.8	0.8		
0.335	0.675	0.4	0.675		
0.335	0.675	0.8	0.8		
0.335	0.675	0.4	0.675	6	0.675

Finally, the risk assessment is associated with the membership function:

$$\mu_S = (0, 0, 0, 0.8, 0.675, 0.675, 0)$$

The weighted average is calculated:

$$\begin{aligned} Z &= \frac{\sum_{i=1}^{7} \mu_i x_i}{\sum_{i=1}^{7} \mu_i} \\ &= \frac{0 \cdot 1 + 0 \cdot 2 + 0 \cdot 3 + 0.8 \cdot 4 + 0.675 \cdot 5 + 0.675 \cdot 6 + 0 \cdot 7}{0 + 0 + 0 + 0.8 + 0.675 + 0.675 + 0} \\ &= 4.94 \end{aligned}$$

Figure 4.7 is used to determine the risk and it is understood as:

Moderate with membership function $\mu_R = 0.85$

High with membership function $\mu_R = 0.75$

Comparing the fuzzy logic results with that of the RPN, the second method puts the risk in more than one category depending on the membership function. Thus gives the decision maker a better understanding of the risk at hand.

4.2.7 Monte Carlo Simulations

Monte Carlo simulations are not a complex set of calculations. It does however, involve extensive computer usage as each possible event for each unit of the model should be sampled repeatedly over the determined mission time. According to Benbow and Broome (2009), a Monte Carlo simulation is defined as follows:

> *" . . . repeated calculations of a system performance are made using randomly selected values based on the probability distributions that describe each element of the model."*

As a result, a large number of values of system performance are generated and these could be used to develop a probability distribution of system performance.

The reliability of a unit could be determined with Equation 4.2.24.

$$\hat{R} = \frac{1 - \text{number of failures}}{N_R} \tag{4.2.24}$$

where $\hat{R}$ is the reliability of the unit and N_R is the number of replications. Thousands of replications can be conducted through the use of a computer-generated Monte Carlo simulation. MS Excel can be easily used to facilitate the simulations.

4.2.8 Multi-criterion Classification of Critical Equipment (MCCE)

The Multi-criterion Classification of Critical Equipment (MCCE) is presented by Gómez de León Hijes and Ruiz Cartagena (2006) and quantifies the criticality of the organization's equipment by assigning a value or criticality index (I_C) to every piece of equipment. Equipment criticality is not regulated by assessing one single factor but rather the result of *"interrelated actions of multiple factors"*. These factors each have their own importance and the MCCE method is designed to take this into consideration.

The first step of the MCCE process is to establish the relative importance (i.e. their weight) with the direct insertion procedure. During this procedure, each criterion is compared to every other criterion in terms of importance in a specific order. The values of the criterion are unknown, but if one criterion is considered more important, then its weight will also be higher.

Let the set of criteria be represented by $c_a, c_b, \ldots, c_i, \ldots, c_n$ in a random order as controlled by experts evaluating the equipment. Obtaining a list of the criteria, ranked from least to most important is thus the end objective of the procedure. The first element, c_a is placed as the first and only criterion in the new vertically ranked list. Then, the criteria from the initial list is taken one at a time and compared to the criterion already on the ranked list in terms of their respective importance. The comparison is started at the top of the list, where the least important criterion is placed, for each of the remaining criterion. Two criterion with the same importance are placed at the same level. The list created is obtained for n criterion with m levels:

$$
\begin{aligned}
&l_1)c_1, c_2, c_3, \ldots, c_i \\
&l_2)c_j, c_k, \ldots \\
&l_m)\ldots, c_n
\end{aligned}
$$

As seen, the relative weight of each criterion is determined in terms of the importance of the criterion, but not according to its numerical value. The resulting list, is a vertical arrangement of the criteria in various levels from least important to most important and in some cases equal importance.

Each criterion is then assigned a weighting factor to be able to calculate the criticality index. A value of one is usually allocated to level 1 thus $w(l_1) = 1$ The relative importance must be determined for each level. For example, level 2 might be double the importance of level one i.e. $w(l_2) = 2$ and the objective is then to find a linear combination of criteria. Level 3 is equivalent to level 1 criteria added to level 2. Thus, $w(l_3) = 3$. Or level 3 could be based on double level 2, thus $w(l_3) = 4$. This process of evaluating and comparing criterion can pinpoint mistakes in the arrangement of the criterion. In practice, it can also be easier and more appropriate to rank the criteria from most too least important.

The two vectors are thus:

$$\text{Criterion vector: } (c_1, c_2, c_3, \ldots, c_i, \ldots, c_n)$$

$$\text{Weighting vector: } (w_1, w_2, w_3, \ldots, w_i, \ldots, w_n)$$

Finally, the equipment is analyzed according to its criteria and the criticality index is calculated. The range of possibilities of every criterion is divided into the same number, d, of degrees, or categories, which represent the different degrees of criticality possible for a piece of equipment with respect to the criteria analyzed. For example, *Very High*, *High*, *Normal*, *Low* and *Very Low* with values 4, 3, 2, 1 and 0. The outcome is a list of n values referred to as the criticality vector.

The equipment criticality index is calculated as

$$I_C = 100 \times \frac{\sum_{i=1}^{n}(d_i \times w_i)}{d \times \sum_{i=1}^{n} w_i} \tag{4.2.25}$$

with n the number of criterion, d is the number of criticality degrees of the criterion, d_i is the criticality degree of a certain equipment according to the criterion c_i and w_i the weight of the criterion.

The second critical area is *Financial Risk Impact* and it is discussed in the next section. Financial information surrounding PAM and risk management is critical to the success of the Risk Management Solutions Flow and the finer details of the quantitative methods associated with the financial element is discussed.

4.3 Financial Risk Impact

Presenting the value of asset management in terms of financial information is a critical part of PAM. Reason being that top management understands the improvement in the organization brought on by PAM, if it is presented in terms of costs and benefits. The quantitative techniques identified associated with financial risk management includes:

(1) Cost-Benefit Analysis (CBA) including:

- Net Present Value (NPV); and
- Benefit-Cost Ratio (BCR).

(2) Economic Value Added (EVA)

(3) Overall Equipment Effectiveness (OEE) and Overall Process Effectiveness (OPE)

An in-depth analysis of the methods listed is given as well as examples where needed. Once again, it is critical to remember that these are not the only methods in the literature, but that they were identified as applicable to the research at hand.

4.3.1 Cost-Benefit Analysis (CBA)

The Cost-Benefit Analysis (CBA) is regarded as the foremost economic evaluation method. Messonnier and Meltzer (2002) confirms that CBA allows for *". . . direct comparison of different types of outcomes resulting from a variety of actions."* If done as intended, it determines the beneficial and costly consequences associated with monetary measures of an action. The CBA can determine who wins and who loses (pays) as well as the extent of the gain or loss. All the costs and benefits associated with the analysis are measured in monetary terms and combined into one value. Examples of these values are the Net Present Value (NPV) and the Benefit-Cost Ratio (BCR). The NPV method will be discussed first.

4.3.1.1 Net Present Value (NPV)

Winston (2004) determines that there exists an investment for which every \$1 invested at a specific time will yield $\$(1+r)$ one year later. Thus, \$1 now $= \$(1+r)^k$, k years from now and to determine what \$1 received k years from now is worth at the moment, $\$(1+r)^{-k}$ is used. The NPV is computed by adding the monetary benefits and subtracting the monetary costs. The formula for NPV is depicted in Equation 4.3.1.

$$NPV = \sum_{t=0}^{N_Y} \frac{(\text{benefits} - \text{costs})_t}{(1+r)^t} \tag{4.3.1}$$

where:

t_y = year (from 0 ... N)

N_Y = numbers of years being evaluated

r = discount rate

A $NPV > 0$ means that the benefits are greater than the total cost and vice versa for a $NPV < 0$.

Example:

Suppose an investment requires a cash outlay of \$12,000 at time 0, a cash outlay of \$10,000 two years from now and yields a cash flow of \$22,000 one year from now. Assuming that $r = 0.3$, the NPV of the investment is,

$$\begin{aligned} \text{NPV} &= -12,000 + \frac{22,000}{1+0.3} - \frac{10,000}{(1+0.3)^2} \\ &= -\$994.08 \end{aligned}$$

The negative value indicates that the cost outweighs the benefits and that this is not the best investment at the given interest rate.

4.3.1.2 Benefit-Cost Ratio (BCR)

The total benefits are divided by the total costs to provide the BCR. Equation 4.3.2 shows the calculation for BCR.

$$BCR = \frac{PV_{\text{benefits}}}{PV_{\text{costs}}} \tag{4.3.2}$$

where:

PV_{benefits} = present value of benefits

PV_{costs} = present value of costs

A BCR of 1.10:1, for example, is interpreted as for every 1 monetary value invested, the gain would be 1.10.

4.3.2 Economic Value Added (EVA)

Stern Stewart Management Services of New York City defines Economic Value Added (EVA) as *" . . . the difference between a company's net operating income after taxes and its cost of capital of both equity and debt"* and uses the following equation:

$$\text{EVA} = (\text{Return on Capital - Cost of Capital}) \times \text{Total Capital} \tag{4.3.3}$$

where:

(i) total capital is defined as the sum of total equity and interest-bearing debt, and

(ii) cost of capital is weighted average cost of these two capital components.

Chen and Dodd (1997) also describes it as a useful measure of an organization's performance. Many successful companies in the world have adopted EVA.

The concept of EVA is described by Amadi-Echendu (2004) as it is applicable to a physical asset management environment. The following equations are applicable:

$$EV_{PAM} = NQB - WACC \tag{4.3.4}$$

$$EV_{PAM} = \{norm(Otp - OpCosts) - \%WACC\} \times capital \tag{4.3.5}$$

$$EV_{PAM} = \{norm(Otp \times OEE - OpCosts) - \%WACC\} \times capital \tag{4.3.6}$$

where:

EV_{PAM} = Economic Value of Physical Asset Management

NQB = Net Quantifiable Benefits

$WACC$ = Weighted Average Cost of Capital

Otp = Output

Op = Operating

OEE = Overall Equipment Effectiveness

Equation 4.3.4 provides a measure of ownership performance and Equation 4.3.5 and 4.3.6 shows that management and utilization processes do actually sustain or enhance the value profile desired by stakeholders.

4.3.3 Overall Equipment Effectiveness (OEE) and Overall Process Effectiveness (OPE)

Total Quality Management (TQM) is used to improve managerial or technical systems and is based on the Deming cycle (plan-do-check-act-plan, etc.). Sherwin (2000) analyzed the importance of TQM and claims that maintenance should be incorporated with production. In his research, he identified the measurements associated with TQM namely Overall Equipment Effectiveness (OEE) (Equation 4.3.7) and Overall Process Effectiveness (OPE) (Equation 4.3.8).

$$OEE = A.\eta.(1 - p_d) \tag{4.3.7}$$

$$\begin{aligned} OPE = &\{1 - N_s/\phi T\}. \\ &\{1 - (\eta_m/\phi_m + t_r)/t_O\}. \\ &\{1 - (\eta_f + \eta_c + \eta_s)/\eta\} \end{aligned} \tag{4.3.8}$$

$$\Delta CE = 1 - C_a/C_b \tag{4.3.9}$$

where:

A = Availability (including preventive downtime)

η = Speed (actual production rate/theoretical production rate)

p_d = Proportion defective ($1-p_d$ is the quality)

N_s = Number of stoppages

ϕ = Repair rate

T = Loading time

η_m = Number of minor stoppages

ϕ_m = Minor repair rate

t_r = Time lost to reduced speed operation

t_O = Operating time

η_f = Defectives made just after stoppages

η_c = Defectives made when process was in control

η_s = Defectives due to assignable quality control causes

η = Total number made

ΔCE = Improvement in cost effectiveness measured in terms of the total costs for a batch of the same size (n) before (b) and after (a) a change in the policy

The improvement in cost effectiveness is also considered in Equation 4.3.9. Finally, *Failure Analysis* is discussed as the last critical area related to PAM and risk management. Predicting when an asset will fail will improve the process of managing physical assets greatly.

4.4 Failure Analysis

Statistical Failure Analysis is paramount to the management of physical assets and specific quantitative methods are identified that promotes the process of determining when assets will fail:

- Weibull Analysis
- Log-Linear Model
- Power Law Model
- MTTF, MTBF and MFOP
- Markov Analysis
- Forecasting Models
- Utility Theory and Decision Trees

Another important part of failure analysis is the deduction of a trend in the data. This is particularly applicable to more zealous methods such as Log-Linear and Power Law Models. As mentioned for the Criticality Analysis section and Financial Risk Impact section, Failure Analysis is not merely identified by these methods, but they are most appropriate for this research.

4.4.1 Trend Analysis

The first step to conduct a failure analysis is to determine if there is a trend in the data. Laplace's trend test is mostly used and proposed by Vlok (2011) and Louit *et al.* (2009). If a trend is found, increasing or decreasing, the data set should be considered as that of a repairable system and an appropriate lifetime model should be selected. When no trend is found, there should be tested for dependencies between interarrival times.

The Laplace trend test determines if an observed series of events are a Homogeneous Poisson Process (HPP) or Non-Homogeneous Poisson Process (NHPP). Both HPP and NHPP are sequences that cannot be terminated and characterized by X_i's that are identically exponential and independent. The hypothesis for the test is thus:

H_0: HPP

H_1: NHPP

Laplace's trend is based on the assumption associate with the HPP stating that the first $r_A - 1$ arrival times, $S_1, S_2, \ldots, S_{r_A-1}$ are the order statistics for a uniform distribution on $(0, S_{r_A}]$. The calculation for the Laplace trend test is,

$$U = \frac{\frac{\sum_{i=1}^{r_A-1} S_i}{r_A-1} - \frac{S_{r_A}}{2}}{S_{r_A}\sqrt{\frac{1}{12(r_A-1)}}} \tag{4.4.1}$$

U approximates a standardized normal variate at a 5% level of significance as soon as $r \geq 4$.

The following cases applies to the Laplace trend test:

$U \geq 2$	Strong evidence of reliability degradation.
$U \leq -2$	Reliability improvement.
$1 \geq U \geq -1$	No evidence of underlying trend. Referred to as non-committal data set.
$2 > U > 1$ or $-1 > U > -2$	Cannot with certainty indicate if a trend is present or not. Alternative test is needed. Alternative tests suggested by Vlok (2011) include the Lewis-Robinson Test, the Mann tests and Anderson-Darling test. Wang and Coit (2005) discuss the Crow and Pairwise Comparison Non-parametric (PCNT) tests and Louit *et al.* (2009) mentions the military handbook test. These are beyond the scope of this research and will thus not be discussed in detail.

The trend analysis enables the data to be analyzed correctly by means of methods such as the Weibull Analysis, and Log-Linear and Power Law Models.

4.4.2 Weibull Analysis

The Weibull distribution is a density function used for reliability calculations. This distribution provides the necessary information for troubleshooting, classifying failure types, scheduling preventive maintenance and inspections as summarized by Dodson (2006).

The Weibull Probability Density Function (PDF) is defined in Equation 4.4.2.

$$f(x) = \frac{\beta}{\eta}\left(\frac{x}{\eta}\right)^{\beta-1} \cdot \exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right] \tag{4.4.2}$$

where

$\beta =$ the shape parameter

$\eta =$ the scale parameter

All three the parameters are continuous. It is often seen that η takes on a discrete value, but this is only possible when the data behaves as if continuous when the magnitude is large enough. These parameters are estimated by means of analytically methods such as the Maximum Likelihood Method or Least Squares Method. The acceptable ranges for the values are

$$0 < \beta < \infty, \text{ and}$$
$$0 < \eta < \infty$$

Depending on the value of β, the Weibull distribution can take on or approximate several other distributions. These include:

$\beta = 1$	The Weibull distribution is equivalent to the exponential distribution.
$\beta = 2$	The Weibull distribution is equivalent to the Rayleigh distribution.
β is between 1 and 3.6	The Weibull distribution approximates the lognormal distribution.
β is between 3 and 4	The Weibull distribution approximates the normal distribution ($\beta = 3.6$ provides the best estimation; this is when the skewness of the Weibull distribution is minimized).
$\beta = 5$	The Weibull distribution approximates the peaked normal distribution.

The Weibull PDF or $f(x)$ is graphically illustrated in Figure 4.8 for different values of β.

The cumulative failure distribution (up to time x) determines if a failure will occur within the interval $(0, x)$. The probability of failure is calculated with Equation 4.4.3

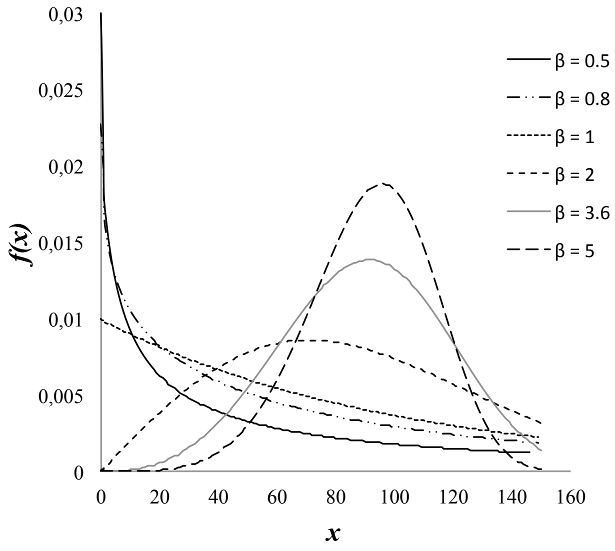


FIGURE 4.8: The Weibull PDF for different β values.
Adapted from Vlok (2011)

by integrating the PDF over the interval (0, x).

$$\begin{aligned} F(x) &= \int_0^x f(\tau)d\tau \\ &= 1 - exp\left[-\left(\frac{x}{\eta}\right)^\beta\right] \end{aligned} \tag{4.4.3}$$

Furthermore, the reliability of the system is presented in Equation 4.4.4.

$$\begin{aligned} R(x) =& 1 - F(\tau) \\ =& \int_x^\infty f(\tau)d\tau \end{aligned} \tag{4.4.4}$$

Figure 4.9 shows the graphical representation of $F(x)$, the failure probability curve, for different values of β. Furthermore, the relationship between $f(x)$ and $R(x)$ is known as the hazard function and is used to measure the tendency to fail and the failure characteristics.

$$\begin{aligned} h(x) &= \frac{f(x)}{R(x)} \\ &= \frac{\beta(x)^{\beta-1}}{\eta^\beta} \end{aligned} \tag{4.4.5}$$

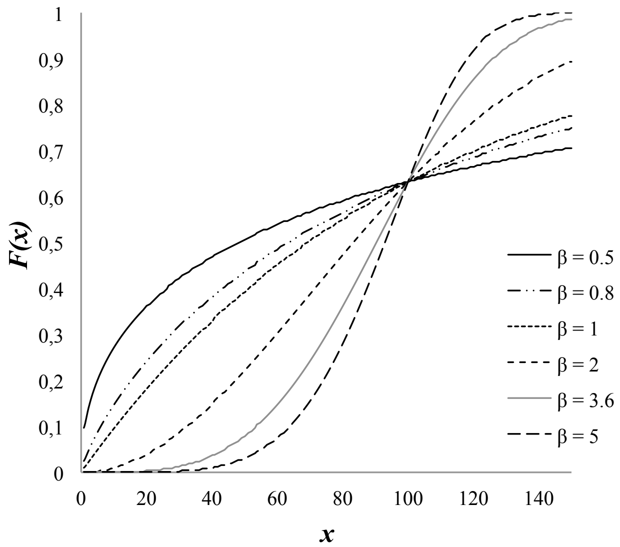


FIGURE 4.9: Failure probability curve $F(x)$ for different β values.
Adapted from Vlok (2011)

Figure 4.10 shows $R(x)$, the reliability curve, for different values of β. Clearly, $R(x)$ is the compliment of $F(x)$.

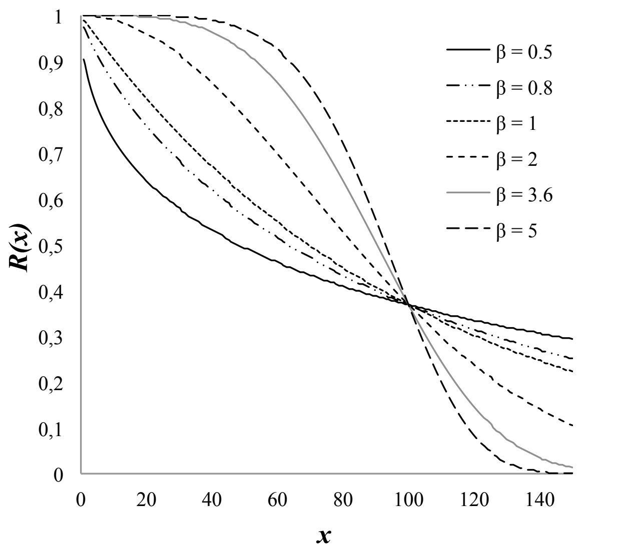


FIGURE 4.10: Reliability curve $R(x)$ for different β values.
Adapted from Vlok (2011)

The hazard function is also known as the instantaneous failure rate, thus providing the probability of impending failure. Figure 4.11 represents the hazard function for different values of β. An increase in the hazard rate results in an increase in probability of impending failure.

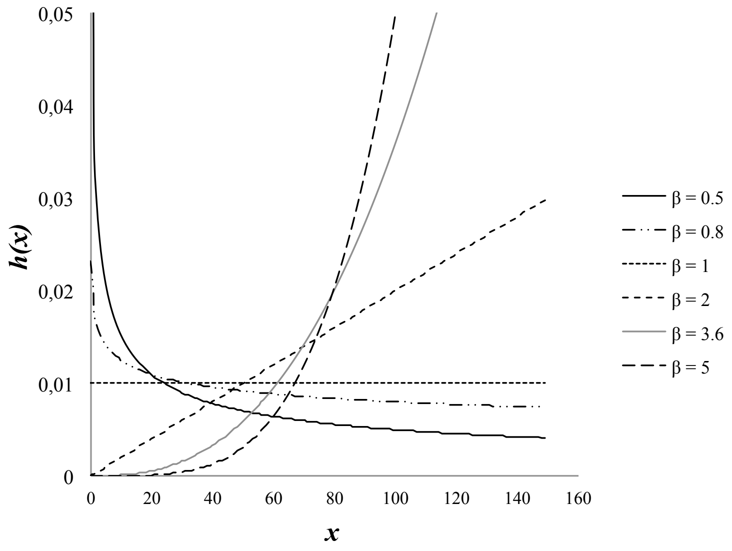


FIGURE 4.11: The Weibull hazard function for different β values.
Adapted from Vlok (2011)

Example:

A Continuous Miner (CM) runs 24 hours a day, 7 days a week. The machine fails according to a Weibull distribution with parameters $\beta = 1.7$ and $\eta = 150$ hours. The reliability of the CM on day 6 can be calculated as follows:

$$\begin{aligned} R(x) &= 1 - F(x) \\ &= e^{\left(-\left(\frac{x}{\eta}\right)^{\beta}\right)} \\ &= e^{\left(-\left(\frac{144}{150}\right)^{1.7}\right)} \\ &= 0.3934 \\ &\Rightarrow 39.34\% \end{aligned}$$

The hazard function is then calculated as:

$$\begin{aligned} h(144) &= \frac{\beta(x)^{\beta-1}}{\eta^{\beta}} \\ &= \frac{1.7(144)^{0.7}}{150^{1.2}} \\ &= 0.0110 \\ &\Rightarrow 1.10\% \end{aligned}$$

Interpreting the results, the CM has a 39.34% chance of surviving to the sixth day and at this specific point in time, there is a 1.10% chance that a failure is about to occur. This information enables the decision maker to determine which assets are critical to the organization.

4.4.3 Log-Linear Model

The log-linear model is often used when the survival of technical products with the tendency to deteriorate rapidly are analyzed (Gasmi (2013)). It is thus a very important model for establishing the probabilistic behavior of real events happening in large groups. The model can cover a large variety of failure instances. Darroch and Ratcliff (1972) discuss the full theory of iterative scaling for log-linear models.

Vlok (2011) also did some valuable research on the log-linear model and gives the function as:

$$\rho_1(t) = \exp(\alpha_0 + \alpha_1 t) \tag{4.4.6}$$

with α_0 and α_1 the parameters required for the log-linear process. $\alpha_1 > 0$ for repairable systems. The continuous global time is represented by t.

The expected number of failures, N_F, between any two instances represented by t_1 and t_2 is calculate by integrating Equation 4.4.6:

$$\mathrm{E}[N_F(t_1 \to t_2)] = \frac{1}{\alpha_1}[\exp(\alpha_0 + \alpha_1 t_2) - \exp(\alpha_0 + \alpha_1 t_1)] \tag{4.4.7}$$

Thus it is possible to calculate the MTBF between instances t_1 and t_2:

$$\mathrm{MTBF}_{\rho_1}(t_1 \to t_2) = \frac{\alpha_1(t_2 - t_1)}{\exp(\alpha_0 + \alpha_1 t_2) - \exp(\alpha_0 + \alpha_1 t_1)} \tag{4.4.8}$$

Furthermore, the reliability of the system could also be calculated:

$$R(t_1 \to t_2) = e^{-[\exp(\alpha_0 + \alpha_1 t_2) - \exp(\alpha_0 + \alpha_1 t_1)]/\alpha_1} \tag{4.4.9}$$

Vlok (2011) goes further to describe methods to calculate the parameter estimation and variance to determine confidence bounds.

4.4.4 Power Law Model

Burnett (2013) indicates that the power law model is used *" . . . to characterize the failure behavior of repairable systems"* by making use of past failure behavior and the function is given by:

$$\rho_2(t) = \lambda \delta t^{\delta - 1} \tag{4.4.10}$$

with λ and δ being the parameters required and t once again the continuous global time. $\delta < 0$ for repairable systems. As with the log-linear model, it is possible to determine the expected number of failures, N_F, between any two instances t_1 and t_2. Equation 4.4.10 needs to be integrated to achieve this:

$$\mathrm{E}[N_F(t_1 \to t_2)] = \lambda(t_2^\delta - t_1^\delta) \tag{4.4.11}$$

Thus it is possible to determine the MTBF of the system:

$$\text{MTBF}_{\rho_2}(t_1 \to t_2) = \frac{(t_2 - t_1)}{\lambda(t_2^{\delta} - t_1^{\delta})} \tag{4.4.12}$$

Finally, the reliability of the system is determined from t_1 and t_2.

$$R(t_1 \to t_2) = e^{-\lambda(t_2^{\delta} - t_1^{\delta})} \tag{4.4.13}$$

The Power Law Model is a potent analysis technique, but can be complicated for employees with no statistical background.

4.4.5 MTTF, MTBF and MFOP

The average time to failure of identical products operating under identical conditions is known as the *mean life* of the product (Benbow and Broome (2009)) or better known as Mean Time Between Failure (MTBF). MTBF is the most used reliability metric and is defined by Smith (2005) as *" . . . a stated period in the life of an item, the mean value of the length, of time between consecutive failures, computed as the ratio of the total cumulative consecutive observed time to the total number of failures"*.

Burnett (2013) describes MTBF as the expected time between two successive failures and gives Equation 4.4.14 to calculate MTBF.

$$\text{MTBF} = \frac{\sum_{i=1}^{N_F} x_i}{N_F} \tag{4.4.14}$$

with N_F being the total number of failures and x_i the time elapsed from $(i-1)^{\text{th}}$ failure to the i^{th} failure.

Figure 4.12 graphically explains the calculation of MTBF. The values of Time To Repair (TTR) and Time To Failure (TTF) are shown in the figure.

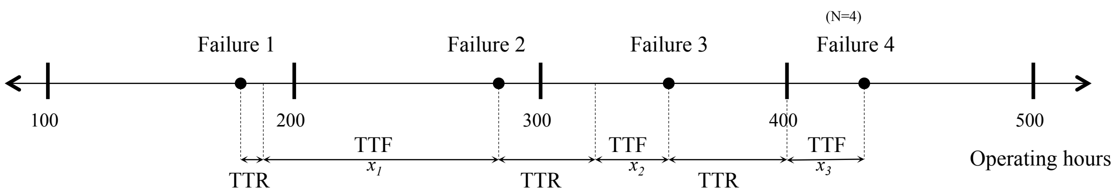


FIGURE 4.12: Graphic information to calculate MTBF.
Adapted from Burnett (2013)

MTBF is used for repairable items and the work done by Benbow and Broome (2009), gives the Mean Time To Failure (MTTF) calculation for non-repairable items as seen in Equation 4.4.15. The mean life or MTTF (also denoted as $\hat{\theta}$) is calculated by obtaining the average of the failure times.

$$\text{MTTF} = \hat{\theta} = \frac{\sum t_i}{n} \tag{4.4.15}$$

where n is the number of items tested and t_i's are failure times.

In the past, MTBF has been the preferred reliability specification for many industries. However, users did not realize that it is almost impossible to demonstrate MTBF. Dinesh Kumar *et al.* (1999) determined two main shortcomings of the MTBF:

(1) When the time-to-failure distribution is not exponential, it is near impossible to predict MTBF.

(2) The exponential distribution is also the foremost methodology used when calculating MTBF and failure rate. The exponential distribution is used to model failure times and is used mainly due to the "mathematical friendliness" of the method and not because of scientific reasoning.

Al Shaalane and Vlok (2013) states that MTBF has created a culture of acceptance of failure where the *when* and *why* associated with failure is not questioned. Thus, a relatively new reliability metric is considered and known as the Maintenance Free Operating Period (MFOP). MFOP was introduced by the Royal Air Force and is defined by Brown and Hockley (2001):

> *"A period during which the equipment shall operate without failure and without the need for any maintenance; however, faults and minor, planned, contractually agreed maintenance are permissible i.e. all planned operations and cycles are completed without external inputs to system. "*

Dinesh Kumar *et al.* (1999) goes further and describes MFOP as "*. . . the probability of not having any unscheduled maintenance for the period of t_{mf} life units given the current age of the item"*. MFOP also gives the probability that the functionality of the item is kept (at least for the period of t_{mf} life units), without corrective maintenance. In theory, there is no occasion where unscheduled maintenance is required and the only maintenance is scheduled during the Maintenance Recovery Period (MRP). During this period, full recovery to operative state is evident before the next MFOP.

Measuring the probability that a mission can be completed successfully without maintenance during MFOP, it is necessary to measure MFOP Survivability. MFOPS is thus *"the level of confidence that no unscheduled maintenance activities will be required during each MFOP"* as researched by Long *et al.* (2009). To calculate MFOPS with Weibull distributed failure times, Equation 4.4.16 is used.

$$\text{MFOPS}(t_{\text{mf}}) = \frac{R(t+t_{\text{mf}})}{R(t)} = \exp\left[-\frac{t^{\beta}-(t+t_{\text{mf}})^{\beta}}{\eta^{\beta}}\right] \tag{4.4.16}$$

where t_{mf} is the surviving units of time (given that the system has survived t units of time), η is the scale parameter and β is the shape parameter of the Weibull distribution. $R(t)$ is the reliability of the system which is given in Equation 4.4.17.

$$R(t) = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right] \tag{4.4.17}$$

The MFOP calculation is described in Equation 4.4.18.

$$\text{MFOP} = \eta \cdot \ln\left(\frac{1}{\text{MFOPS}}\right)^{\frac{1}{\beta}} \tag{4.4.18}$$

Figure 4.13 shows the distribution of MFOPs over time.

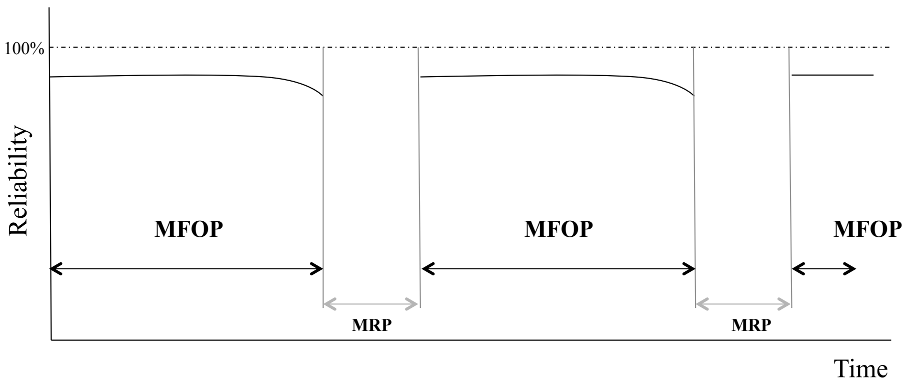


Figure 4.13: Graphic representation of MFOP.
Adapted from Brown and Hockley (2001)

Although MFOP is regarded as the more superior method, MTBF and MTTF still brings value to the analysis and are used by many organizations.

4.4.6 Markov Analysis

A Markov Analysis or Markov Chains are used for complex systems to determine the probability of being in a given state at some future point in time if the probability of moving from one state to another is known and remains constant. All states in the future are independent of past states and the system is only viable one state at a time. This does not apply to the immediate preceding state. Winston (2004) defines a Markov chain as follows:

> A discrete-time stochastic process is a **Markov chain** if, for $t = 0, 1, 2, \ldots$ and all states,
> $P(\mathbf{X}_{t+1} = i_{t+1} | \mathbf{X}_t = i_t, \mathbf{X}_{t-1} = i_{t-1}, \ldots, \mathbf{X}_1 = i_1, \mathbf{X}_0 = i_0)$
> $P(\mathbf{X}_{t+1} = i_{t+1} | \mathbf{X}_t = i_t$

Thus, the probability distribution of the state at time $t+1$, depends on the state at time $t(i_t)$ and does not depend on the states the chain passed through on the way to i_t at time t. Assuming for all states i, j and t, $P(\mathbf{X}_{t+1} = j|\mathbf{X}_t = i)$ is independent of t, then the stationarity assumption is:

$$P(X_{t+1} = j|\mathbf{X}_t = i) = p_{i,j} \tag{4.4.19}$$

with p_{ij} being the probability that given the system is in state i at time t, it will be in a state j at time $t+1$.

For the case of risk management, Benbow and Broome (2009) determines that a Markov analysis could be used to "*. . . determine the future probability of a repairable system being in a success state when the failure probability and probability of restoring the system are known*".

A simple system with one unit is considered in Figure 4.14. It is however, not limited to a two state system. The unit can be in a success state (S) or in a failed state (F). Once the unit enters the failed state, it waits to return to the success state. The failure rate and the rate at which the unit can be restored to the success state after failure are represented in the transition probability from one state to another. The following probabilities are applicable as seen in Figure 4.14:

- $P_{S\text{-}F}$ is the probability of transition from state S to F in a given time interval.
- $P_{F\text{-}S}$ is the probability of transition from state F to S in the same time interval.
- $1-P_{S\text{-}F}$ is the probability of remaining in state S if the system in in state S.
- $1-P_{F\text{-}S}$ is the probability of remaining in state F if the system is in state F.

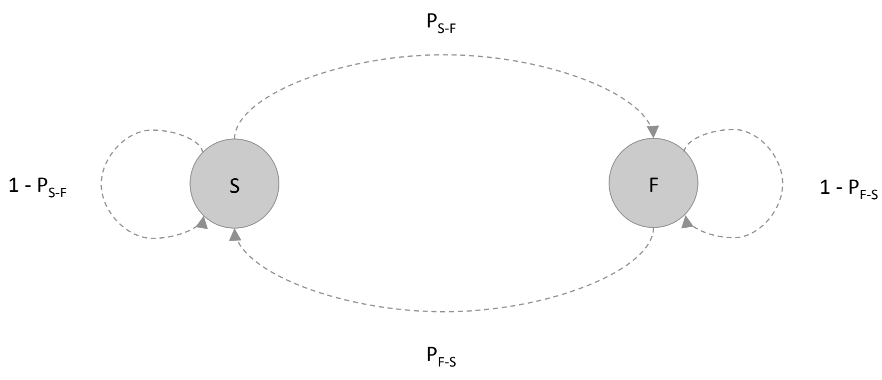


FIGURE 4.14: A transition diagram for a system with two states.
Adapted from Benbow and Broome (2009)

During the Markov analysis the following should be identified:

- All the possible states of the system.
- All of the transitions (moving from one state to another).
- The transition rates from one state to another.
- The probability of the system being in a success state by considering all possible states and rates of transition.

The transition probability matrix is written as:

$$P = \begin{bmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,s} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,s} \\ . & . & & . \\ . & . & & . \\ . & . & & . \\ p_{s,1} & p_{s,2} & \cdots & p_{s,s} \end{bmatrix}$$

For each state i, the following is true given that the state at time t is i and the process is somewhere at time $t+1$:

$$\sum_{j=1}^{j=s} P(\mathbf{X}_{t+1} = j | P(\mathbf{X}_t = i)) = 1 \sum_{j=1}^{j=s} p_{i,j} = 1 \tag{4.4.20}$$

Over the long run, Markov Chains are known to have a certain behavior represented by the following theorem:

> Let P be the transition matrix for an s-state ergodic chain. Then there exist a vector $\pi = [\pi_1 \pi_2 \ldots \pi_s]$ such that

$$\lim_{n\to\infty} P = \begin{bmatrix} \pi_1 & \pi_2 & \cdots & \pi_s \\ \pi_1 & \pi_2 & \cdots & \pi_s \\ . & . & & . \\ . & . & & . \\ . & . & & . \\ \pi_1 & \pi_2 & \cdots & \pi_s \end{bmatrix}$$

Differential equations, Laplace transforms and matrix algebra is used in combination with Markov analysis. Tree diagrams could also be used to model simple systems. If calculations become too complex, a transitional probability matrix (as shown below) enables one to find the state probabilities over many periods of time.

Example:

Assume the Continuous Miner (CM) can be in a working condition or broken down. If the CM is working (State 1), there is 90% chance that it will keep on working in the next maintenance period. If the CM is broken down (State 2), there is 20% chance it will be fixed in the next maintenance period. Thus the transition probability matrix is:

$$P = \begin{array}{c} \\ \text{State 1} \\ \text{State 2} \end{array} \begin{array}{c} \begin{array}{cc} \text{State 1} & \text{State 2} \end{array} \\ \begin{bmatrix} 0.90 & 0.10 \\ 0.20 & 0.80 \end{bmatrix} \end{array}$$

If the machine is broken down, the probability of being fixed two maintenance periods from now can be calculated by determining $P(\mathbf{X}_2 = 1|\mathbf{X}_0 = 2) = P_{2,1}(2) =$ element 2,1 of P^2:

$$P^2 = \begin{bmatrix} 0.90 & 0.10 \\ 0.20 & 0.80 \end{bmatrix} \begin{bmatrix} 0.90 & 0.10 \\ 0.20 & 0.80 \end{bmatrix} = \begin{bmatrix} 0.83 & 0.17 \\ 0.34 & 0.66 \end{bmatrix}$$

Hence, $P_{2,1} = 0.34$. This means that there is a 34% chance that the CM will be fixed two maintenance periods from now.

To find the steady state-probabilities (π_1 and π_2), the following matrix is used:

$$\begin{bmatrix} \pi_1 & \pi_2 \end{bmatrix} = \begin{bmatrix} \pi_1 & \pi_2 \end{bmatrix} \begin{bmatrix} 0.90 & 0.10 \\ 0.20 & 0.80 \end{bmatrix}$$

The following two equations are given:

$$\pi_1 = 0.90\pi_1 + 0.20\pi_2$$
$$\pi_2 = 0.10\pi_1 + 0.80\pi_2$$

Solving the two equations gives $\pi_1 = \frac{2}{3}$ and $\pi_2 = \frac{1}{3}$. Thus, after a long time, there is a given $\frac{2}{3}$ or 66.67% probability that the CM will be in a working condition and a $\frac{1}{3}$ or 33.33% probability that the CM will be broken down.

4.4.7 Forecasting Models

The number of forecasting methods is extremely vast. Winston (2004), Moghram and Rahman (1989) and Ghobbar and Friend (2003) are but a few that have done research on the topic. Some of the methods mentioned by them include:

- Moving-Average Method
- Weighted Moving Average
- Exponentially Weighted Moving Average

- Simple Exponential Smoothing
- Double Exponential Smoothing
- Holt's Method
- Winter's Method
- Additive Winter's Method
- Multiplicative Winter's Method
- Simple Linear Regression
- Multiple Regression
- Seasonal Regression.
- Croston's Method
- Stochastic Time Series
- State Space Method
- Knowledge-Based Approach

The most widely used methods will be explored and includes the Moving Average Method, the Simple Exponential Smoothing Method, Holt's Method, Winter's Method and Simple Linear Regression.

4.4.7.1 Moving Average Method

One of the most widely used forecasting methods is the moving average method. This method is specifically popular when a time series fluctuates about a constant base level. For this method, $f_{t,1}$ is defined as the forecast period for period $t + 1$ after observing x_t. Thus,

$$\begin{aligned} f_{t,1} &= \text{average of the last } N_P \text{ observations} \\ &= \text{average of } x_t, x_{t-1}, x_{t-2}, \ldots, x_{t-N_P+1} \end{aligned} \tag{4.4.21}$$

with N_P a given parameter of the number of periods used to compute the moving average. To choose a value for N_P, the Mean Absolute Deviation (MAD) is used. The first step in calculating MAD is knowing the forecast error e_t. Thus, for a forecast for x_t,

$$e_t = x_t - (\text{forecast for } x_t) \tag{4.4.22}$$

The MAD is just the average of the absolute values of all the e_t's and N_P is chosen to minimize MAD.

4.4.7.2 Simple Exponential Smoothing

When a time series fluctuates about a base level, simple exponential smoothing is a good method to forecast future values. Simple exponential smoothing is defined by

$$A_t = \alpha x_t + (1 - \alpha)A_{t-1} \tag{4.4.23}$$

with A_t equal to the smoothed average of a time series after observing x_t and α the smoothing constant that satisfies $0 < \alpha < 1$. A value for A_0 is needed to initialize the process and is usually chosen as the observed value for the period immediately preceding period 1. Furthermore, $f_{t,k}$ is the forecast for x_{t+k} made at the end of period t. Thus,

$$A_t = f_{t,k} \tag{4.4.24}$$

Assuming a prediction for one period ahead, the error (e_t) for predicting x_t is given by

$$e_t = x_t - f_{t-1,1} = x_t - A_{t-1} \tag{4.4.25}$$

Once again the MAD equation is used to determine α and the objective is to minimize MAD.

4.4.7.3 Holt's Method

Holt's method is used when a time series exhibits a linear trend and no seasonality. This method yields an estimate of the base level (L_t) and the per-period trend (T_t) of the series. Equation 4.4.26 and 4.4.27 shows the calculations for these two values.

$$L_t = \alpha x_t + (1 - \alpha)(L_{t-1} + T_{t-1}) \tag{4.4.26}$$

$$T_t = \beta(L_t - L_{t-1}) + (1 - \beta)T_{t-1} \tag{4.4.27}$$

α and β are smoothing constants and adheres to $0 < \alpha < 1$ and $0 < \beta < 1$.

Once again $f_{t,k}$ is defined as the forecast for x_{t+k} made at the end of period t. Thus,

$$f_{t,k} = L_t + kT_t \tag{4.4.28}$$

An initial estimate of the base (L_0) and the trend (T_0) is needed to initialize the method. Therefore, T_0 is set equal to the average monthly increase in the time series during the previous year and L_0 is equal to the last month's observation.

4.4.7.4 Winter's Method

In contrast to Holt's method, Winter's method is used for forecast time series with trend and seasonality present. L_t and T_t has the same meaning as with Holt's method and is defined as follows,

$$L_t = \alpha \frac{x_t}{s_{t-c}} + (1-\alpha)(L_{t-1} + T_{t-1}) \tag{4.4.29}$$

$$T_t = \beta(L_t - L_{t-1}) + (1-\beta)T_{t-1} \tag{4.4.30}$$

with c being the number of periods in the length of the seasonal pattern and s_t an estimate of a seasonal multiplicative factor for month t obtained after observing x_t by using

$$s_t = \gamma \frac{x_t}{L_t} + (1-\gamma)s_{t-c} \tag{4.4.31}$$

Once again α, β and γ are smoothing constants between 0 and 1. At the end of period t, the forecast ($f_{t,k}$) for month $t+k$ is given by

$$f_{t,k} = (L_t + kT_t)s_{t+k-c} \tag{4.4.32}$$

4.4.7.5 Simple Linear Regression

Linear regression is used to determine the relationship between an independent and dependent variable that are related in a linear fashion. To model the relationship between a variable x_i and y_i the following equation is used:

$$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i \tag{4.4.33}$$

with ε_i being the error term. However, it is expected that ε_i average out to 0. β_0 and β_1 are unknown and estimated using $\hat{\beta}_0$ and $\hat{\beta}_1$ respectively. This leads to Equation 4.4.34.

$$\hat{y}_i = \hat{\beta}_0 + \hat{\beta}_1 x_i \tag{4.4.34}$$

For a given data set with points $(x_1, y_1), \ldots, (x_n, y_n)$, $\hat{\beta}_0$ and $\hat{\beta}_1$ are estimated as follows and referred to as the least square regression line:

$$\hat{\beta}_1 = \frac{\sum(x_i - \overline{x})(y_i - \overline{y})}{\sum(x_i - \overline{x})^2} \tag{4.4.35}$$

$$\hat{\beta}_0 = \overline{y} - \hat{\beta}_1 \overline{x} \tag{4.4.36}$$

The least square regression line needs to be tested if it provides a good fit to the data points. The Sum of Squares Total (SST) measures the total variation of y_i about its mean $\overline{y}$ and is given by

$$\text{SST} = \sum (y_i - \overline{y})^2 \tag{4.4.37}$$

The Sum of Squares Error (SSE) is given by

$$\text{SSE} = \sum (y_i - \hat{y}_i)^2 = \sum e_i^2 \tag{4.4.38}$$

SSE $= 0$ if the least square line passes through all the data.

The Sum of Squares Regression (SSR) is given as

$$\text{SSR} = \sum (\hat{y}_i - \overline{y})^2 \tag{4.4.39}$$

Thus it can be shown that

$$\text{SST} \ = \ \text{SSR} + \ \text{SSE} \tag{4.4.40}$$

It is also important to note the coefficient of determination (R^2) for y by

$$R^2 = \frac{\text{SSR}}{\text{SST}} = \ \text{percentage of variation in } y \text{ explained by } x \tag{4.4.41}$$

A measure of the linear association between x and y is the sample linear correlation r_{xy}. The standard error of the estimation (s_e) is a measure of the accuracy of predictions derived from regression. Equation 4.4.42 shows how s_e is calculated.

$$s_e = \sqrt{\frac{\text{SSE}}{n-2}} \tag{4.4.42}$$

with n the number of observations.

As mentioned, many more forecasting methods exist in the literature, but these are beyond the scope of this thesis.

4.4.8 Utility Theory and Decision Trees

Hansson (1994) defines expected utility as follows:

> *"The dominating approach to decision-making under risk i.e. known probabilities, is expected utility (EU).*

EU is also known as the probability-weighted utility theory. Each alternative is assigned a weighted average of its utility values. Winston (2004) uses the Von Neumann-Morgenstern concept of utility function. The lottery, L is defined by

$(p_1, r_1; p_2, r_2; \ldots; p_n, r_n)$ with $i = 1, 2, \ldots, n$, r_i the reward received with probability p_i. The lottery is often represented with a tree as seen in Figure 4.15. Each branch represents the probability that the outcome will occur.

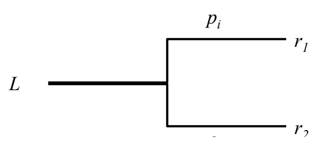


FIGURE 4.15: Utility theory decision tree.

The Von Neumann-Morgenstern method goes further and defines the decision maker's utility function as $u(r_i)$. The utility of the reward is the number q_i such that the decision maker is indifferent between the two lotteries as seen in Figure 4.16. Thus for a given lottery L, the expected utility written as $E(U \text{ for } L)$ is calculated with:

$$E(U \text{ for } L) = \sum_{i=1}^{i=n} p_i u(r_i) \tag{4.4.43}$$

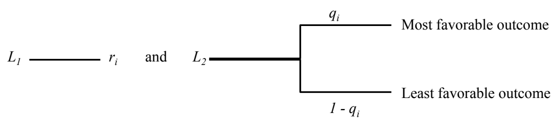


FIGURE 4.16: Utility theory decision tree between two lotteries.

A decision tree is used to make optimal decisions at different point in time. It enables the user or decision maker to solve large complex decision problems by decomposing it into several smaller problems.

Rokach and Maimon (2005) defines a decision tree as:

> *"A decision tree is a classifier expressed as a recursive partition of the instance space"*

The decision tree consists of two kinds of forks: decision forks (denoted by □) and event forks (denoted by ◯). According to Winston (2004), a decision fork is used when a decision needs to be made and an event fork when outside influences determine which of several random events will occur.

Figure 4.17 shows an example of a decision tree with *Yes* and *No* depicting one of two choices made by the decision maker (i.e. at a decision fork or □) and *Win* and *Lose* depicting one of two possible outcomes due to external forces (i.e. event fork or ◯).

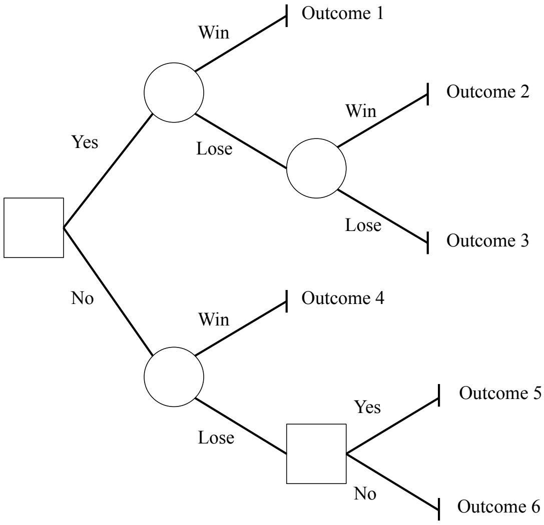


FIGURE 4.17: Decision tree.

Example:

A mine has $150,000 to decide whether to run a maintenance program on the Continuous Miner (CM). The biggest risk factor on the CM, has been determined to be the oil pressure gage. They have three alternatives:

> **Alternative 1:** Test the oil pressure gage and use this to determine whether further maintenance is needed.
>
> **Alternative 2:** Immediately run a full maintenance program.
>
> **Alternative 3:** Immediately abstain from running a full maintenance program.

The mine believes that there is a 55% chance of improving the CM and 45% chance of seeing no improvement. If there is an improvement, the mine's asset position will increase with $300,000 and if there is no improvement, their asset position will decrease with $100,000. If they decide to test the oil pressure gage (at a cost of $30,000), there is a 40% chance that maintenance is needed i.e. the oil pressure gage yields unfavorable results. If no maintenance is needed and they run the full maintenance program, there is a 15% chance of an improvement and an 85% chance of no improvement. If maintenance is needed and they run the full maintenance program, there is a 90% chance of improvement. The decision tree is shown in Figure **??** and the strategy followed by the mine can be determined to maximize their final asset position.

The final asset position for each branch is shown in the decision tree. The next step is to determine asset positions for the following three event forks:

(1) Run maintenance program after *No maintenance needed.* Final asset position $= 0.15(\$420,000) + 0.85(\$20,000) = \$80,000$.

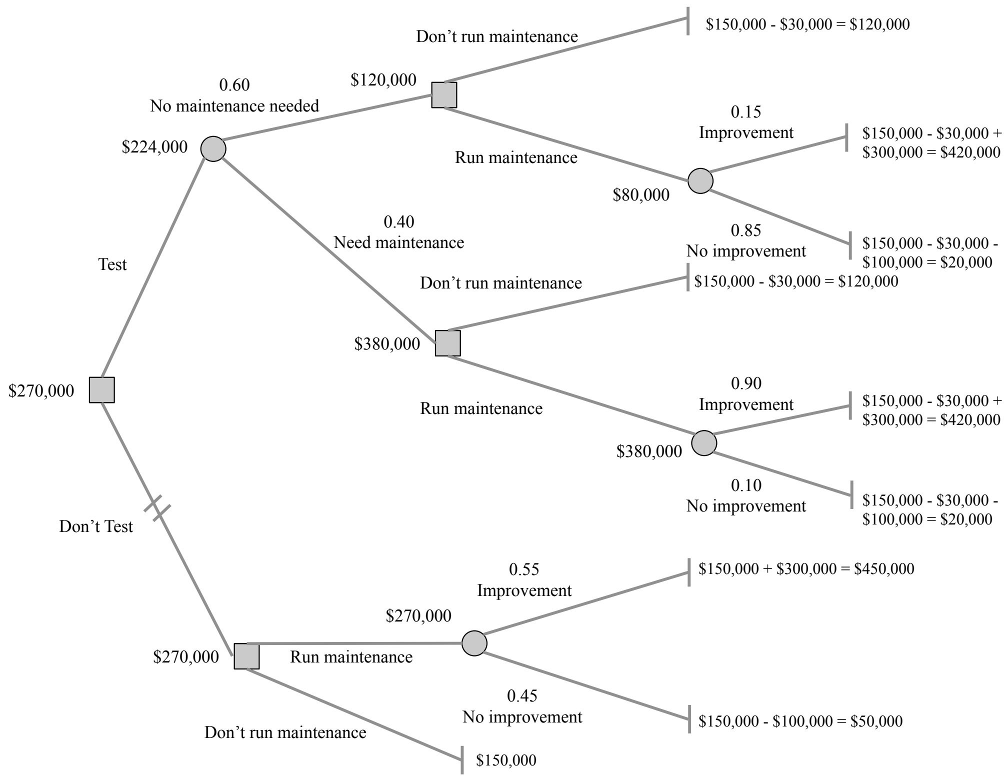
(2) Run maintenance program after *Maintenance is needed.* Final asset position $= 0.90(\$420,000) + 0.10(\$20,000) = \$380,000$.

(3) Run maintenance program after *No test done* on oil pressure gage. Final asset position $= 0.55(\$450,000) + 0.45(\$50,000) = \$270,000$.

Three decision forks are evaluated and the results are shown on the decision tree. With the decision fork, the best possible asset position is choosing from the two options. For example, at the *Don't test* decision fork, the best asset position between *Run maintenance* and *Don't run maintenance* is \$270,000. The test event fork asset positions is then determined:

$$\text{Final asset position} = 0.60(\$120,000) + 0.4(\$380,000) = \$224,000$$

The final decision fork is evaluated and it is determined that the best asset position gives a total of \$270,000. Thus the mine should just run the maintenance program without testing the oil pressure gage.



4.5 Chapter Summary

Chapter 4 is an extensive literature review of the quantitative methods associated with the three critical areas identified in Chapter 2. The three sets are:

- Criticality Analysis
- Financial Risk Impact
- Failure Analysis.

The chapter aims to give an overview of the quantitative methods available for usage and enables understanding of the full extent of methods in rotation regarding PAM and risk management. Various methods are identified for each of the sections and analyzed in detail. Analyzing the methods, especially those associated with failure analysis, it is determined that a basic understanding of complex mathematical calculations, a simplified background in basic statistics and a knowledge of reliability are required. The objective of the research is to design an easy-to-understand framework to manage risk as part of the PAM and ISO 55000 environment. Therefore, it is fundamental to evaluate the methods with a critical eye and focus on those that can provide the best solution.

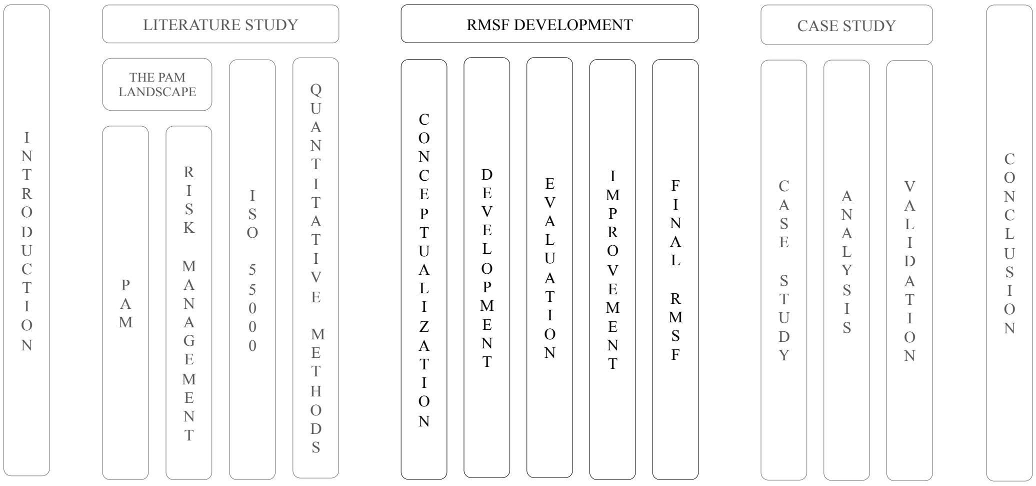
After objective six and seven are conformed to in this chapter, the next chapter uses the techniques evaluated to develop the RMSF framework. Foremost, the next chapter enables the use of the most effective and appropriate quantitative methods to simplify the process of analyzing an organization's assets in terms of risk management and the ISO 55000 series.

Chapter 5

Risk Management Solutions Flow

Chapter Aim:

The aim of this chapter is to develop a robust risk management framework incorporating quantitative methods in relation to criticality analysis, financial risk impact and failure analysis. In accordance with the objectives of the research, the framework initiates the process of becoming ISO 55000 compliant.



Chapter Outcomes:

- Conceptualization of the Risk Management Solutions Flow (RMSF).
- Delineation of the steps of the RMSF.
- Description of the steps of the RMSF.
- Identification of applicable quantitative methods.

5.1 Risk Management Solutions Flow (RMSF) Conceptualization

The problem statement in Chapter 1 stated that the novelty of the ISO 55000 series has caused confusion in terms of achieving accreditation. There is also little being done in terms of risk management and the quantitative side of risk management as well as asset management in organizations. Chapter 2 explored the background of PAM in general and Chapter 3 dived into the entire ISO 55000 series. Both these chapters form part of the foundation for the Risk Management Solutions Flow (RMSF). Finally, Chapter 4 analyzed the quantitative methods available and enabled the RMSF to incorporate the methods most suitable. Enabling the development of the RMSF, six consecutive phases are used and Figure 5.1 shows the flow of these phases. Each phase is outlined below.

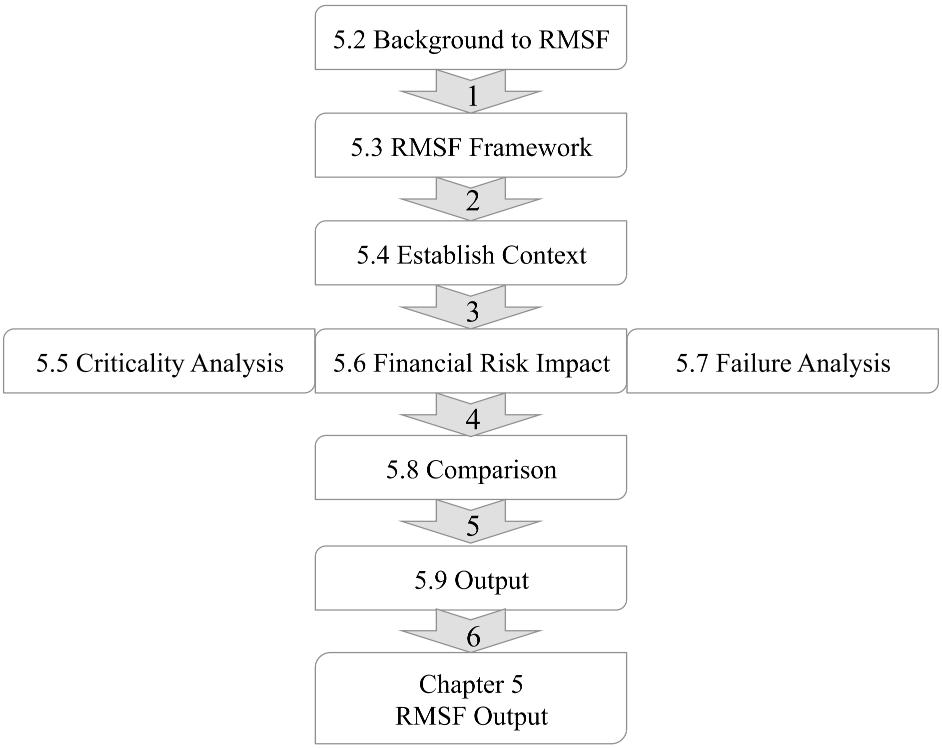


FIGURE 5.1: Basic steps of the RMSF development.

Phase 1: Preparatory Considerations
Phase 1 introduces and summarizes the literature as to what is required from the RMSF to be successful. Questions are posed and specific objectives are listed.

Phase 2: Framework Development
After all the different aspects of the RMSF has been taken into account in *Phase 1*,

the RMSF framework can be developed in full. Each of the six steps of the RMSF is discussed individually in the subsequent phases.

Phase 3: Establish the Context of the Organization
The context is determined by raising a range of questions to understand the organization before starting with data analysis in *Phase 4*. Specific information is needed in regards to the asset register and the specific assets listed. Another crucial part of this phase is to determine if the organization has identified the critical assets. Two more important factors are the current risk management plan and the requirements by the ISO 55000 series. *Phase 3* acts as the first step in the RMSF

Phase 4: Data Analysis
Data Analysis is the core development of *Phase 4*. The three areas ready for expansion are *Criticality Analysis*, *Financial Risk Impact* and *Failure Analysis*. These three areas are part of the RMSF and constitutes Step 2, 3 and 4.

Phase 5: Comparison
Comparing the *"what* ***is*** *being done"* to *"what* ***should*** *be done"* is part of the RMSF and Step 5 in the sequence. The proposal made while moving through the RMSF is compared to what the organization is already undertaking in terms of risk management.

Phase 6: Results of the RMSF
The final phase includes the conclusion of the RMSF and what it entails for the organizations. It is Step 6 of the RMSF.

5.2 Background to RMSF

The following section focuses on the literature study providing the foundation and requirements for the RMSF corresponding to *Phase 1*. Constructing the RMSF requires the aim of this thesis to be reviewed and act as the focus point of the development. The important questions asked to develop the Risk Management Solutions Flow (RMSF) are listed below as determined through the literature in Chapter 2:

- What is the context of the organization?
- Is there an asset register and what assets are listed?
- What is the current risk management plan?
- What is required in terms of ISO 55000?
- What is the risk criteria?
- What are the critical assets?
- How does the risk impact relate financially?
- When will the critical assets fail?

– How does the organization's risk management plan compare to the RMSF?

– What should be done in contrast to what is being done?

These questions are used to develop objectives to guide the development of the RMSF:

(1) Establish the context of the organization.

(2) Determine the critical assets.

(3) Determine the financial risk impact.

(4) Determine when the critical assets will fail.

(5) Compare the current risk management plan with the proposed RMSF.

(6) Come to a conclusion on the validity of the RMSF.

The problem statement in Chapter 1 summarizes the main objective of the research as follow:

> *"This study aims to address this need in a practical and easy to understand manner. The goal is to introduce organizations to the newly launched ISO 55000 series and start the process of becoming accredited. The primary focus is risk management and quantitative methods which are identified as the most critical areas of concern in the ISO 55000 series. It was decided that a user-friendly, risk management framework applicable to any industry to implement quantitative methods that will facilitate the asset management process and lead to ISO 55000 accreditation, is the ultimate solutions."*

This statement clearly focuses on the ability of the RMSF to be easy to understand and easy to use. Thus, the quantitative methods identified in Chapter 4 should be considered and evaluated to be able to determine which methods are appropriate. The criteria each method is weighted against are: easy to use, effortless, easy to understand, easy to implement and not time consuming.

5.3 RMSF Framework

The following engages in *Phase 2* of the conceptualization of the RMSF. All the objectives recorded in Section 5.2 forms the foundation for the RMSF and from these six objectives, a six step RMSF is developed. The six steps are:

(1) Establish Context

(2) Criticality Analysis

(3) Financial Risk Impact

(4) Failure Analysis

(5) Comparison

(6) Output

Figure 5.2 shows the summarized version of the RMSF. The *Output* is the final step, but because this RMSF is a continuous process, a feedback loop returns to *Step 1* of the RMSF. The six steps will be discussed in detail as well as the relation to ISO 55000 and the required quantitative methods.

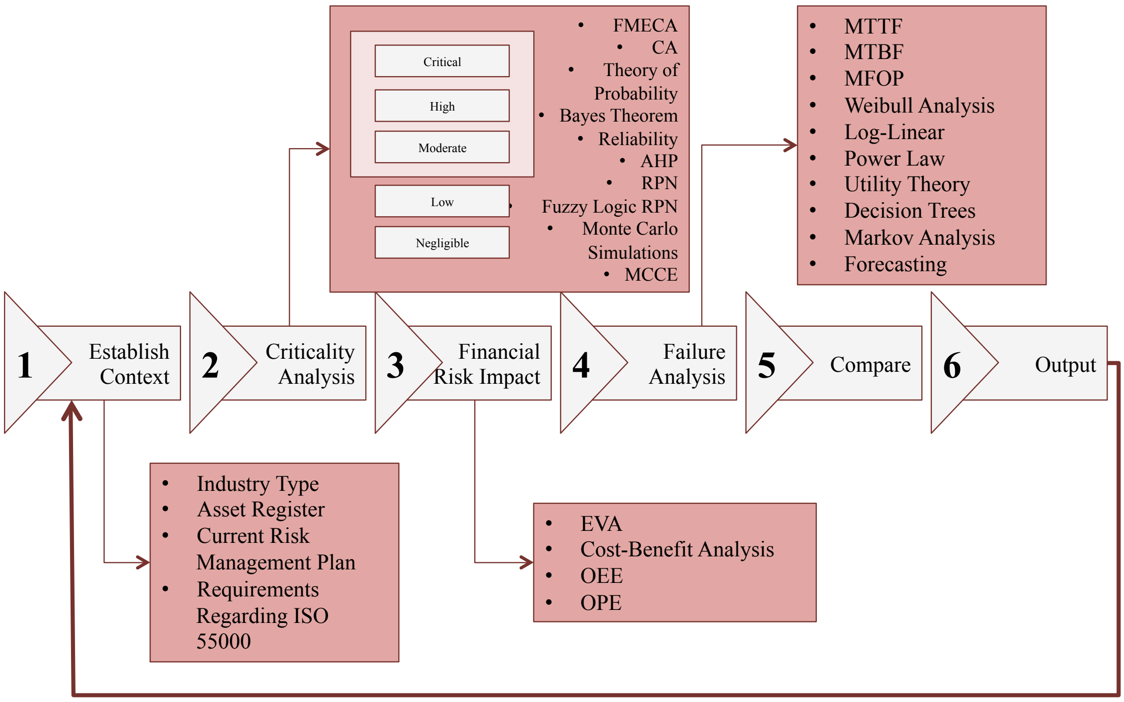


Figure 5.2: The Risk Management Solutions Flow (RMSF).

The ready-to-use version is shown in Figure 5.3 and included once again in Appendix 2 for a magnified version. The ready-to-use version is basically an easy to read and understand model and aesthetically pleasing to the eye. This version is also much more elegant and thus will be demonstrated to the organization and then implemented for the employees to refer back to and use when conducting the RMSF.

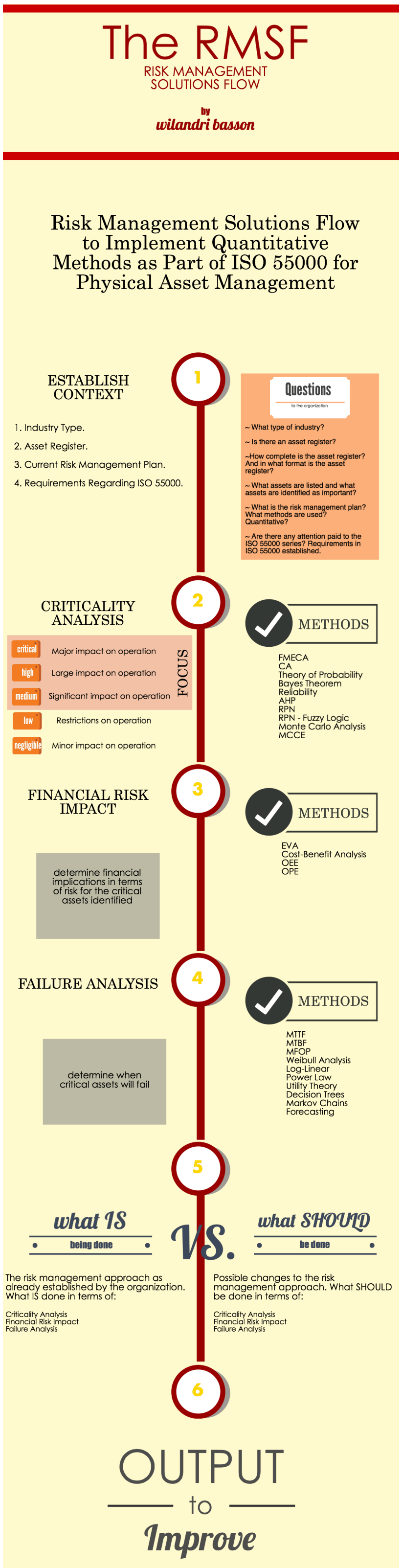


FIGURE 5.3: The ready-to-use Risk Management Solutions Flow (RMSF).

5.4 Establish Context

Determining the context of the organization is vital to the development of the steps that follow. In ISO 55001 Section 4.1 and ISO 55001 Section 4.2, the requirements for understanding the organization, its context and the needs and expectations of the stakeholders are established. ISO 55001 (2014) requires the following in ISO 55001 Section 4.1:

> ***4.1 Understanding the organization and its context***
> *The organization shall determine external and internal issues that are relevant to its purpose and that affect its ability to achieve the intended outcome(s) of its asset management system.*

as well as ISO 55001 Section 4.2

> ***4.2 Understanding the needs and expectations of stakeholders***
> *The organization shall determine:*
>
> – *the stakeholders that are relevant to the asset management system;*
> – *the requirements and expectations of these stakeholders with respect to asset management;*
> – *the criteria for asset management decision making;*
> – *the stakeholder requirements for recording financial and non-financial information relevant to asset management, and for reporting on it both internally and externally.*

Both these sections are referred to in ISO 55001 Section 6.1 in which referrers to addressing risks and opportunities. ISO 55002 Section 4.2 and ISO 55002 Section 4.3 expands on the requirements in ISO 55001 and is again referred to in ISO 55002 Section 6.1 which again focus on risk and opportunity in the organization.

Gómez de León Hijes and Ruiz Cartagena (2006) researched the process of determining the best maintenance strategy and identified specific points of focus while conducting such an analysis:

– A detailed inventory or asset register of all equipment and facilities (i.e. characteristics and functional interrelationships).

– Past failure records.

– Acquisition and supply costs.

– Cost associated with maintenance (direct and indirect costs).

– Operational factors and needs.

– Legal or contractual maintenance obligations

– Legal and contractual obligations of the organization.
– Means for maintenance (i.e. tools, equipment etc.).
– Human resources and personnel qualifications.
– Maintenance task that has the possibility to be contracted out.
– Any other relevant aspects that are applicable to the specific case.

The following is addressed during the process of inaugurating the context of the organization:

– The type of industry the organization is exhibited as.
– The extent of the completeness of the asset register.
– The format (for example MS Excel) of the asset register.
– The specific assets listed in the asset register.
– The important assets identified internally by the organization.
– What the organization currently has in place in terms of risk management.
– What is required in the ISO 55000 series in terms of risk.
– The use of quantitative methods in terms of PAM.

The next section is focused on discussing each of the identified areas of concern in detail to ensure a smooth implementation process of the RMSF

5.4.1 Industry Type

Risk management and the laws and regulations associated with it, varies from industry to industry. Thus, it is important to establish the type of industry the organization falls into. Industries approached in this research, are identified as manufacturing, mining, energy, health care and agriculture. The reason these specific industries are applicable to the research, is due to the fact that all of them rely heavily on their assets. Once the type of industry is determined, external and internal issues can be diagnosed. Issues include limitations, rules, regulations, requirements from management or stakeholders. Basically, any problem that could affect the physical assets, the PAM process and/or risk management.

5.4.2 Asset Register

This entire RMSF is based on the assets owned by the organization. The asset register is the starting point for the flow of events. An existing asset register facilitates and simplifies the RMSF and all information associated with the register should be gathered. An initial idea is also created of what assets are regarded as important by the organization and the format of the asset register is made known.

5.4.3 Current Risk Management Plan

The end goal of the RMSF is a comparison between the existing and proposed risk management plan. Therefore, the current risk management plan should be identified, if there exists such a plan. This risk management plan is not the general risk management plan of the organization but rather one focused on the physical assets of the organization and the asset management system implemented at the organization. Rarely such a plan exists, making the *Comparison* step difficult.

5.4.4 Risk Management Requirements in ISO 55000

ISO 55000 gives a definition of risk:

> *"effect of uncertainty on objectives"*

Furthermore, it elaborates on risk in terms of five notes describing risk in more detail, the different disciplines and levels applicable and the characterization of risk.

Section 6.1 in both ISO 55001 and ISO 55002 address the requirements in terms of risk. For further reference, Chapter 3 can be of help. A well-constructed knowledge of ISO 55000 is also a requirement.

5.5 Data Analysis

Data Analysis is based on what needs to be measured and incorporates three different sections as was decided in Chapter 2:

(1) Criticality Analysis

(2) Financial Risk Impact

(3) Failure Analysis

Each of these areas requires quantitative methods researched in Chapter 4 and the methods are evaluated in the succeeding sections by weighing the methods against one another in terms of five important values:

- ease of use;
- effortlessness;
- ease of understanding;
- ease of implementation; and
- time frame.

The values chosen are done so in order to satisfy the original objective of this thesis as mentioned in Chapter 1.

Therefore, it is critical that the quantitative methods are easy to use and applicable to any industry and time frame. Another important factor to consider, is the data available from the organization. This will determine the if the method chosen can be used. Different organzations make use of different data capturing.

Knowing the specification required from the quantitative methods, the next three sections determines the most appropriate method for each of the critical areas namely *Criticality Analysis*, *Financial Risk Impact* and *Failure Analysis*.

5.6 Criticality Analysis

The criticality of equipment is the *"importance in the objectives for which it is used and, therefore, to the company"* (Gómez de León Hijes and Ruiz Cartagena (2006)).

Equipment criticality is a valuable tool for any organization as it enables the organization to determine the critical assets. The critical assets are assets with a high risk associated with it. The *Criticality Analysis* is the first quantitative based analysis used in the RMSF. Assets are classified as *Very High*, *Critical*, *Medium*, *Low* and *Negligible* in regards to the risk associated with the assets.

Once the criticality analysis is concluded, the RMSF requires the organization to focus on the Critical, High and Moderate risk rated assets.

The criticality of the asset is determined with one or more of the following methods:

- Failure Mode and Effects Criticality Analysis (FMECA)
- Criticality Analysis (CA)
- Theory of Probability and Bayes Theorem
- Reliability
- Analytic Hierarchy Process (AHP)
- Risk Priority Number (RPN)
- Fuzzy Logic RPN
- Monte Carlo Simulations
- Multi-criterion Classification of Critical Equipment (MCCE)

Table 5.1 is a comparison of the five quantitative methods, discussed in detail in Chapter 4, associated with criticality analysis.

Table 5.1 indicates that traditional RPN, Fuzzy Logic RPN or Monte Carlo simulations are the superior methods due to the fact that they adhere to the most

TABLE 5.1: Comparison of quantitative methods for Criticality Analysis.

Quantitative Method	Easy to Use	Effortless	Easy to Understand	Easy to Implement	Not Time Consuming
FMECA	x		x	x	
CA	x	x	x	x	
Bayes Theorem	x	x			
Reliability	x	x			x
AHP	x		x	x	
RPN	x	x	x	x	x
Fuzzy RPN	x	x	x	x	x
Monte Carlo	x	x	x	x	
MCCE					x

objectives. Considering each of these methods, the Fuzzy Logic RPN will be the preeminent method. Fuzzy Logic RPN proved, through the research in Chapter 4, to be a more evolved method than the traditional RPN with minor additions to the calculations. An important fact to determine before deciding on using Fuzzy Logic RPN, is to determine the ratings associated with the three values, Probability of Failure (O), Severity of Failure (S) and Probability of Not Detecting Failure (D). The tables can be set up in terms of the data available from the organization. Tables 5.2, 5.3 and 5.4 are suggested ratings for O, S and D as well as the data requirements for each.

TABLE 5.2: Suggested ratings for Probability of Failure.

Suggested Rating	Data Requirements
Frequency of failure occurrence/Failure rate	History of failures and date or time associated with each failure.
Number of failures	History of failures
Number of corrective maintenance activities	Maintenance activities logged as corrective maintenance.

TABLE 5.3: Suggested ratings for Severity of Failure.

Suggested Rating	Data Requirements
Cost of failure	Cost associated with failure i.e. cost of repair, cost of maintenance, cost of replacement, cost of Work Order (WO) etc.
Hazard level of failure	Impact on health, safety or environment.
Equipment functioning/not functioning	Description of failures.
Impact on operations	Description of failure and impact.
Compliance with rules and regulations	Understanding of laws and regulations.
Occurs with warning/no warning	History of failure occurrence.

TABLE 5.4: Suggested ratings for Probability of Not Detecting Failure.

Suggested Rating	Data Requirements
Chance of detecting failure	History of detecting previous failures.
Number of predictive and/or proactive maintenance activities	Failures logged with maintenance type.

5.7 Financial Risk Impact

Risk management has been long associated with the financial industry and it is an important measure for management to determine which risks will have a significant impact on the financial side of the organization. Money made or money lost is something most employees will understand and will thus strengthen the case for the need for an asset management system. The following methods are associated with financial risk management:

- Cost-Benefit Analysis (CBA)
- Benefit-Cost Ratio (BCR)
- Economic Value Added (EVA)
- Overall Equipment Effectiveness (OEE) and Overall Process Effectiveness (OPE)

Table 5.5 is the comparison of the above mentioned quantitative methods to discover the best method to include in the RMSF.

TABLE 5.5: Comparison of quantitative methods for Financial Risk Impact.

Quantitative Method	Easy to Use	Effortless	Easy to Understand	Easy to Implement	Not Time Consuming
CBA	x	x	x	x	
BCR	x	x	x	x	
EVA	x	x			x
OEE/OPE	x	x			x

From Table 5.5, the best ranked methods are indicated as CBA and BCR. Both methods are important and can be used in the RMSF. However, determining the data available provided by the organization in question, is key to deciding on the appropriate method to use. A CBA can only be conducted if all monetary costs and benefits associated with the asset are available. The BCR can be calculated according to what the organization defines as benefits and costs.

5.8 Failure Analysis

Statistical failure analysis is the process of collecting data to determine when an asset will fail by looking at the historical failure data. It enables the organization to determine when the risk could be expected and is a valuable method to assist the risk management process. The quantitative methods associated with failure analysis are as follows:

- MTBF, MTTF and MFOP
- Weibull Analysis
- Log-Linear Model
- Power Law Model
- Markov Chains
- Decision Trees
- Utility Theory
- Forecasting.

To compare the different methods to one another, Table 5.6 is included. The methods are weighted against each other in terms of the requirements identified earlier in this chapter.

TABLE 5.6: Comparison of quantitative methods for Failure Analysis.

Quantitative Method	Easy to Use	Effortless	Easy to Understand	Easy to Implement	Not Time Consuming
Laplace	x	x		x	x
MTBF	x	x	x	x	x
MTTF	x	x	x	x	
MFOP	x	x	x	x	x
Weibull					
Log-Linear					
Power Law					
Markov	x	x	x		
Moving Average	x	x	x	x	
Exponential Smoothing	x	x	x	x	
Holt's	x		x		
Winter's	x		x		
Linear Regression	x	x	x		
Utility Theory	x		x	x	

The two methods with the highest ranking are MTBF and MFOP. In terms of the industry, MTBF is the most recognized method, but MFOP is proven to be the more advanced method. It is therefore, once again, crucial to determine the data available from the organization. As deduced in Chapter 4, MFOP is a viable method when the scale and shape parameters are available as well as the surviving units of time.

5.9 Comparison

As part of Step 1, *Establish Context*, the current risk management plan is identified and scrutinized. This enable the proposed risk management plan to be compared to what the organization is currently doing in terms of managing risk related to the management of fixed assets.

The purpose of the RMSF is not to tell the organization what to do in terms of risk, but rather how to identify the risk and the ability to use the appropriate methods to determine the biggest risks. A *Before* and *After* comparison table is an advantageous analysis validation.

5.10 Output

Concluding the development of the RMSF, an integrated model following the six steps as identified in the beginning of this chapter is constructed. As a result, Figure 5.4 represents the final version of the RMSF. The ready-to-use version is shown in Figure 5.5 and once again included in Appendix 3 for a magnified version. Furthermore, a review of the model is done below. The RMSF is an ongoing process and will be repeated continuously throughput the life of the organization.

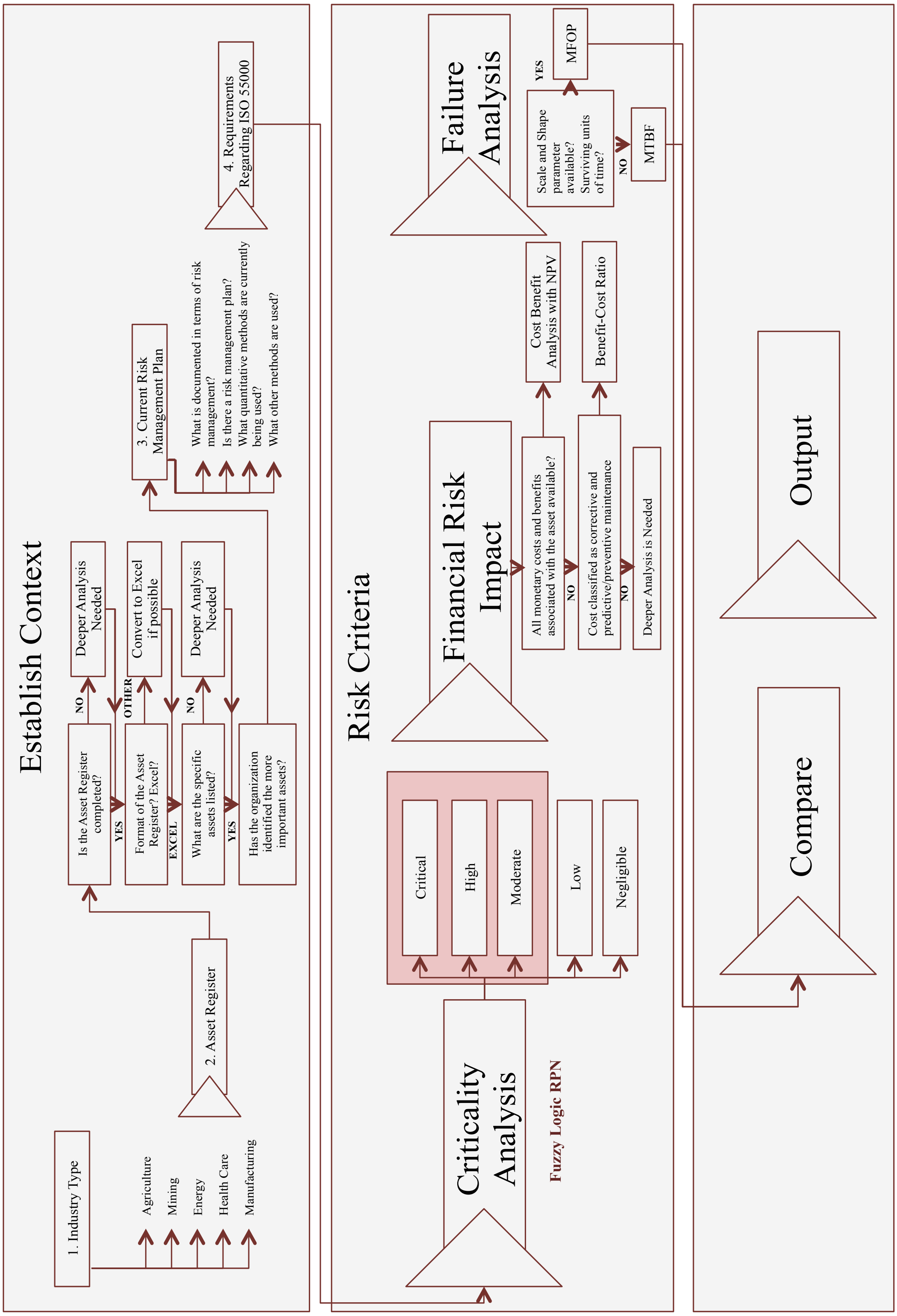


Figure 5.4: The detailed Risk Management Solutions Flow (RMSF).

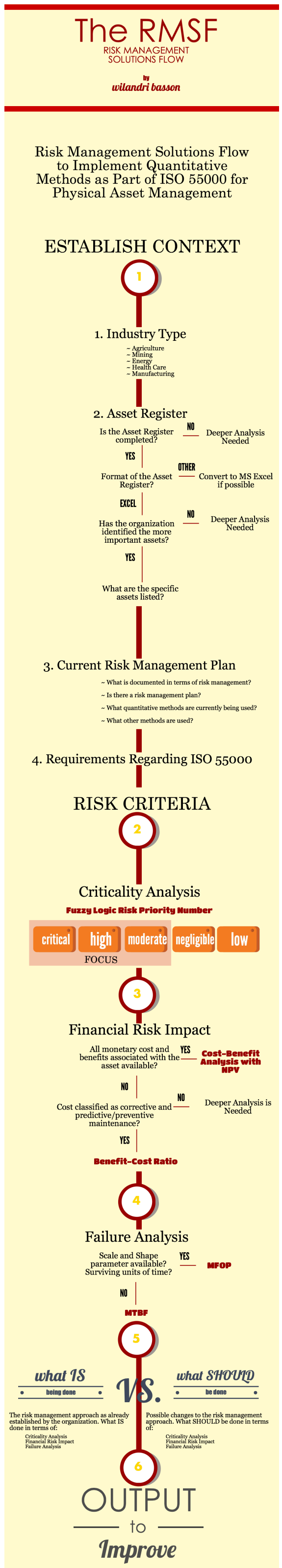


Figure 5.5: The ready-to-use detailed Risk Management Solutions Flow (RMSF).

Step 1: Establish Context

Establishing the context of the organization entails four important sections that need addressing before initializing the data analysis phase. These include:

(1) The type of industry the organization falls under.

(2) The availability of the asset register.

  - Is the asset register complete?
  - What is the format of the asset register?
  - What assets are listed?
  - Has the organization identified the more important assets?

(3) The current risk management plan, related to assets, adopted by the organization.

(4) The requirements stipulated in ISO 55000 regarding risk management.

Identifying the industry type is an important part of risk management. It is of great value to know what assets bring value to the organization. It also influences the laws and regulations that need to be adhered to that specifically apply to the industry type. Currently, the RMSF is directed at organizations that rely heavily on their physical assets including the agriculture, mining, energy, manufacturing and health care industries.

When the industry type is determined, the asset register is brought under evaluation. The first question to be answered is whether the asset register is complete. If not, a deeper analysis of the organization and questioning of employees and management specifically is needed. A complete asset register triggers the next question: What is the format of the asset register? The RMSF analysis is conducted by means of MS Excel and if the data is in another format, it is necessary to convert it to MS Excel. The next step is to confirm if the organization has listed specific assets in the register. Once again if this step is not completed a further analysis or questioning of the employees is mandatory. The final action is to ascertain if the organization focused on more important assets. This step is not critical to the RMSF, but it will facilitate a better understanding of the organization and where to place the focus of the RMSF.

Section 3 involves determining the current risk management plan implemented by the organization by asking the following questions:

- What is documented in terms of risk management?
- Is there a risk management plan?
- What quantitative methods are currently being used?

– What other methods are used?

Finally, an overview of the risk management requirements in the ISO 55000 series is analyzed and described as the aim of the research is to move towards becoming ISO 55000 accredited.

Step 2: Criticality Analysis

Step 2 is the criticality analysis where the Fuzzy Logic RPN quantitative method is used to calculate a Z-value for each of the assets and then ranked from most critical (highest Z-value) too least critical (lowest Z-value). Assets are classified as critical, high, moderate, low and negligible. Assets grouped as critical, high and moderate are scrutinized and a *Financial Risk Impact* and *Failure Analysis* is conducted on each of the assets.

Step 3: Financial Risk Impact

Financial Risk is a vital part of risk management as it translates risk related information into financial terms enabling upper management to also understand the value of risk management and becoming ISO 55000 accredited.

As determined, the superior methods are the Cost-Benefit Analysis or the Cost-Benefit Ratio. Understanding the value of both these methods resulted in a two-way option depending on the information available. The Cost-Benefit Analysis with NPV calculated, is used when all monetary costs and benefits associated with each asset are accessible. In a case where this information is absent, a Benefit-Cost Ratio is calculated based on the costs classified as preventive/predictive maintenance and corrective maintenance. If neither of the information is evident, a more profound analysis of the organization is needed.

Step 4: Failure Analysis

Failure Analysis is the last step in the data analysis phase. MTBF and MFOP are identified as the two quantitative methods and once again, it is reliant on the information obtainable. MFOP is only used if the scale and shape parameters are defined and the surviving units of time of each asset are documented.

Step 4 concludes the data analysis of the RMSF and advances the process to the penultimate step, *Comparison*.

Step 5: Comparison

Comparing *"what is being done"* to *"what should be done"* is the essence of the RMSF and the aim of the thesis and the solution to the problem identified in Chapter 1. As confirmed previously, a *Before* and *After* comparison table could be a valuable attribute and measuring technique.

Step 6: Output

Concluding the RMSF is *Step 6*, the *Output*. A conclusion is drawn and suggestions and directions are given to the organization to move forward with expansion. Establishing or renewing their risk management plan is another essential feature of the RMSF. Further guidelines are given in terms of becoming ISO 55000 accredited.

5.11 Chapter Summary

Chapter 5 is the salient chapter in this thesis and adheres to objective eight. The full development of the RMSF is explored and through the conceptualization, the result is a completed framework. As established, the RMSF is a six step process consisting of the following stages:

Step 1: Establish Context

Step 2: Criticality Analysis

Step 3: Financial Risk Impact

Step 4: Failure Analysis

Step 5: Comparison

Step 6: Output

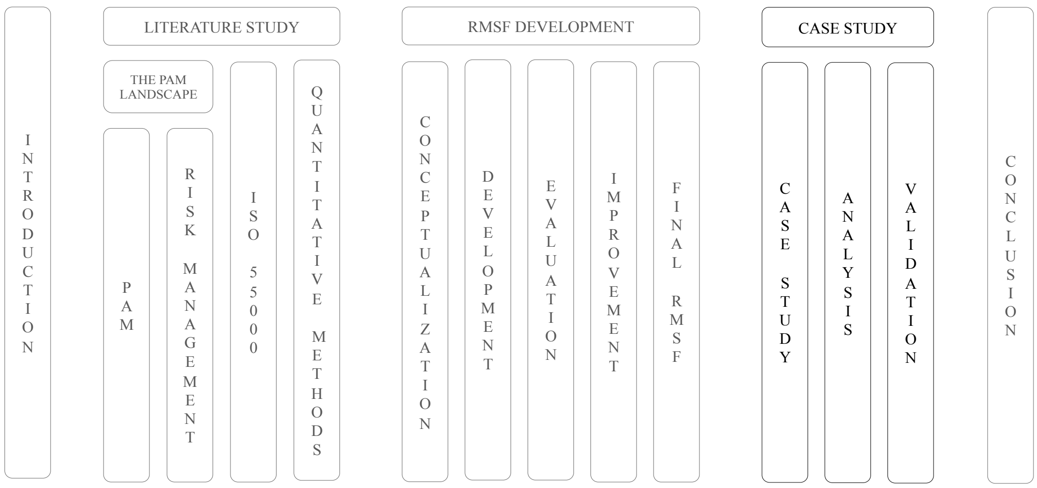
Concluding the RMSF evolution and therefore Chapter 5, the research can now proceed to the application of the RMSF by means of a case study.

Chapter 6

Case Study

Chapter Aim:

The aim of this chapter is to utilize the previously developed RMSF in a case study. In order to establish the validity of the real-world application of the process, the case study is immensely important.



Chapter Outcomes:

- Introduction to the case study.
- Application of RMSF to the case study organization.
- In depth exploration of the steps in the RMSF.
- Analysis of results.

6.1 Getting Started

The literature study composed of Chapter 2, Chapter 3 and Chapter 4 finds a comprehensive link between the newly launched ISO 55000 series, risk management and quantitative methods. As pertained in Chapter 5, the Risk Management Solutions Flow (RMSF) is proposed as a six step process and therefore the RMSF acts as the foundation for the case study executed in cooperation with an asset-focused organization. Chapter 6 is the adaption and application of the RMSF to explore the ability of the process to manage risks related to PAM, ISO 55000 and specific quantitative methods.

Initializing a case study requires preliminary steps including: seeking the commitment of research partners, introducing the RMSF while accepting input regarding changes to the methodology and obtaining the required data.

The primary objective of the research collaboration is to determine who the research partners are and procure sponsorship from senior management. Thus, the first step is to introduce the RMSF to the identified organization and determine the modifications as proposed by the organization. In addition, the availability of the required data is also determined. In this case, the research partners were identified in early March 2014 when the initial introductions were made. Preliminary thesis topics were introduced and feedback from the research partners was received. Establishing further contact was needed and in September 2014 time was spent on a mine to test possible research proposals. The two weeks spent at the coal mine provided valuable knowledge and background information. This led to the conceptualization of the thesis title. The RMSF was developed and launched in May 2015 to receive input from the research partners. Minor modifications were suggested by the research partners and are considered in the further development of the RMSF. It is further analyzed in Section 6.2.

The final step was to elaborate on the initial contact with the organization and establish a firm point of contact to acquire the necessary data and information. Chapter 6 is the application of the RMSF to a specific mine identified through the research partners.

6.2 Modification to the RMSF

Receiving input from the organization resulted in certain adjustments in the development of the RMSF and in conducting the case study. It was necessary to adapt the research with the following modifications as dictated by the research partners:

- The first question was raised regarding the sequence of events in the RMSF. It was proposed that some of the steps would not follow one another, but rather be performed in parallel. A decision was made to keep the RMSF as is, but to approach the process more holistically and inaugurate flexibility when considering the concatenation of steps as required by the organization.

- According to the RMSF, a risk management plan currently implemented at the organization was required to be able to compare what is being done to what should be done. It was determined that no such plan exists, only a risk management matrix, which will be used to conduct the *Comparison* step.
- Another important modification to mention is the exclusion of *Health, Safety and Environmental Impact* from the RMSF. This is also seen as a critical area in risk management, PAM and ISO 55000, but the extent and reach of the field is much too large for the scope of this thesis.

6.3 Case Study

The case study was conducted in cooperation with an iron ore mine [1]. The initial contact point was able to provide the needed assistance and was eager to help the research. The quantitative data as well as background information to the mine in question was provided.

Through conversations with employees invested in assets and maintenance management, it was clear that the ISO 55000 document has not received the attention it deserves. The PAM program already implemented at the mine is still very immature and there is clearly much room for improvement. The organization is well aware of the ISO 55000 series and the value that a proper PAM process can provide, but they have not adopted the ISO 55000 requirements specifically. However, the asset management programs implemented at the mine is based on the same principles as ISO 55000. Hence, it will be not be laborious to streamline the existing PAM process with the ISO 55000 guidelines. Very basic quantitative methods were used at the mine as seen. The lack of quantitative methods when conducting asset management and maintenance is of a concern. Implementing the RMSF proposed in this thesis will address the lack of quantitative methods regarding PAM, improve asset management and risk management and initiate the process of adhering to the ISO 55000 series to become accredited.

Considering the RMSF and the distinct six step process, it is the natural guide to the development of the case study. Therefore, the case study is conducted according to the same stages namely:

(1) Establish Context

   a) Context of the Organization
   b) Asset Register
   c) Risk Management Requirements in ISO 55000
   d) Current Risk Management Plan

[1] Due to the confidentiality and sensitive nature of the data, the mine or organization will not be named.

(2) Criticality Analysis

(3) Financial Risk Impact

(4) Failure Analysis

(5) Comparison

(6) Output

6.3.1 Establish Context

Establishing the context of the organization is an essential part of the RMSF, providing the foundation for the development of an improved risk management plan. As mentioned, the context includes the context of the organization, the asset register, the current risk management plan (or lack there off), the risk management requirements as stipulated by ISO 55000 and the risk criteria entailed by the organization. The organization supplied information to support this research in the form of raw Work Order (WO) data that provides the CMMS SAP data dumps, cost sheets on the mining production equipment as well as an analysis conducted using the raw data. Contact with the research partners also provided beneficial material to develop an understanding of the context.

Due to the confidentiality of the data used for this case study, the context and background of the mine could not be scrutinized as is required by the RMSF. Thus, when the RMSF is implemented at a mine a detailed background study will enable a much better output and therefore improved results. Although the context is not analyzed profoundly, the four areas that define the *Establish Context* phase are still developed individually .

6.3.1.1 Context of the Organization

A detailed assessment of the maintenance history and risk management processes of the assets at the iron ore mine used for the application of the RMSF is conducted to support the case study. The SAP PM ERP system is used to record the data at the mine. Each maintenance activity is associated with a work type code as seen in Table 6.1.

TABLE 6.1: Work type classification.

Work Type	Definition	Classification
PM01	Corrective Maintenance	Corrective
PM02	Repairs	Corrective
PM03	Preventive Maintenance	Preventive
PM04	Quoted Repairs	Predictive
PM05	Inspections	Preventive
PR01		
SM01		

The classification is the grouping of maintenance activities into corrective, preventive and predictive maintenance.

The Maintenance Activity Type (MAT) codes are also associated with a specific type of maintenance activity as seen in Table 6.2. Classification is done in terms of preventive, preventive and scheduled corrective, expedited predictive, predictive, proactive and scheduled corrective.

TABLE 6.2: Maintenance Activity Type (MAT) classification.

MAT Code	Definition	Classification
1	Inspections	Preventive
2	Services	Preventive and Scheduled Corrective
3	Repair	Expedited Predictive
4	Replacement	Predictive
5	Upgrade	Proactive
6	Installations	Proactive
7	Manufacture	Proactive
8	Strip and Quote	Predictive
100	Ad Hoc Tasks	Scheduled Corrective
101	Service	Preventive
102	Order Parts	Predictive
103	Test	Preventive

Figure 6.1 shows the work flow associated with the MAT codes as described by the mine. The red and green blocks indicate respectively the current (in terms of Cost Balance) and target (in terms of labour hours) percentages dedicated to a specific maintenance type.

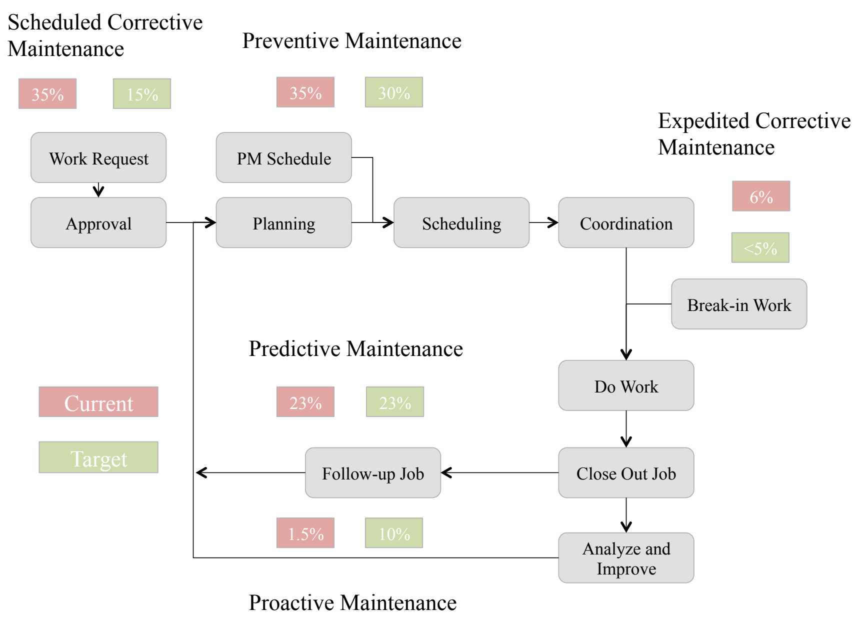


FIGURE 6.1: Work flow for Maintenance Activity Type (MAT).
Adapted from the mine.

The target percentages are set by the average percentages associated with organizations in this industry. Each maintenance type is assigned to an activity in the work flow. For example, *Scheduled Corrective Maintenance* is allocated at the start of the work flow or *Work Request*. Currently 35% of costs are used for *Scheduled Corrective Maintenance* with the target being 15% of labour hours. This leads to the following findings:

- The rate of failure at the mine is within tolerance of good practice.
- The balance between corrective and predictive maintenance is out of balance. This could be due to corrective maintenance activities not being updated on the system as such.
- More attention should be paid to condition-based maintenance and proactive maintenance to reduce costs and lower operational losses.

Addressing these problems in the RMSF application could be of great value to the organization.

6.3.1.2 Asset Register

The information provided by the mine is summarized in Table 6.3 to enable the reader to understand the context of the organization in terms of the assets, where the assets are located as well as the WOs and cost associated with the assets.

TABLE 6.3: Summary of the asset register.

Number of Assets	75 527
Number of Assets at Parent Level	13 827 (18.3%)
Number of Assets with WOs	40 976 (54.3%)
Number of Locations	29 345
Number of Locations at Parent Level	1 (0%)
Number of Locations with WOs	16 185 (55.2%)
Number of WOs	484 926
Number of WOs with Zero Cost Data	88 301 (18.2%)
Number of WOs with Zero Labour Hours	484 926 (100%)
Number of WOs with NULL Request Date	0 (0%)
Number of WOs with NULL Assets and NULL Locations	0 (0%)
Number of WOs with NULL Assets	51 781 (10.7%)
Number of WOs with NULL Locations	0 (0%)
Date of First Work Order	02/01/2009
Date of Last Work Order	10/04/2015
Number of WOs with NULL GL Codes	51 781 (10.7%)

The data provided included an asset register for the Mining and Plant side of the mine. To facilitate a deeper understanding of the research, it was determined that focus should be placed on the Mining side and to conduct the case study with the data associated with Mining.

The asset register was given in MS Excel format, which facilitated the analysis. Although a sufficient amount of data was provided, the asset register was not complete. Specifically, the lack of an equipment number or a functional location related to a work order. Certain start and finish dates were also missing from the data. Using both a MAT code and work type code caused some confusion. This, however, did not impact the case study negatively.

During a previous reliability study on the mine, a list of 50 important assets was identified. These assets were ranked according to the number of WOs associated with each. Table 6.4 shows the 50 assets as identified by the study.

Table 6.4: Important assets ranked according to Work Orders (WO).

Asset Number	Description	WOs
10140410	PC 8000-6 Komatso Hydraulic Shovel	543
10124110	Liebherr R996 Litronic Hydraulic Shovel	399
10151123	R 996 LIEBHERR	382
10124067	Liebherr R996 Litronic Hydraulic Shovel	358
10151163	R 996 LIEBHERR	287
10053756	R 9800 LIEBHERR	273
10119090	R 996 LIEBHERR	251
10065636	Le Tourneau L2350	245
10119134	R 996 LIEBHERR	240
10115248	Atlas Copco PV351D	235
10145724	Komatsu Wa 1200 Front End Loader	216
10069971	4100 XPC P&H Rope Shovels	186
10080067	Haulpack 730E Statex III	186
10115346	Atlas Copco PV351D	183
10150091	Cat 994 H Front End Loader	179
10081134	2300xpb P&H Rope Shovel	176
10129614	Atlas Copco PV351D	176
10043990	4100 XPC P&H Rope Shovels	173
10033624	Komatsu Wa 1200 Front End Loader	172
10112745	Cat Haultruck	172
10129471	Atlas Copco PV351D	172
10079699	Haulpack 730E Statex III	169
10100838	Haulpack 730E Statex III	169
10131452	Cat Haultruck	169
10112889	Cat Haultruck	167
10060074	Komatsu Wa 1200 Front End Loader	165
10146939	Atlas Copco PV351D	165
10098747	Haulpack 730E Statex III	162
10112816	Cat Haultruck	162
10131236	Cat Haultruck	161
10104522	Komatsu Wa 1200 Front End Loader	157
10094093	2800 XPC P&H Rope Shovels	155
10079920	Haulpack 730E Statex III	152
10041582	P&H Rotary Drill	151
10129574	Atlas Copco PV351D	149
10079848	Haulpack 730E Statex III	147
10147020	Atlas Copco PV351D	144
10100224	WA 800-3 KOMATSU LOADER	143
10050776	Cat 994 H Front End Loader	141
10079098	Haulpack 730E Statex III	141
10100769	Haulpack 730E Statex III	141
10147108	Atlas Copco PV351D	141
10079326	Haulpack 730E Statex III	140
10081495	2300xpb P&H Rope Shovel	139
10079404	Haulpack 730E Statex III	137
10044057	4100 XPC P&H Rope Shovels	135
10080366	Haulpack 730E Statex III	135
10132597	Cat 994 H Front End Loader	135
10139585	Cat SKL Drill	135
10150575	2800 XPC P&H Rope Shovels	134

6.3.1.3 Risk Management Requirements in ISO 55000

Chapter 3 details the requirements concerning risk management in the ISO 55000 series. This step will therefore be universal for all organizations implementing the RMSF as part of their asset management plan. In accordance with this research, the requirements by ISO 55000 that needs to be met, encapsulate the following:

"The organization shall

- *identify actions to address risk management associated with asset management and be aware of the changes that can influence the actions,*
- *consider how these actions can be implemented and prove the effectiveness of these actions,*
- *define the risk criteria (e.g. risk matrix), and*
- *align asset risk management with the organization-wide risk management plan (e.g. business continuity and contingency plans)."*

These guidelines are critical to the development of the RMSF as it strives to aid the process of becoming ISO 55000 accredited. As mentioned in Chapter 5, for a detailed description of the ISO 55000 requirements, Chapter 3 can be referred back to. A meticulous mastery of the ISO 55000 series is also fundamental.

6.3.1.4 Current Risk Management Plan

Section 6.3.1.3 recognized that ISO 55000 requires the organization to *"align asset risk management with the organization-wide risk management plan"* and the current risk management plan already implemented in the company should primarily be supported when developing the RMSF. The organization is fully dedicated to risk management and strives to understand and respond to the key risks in the organization.

The organization has a four step risk management process that basically incorporates the following as described below:

(1) Identifying risks

(2) Analyzing risks

(3) Managing risks

(4) Monitoring risks

Furthermore, the organization classifies risks as either external or operational. This case study is only concerned with operational or internal risks and will thus only assess these risks.

As determined in previous chapters, the risk criteria comprise of three areas of concern namely *Criticality Analysis*, *Financial Risk Impact* and *Failure Analysis*. The steps in the RMSF directly relates to the risk management process already adopted by the mine. A risk matrix was also obtained that is currently used at the iron ore mine. The risk matrix is used in the *Compare* step of the RMSF.

Table 6.5 is an overview of the operational risks.

Table 6.5: Review of the operational risks as identified by them mine.

Risk	Description
Community Relations	Dispute with communities arise frequently.
Environment	Mining operations are known to prompt environmental risks by means of dust, noise, tailing dam breaches and the leaking of harmful substances.
Event Risk	Certain operations are located in areas with exposure to extreme weather conditions. The mining industry is also notorious for asset damage due to fire, explosions or breakdown of critical machinery.
Infrastructure	Not being able to receive supporting facilities, services and installations is a great risk. These include electricity and water supply.
Operational Risk and Project Delivery	Failing to meet targets associated with production, project delivery dates and budgets.
Safety and Health	Mining is a hazardous industry and health and safety is generally priority number one. Employees can be harmed excessively if safety management is not focused on.
Employees	Due to the nature of mining in remote places, gaining skilled employees is a challenge.

6.3.2 Criticality Analysis

In Chapter 5, the evaluation of the different quantitative methods available to determine the critical assets in an organization showed that the RPN is the superior method. During the research in Chapter 4, RPN based on Fuzzy Logic was introduced. This method was proven to be more accurate and to provide a broader picture of the risk involved than the traditional RPN calculations. The case study conducted in this chapter thus makes use of the RPN based on Fuzzy Logic.

As mentioned, the RPN is calculated by using the probability of failure (O), the severity of failure (S) and the probability of not detecting failure (D) to determine a Z-value. The ratings assigned to each of these risk factors is based on the seven point scale as used for the Fuzzy Logic RPN as well as the available data for this specific mine and are identified as follows:

Probability or Frequency of Failure (O) – Number of WOs identified as Corrective Maintenance associated with the asset.

Severity of Failure (S) – Total accumulated cost spent on WOs associated with the asset.

Probability of Not Detecting Failure (D) – Number of WOs identified as Predictive and Proactive Maintenance associated with the asset.

A seven point scale is used to evaluate the risk factors. Thus, it is possible to determine three values (O, S and D) for each of the assets and construct tables for each. Each of the different classifications was chosen according to the data available.

Probability of Failure

The probability of failure is the number of WOs associated with the asset based on Corrective Maintenance. The different classes were determined by calculating the average and standard deviation of the corrective maintenance of the top 50 assets:

Average = 190.86

Standard Deviation = 80.187

These calculations enabled the identification of the bottom value of each of the classes as follows:

Very High 7: Average + 1.5 Standard Deviations

Very High 6: Average + 1 Standard Deviation

High 5: Average + 0.5 Standard Deviations

High 4: Average

Moderate 3: Average - 0.5 Standard Deviations

Low 2: Average - 1 Standard Deviation

Very Low 1: 0

Thus, for the *Moderate* category, the bottom value will be rounded to 150 and for the *High 4* category, the bottom value will be rounded to 190. An asset will then receive a rating of 3 if the WOs associated with it lies between 150 and 190. Table 6.6 shows the final ratings.

TABLE 6.6: Ratings for probability of failure.

Probability of Failure	Number of WOs	Rank
Very High	> 311	7
Very High	> 271 and < 311	6
High	> 230 and < 271	5
High	> 190 and < 230	4
Moderate	> 150 and < 190	3
Low	> 110 and < 150	2
Very Low	< 110	1

Severity of Failure

The severity of failure is based on the median of the data rather than the average. The reason being that specific assets are associated with extremely high costs and influenced the average. Therefore, the ratings are chosen as seen in Table 6.7.

TABLE 6.7: Ratings for severity of failure.

Severity of Failure	Total Accumulated Cost('000)	Rank
Extreme	> 3000	7
Extreme	> 2500 and < 3000	6
High	> 2000 and < 2500	5
High	> 1500 and < 2000	4
Moderate	> 1000 and < 1500	3
Low	> 500 and < 1000	2
Very Low	< 500	1

Probability of Not Detecting Failure

Probability of not detecting failure is the number of WOs accounted to predictive and proactive maintenance for each of the top 50 assets. Once again the average and standard deviation of the data is important and used to determine the ratings:

$$\text{Average} = 19.551$$

$$\text{Standard Deviation} = 13.982$$

These calculations enabled the identification of the bottom value of each of the classes as follows:

Very Low 7: 0

Very Low 6: 3

Low 5: Average - Standard Deviations

Low 4: Standard Deviation

Moderate 3: Average

High 2: Average + 1 Standard Deviation

Very High 1: Average + 2 Standard Deviations

Thus, for *High*, the bottom value will be rounded to 33 and for *Very High*, the bottom value will be rounded to 49. An asset will then receive a rating of 2 if the WOs associated with it lies between 33 and 49.

Table 6.8 shows the final ratings for the probability of not detecting the failure.

TABLE 6.8: Ratings for probability of not detecting failure.

Probability of Not Detecting Failure	Number of WOs	Rank
Very Low	< 3	7
Very Low	> 3 and < 5	6
Low	> 5 and < 13	5
Low	> 13 and < 19	4
Moderate	> 19 and < 33	3
High	> 33 and < 47	2
Very High	> 47	1

After careful analysis of the top 50 assets, Fuzzy Logic based RPN and traditional RPN are calculated and compared in Table 6.9. Here, the traditional RPN and the calculated Z-value is shown together with the ranking of each. After comparison, it was decided to continue use of the Fuzzy Logic inspired RPN calculations. The RPN based on Fuzzy Logic provides a better overall view of the risk associated with each asset as it takes more variables into consideration than the traditional RPN as determined in Chapter 4.

TABLE 6.9: Comparing the traditional RPN and Z-value.

Ranking	**Asset**	S	O	D	**RPN**	**Z-value**	**Z-value Ranking**
1	10124067	7	7	3	147	5.5	8
2	10053756	7	6	3	126	5.5	6
3	10119090	7	5	3	105	5.5	7
4	10151123	7	7	2	98	6.5	4
5	10151163	7	6	2	84	6.5	5
6	10080067	5	3	5	75	4.0581	14
7	10115248	5	5	3	75	5	10
8	10119134	7	5	2	70	5.4576	9
9	10129614	7	3	3	63	5	11
10	10145724	5	4	3	60	5	12
11	10124110	7	7	1	49	6.5	2
12	10140410	7	7	1	49	6.5	3
13	10060074	4	3	3	36	4.5	13
14	10100838	2	3	6	36	2.5	41
15	10112816	2	3	6	36	2.5	43
16	10115346	3	3	4	36	3.5	22
17	10065636	7	5	1	35	6.5	1
18	10050776	5	2	3	30	4	16
19	10069971	2	3	5	30	3.0581	25
20	10079920	2	3	5	30	3.0581	27
21	10094093	2	3	5	30	3.0581	28
22	10033624	3	3	3	27	4	15
23	10129471	3	3	3	27	4	17
24	10150091	3	3	3	27	4	19
25	10079848	3	2	4	24	3.0581	26
26	10104522	2	3	4	24	3.0581	29
27	10146939	2	3	4	24	3.0581	30
28	10147020	4	2	3	24	4	18
29	10081134	1	3	7	21	2.5	39
30	10080366	2	2	5	20	2.5	38
31	10098747	1	3	6	18	2.5	40
32	10132597	3	2	3	18	3.5	23
33	10129574	2	2	4	16	2.5	45
34	10147108	2	2	4	16	2.5	48
35	10043990	1	3	5	15	2.5	36
36	10079699	1	3	5	15	2.5	37
37	10112745	1	3	5	15	2.5	42
38	10112889	1	3	5	15	2.5	44
39	10131236	1	3	5	15	2.5	46
40	10131452	1	3	5	15	2.5	47
41	10079326	1	2	7	14	1.5	49
42	10100769	1	2	7	14	1.5	50
43	10044057	1	2	5	10	2.5424	31
44	10079098	1	2	5	10	2.5424	32
45	10081495	1	2	5	10	2.5424	33
46	10100224	1	2	5	10	2.5424	34
47	10150575	1	2	5	10	2.5424	35
48	10041582	1	3	3	9	3.5	20
49	10139585	2	2	2	8	3.5	24
50	10079404	1	2	0	0	3.5	21

Five categories were recognized in Chapter 5 namely *Critical*, *High*, *Moderate*, *Low* and *Negligible*. Assets are then grouped according to the following criteria:

Critical – Z-value > 5

High – Z-value > 4

Moderate – Z-value > 3

Low – Z-value > 2

Negligible – Z-value > 0

Finally, the ranking of the critical assets according to the Z-value can be seen in Table 6.10.

TABLE 6.10: Ranking of assets according to Fuzzy Logic based RPN .

Asset Risk Classification	Z-value	Asset Number	Asset Description
Critical	6.5	10065636	Le Tourneau L2350
	6.5	10124110	Liebherr R996 Litronic Hydraulic Shovel
	6.5	10140410	PC 8000 -6 Komatso Hydraulic Shovel
	6.5	10151123	R 996 LIEBHERR
	6.5	10151163	R 996 LIEBHERR
	5.5	10053756	R 9800 LIEBHERR
	5.5	10119090	R 996 LIEBHERR
	5.5	10124067	Liebherr R996 Litronic Hydraulic Shovel
	5.4576	10119134	R 996 LIEBHERR
	5	10115248	Atlas Copco PV351D
	5	10129614	Atlas Copco PV351D
	5	10145724	Komatsu Wa 1200 Front End Loader
High	4.5	10060074	Komatsu Wa 1200 Front End Loader
	4.0581	10080067	Haulpack 730E Statex III
	4	10033624	Komatsu Wa 1200 Front End Loader
	4	10050776	Cat 994 H Front End Loader
	4	10129471	Atlas Copco PV351D
	4	10147020	Atlas Copco PV351D
	4	10150091	Cat 994 H Front End Loader
Moderate	3.5	10041582	P&H Rotary Drill
	3.5	10079404	Haulpack 730E Statex III
	3.5	10115346	Atlas Copco PV351D
	3.5	10132597	Cat 994 H Front End Loader
	3.5	10139585	Cat SKL Drill
	3.0581	10069971	4100 XPC P&H Rope Shovels
	3.0581	10079848	Haulpack 730E Statex III
	3.0581	10079920	Haulpack 730E Statex III
	3.0581	10094093	2800 XPC P&H Rope Shovels
	3.0581	10104522	Komatsu Wa 1200 Front End Loader
	3.0581	10146939	Atlas Copco PV351D
Low	2.5424	10044057	4100 XPC P&H Rope Shovels
	2.5424	10079098	Haulpack 730E Statex III
	2.5424	10081495	2300xpb P&H Rope Shovel
	2.5424	10100224	WA 800-3 KOMATSU LOADER
	2.5424	10150575	2800 XPC P&H Rope Shovels
	2.5	10043990	4100 XPC P&H Rope Shovels
	2.5	10079699	Haulpack 730E Statex III
	2.5	10080366	Haulpack 730E Statex III
	2.5	10081134	2300xpb P&H Rope Shovel
	2.5	10098747	Haulpack 730E Statex III
	2.5	10100838	Haulpack 730E Statex III
	2.5	10112745	Cat Haultruck
	2.5	10112816	Cat Haultruck
	2.5	10112889	Cat Haultruck
	2.5	10129574	Atlas Copco PV351D
	2.5	10131236	Cat Haultruck
	2.5	10131452	Cat Haultruck
	2.5	10147108	Atlas Copco PV351D
Negligible	1.5	10079326	Haulpack 730E Statex III
	1.5	10100769	Haulpack 730E Statex III

As per the RMSF, only the *Critical*, *High* and *Moderate* rated assets are focused on and put under evaluation in terms of *Financial Risk Impact* and *Failure Analysis*.

6.3.3 Financial Risk Impact

The *Financial Risk Impact* analysis is a challenge in terms of the data received. All costs related to each of the assets and their respective WOs are available, but the monetary benefits were not documented. This lack of data resulted in the fact that it is impossible to calculate NPV for each of the assets and conduct a Cost Benefit Analysis. Further analysis and questioning could provide the information, but for the current case study, a benefit-cost ratio will suffice.

The organization classified each work order with a Work Type Code and Maintenance Activity Type (MAT) as seen in Figure 6.1 and 6.2. As the research is primarily focused on physical asset management and improving maintenance techniques, it was decided to classify corrective maintenance as a cost and preventive and predictive maintenance as a benefit. Through careful analysis, it was determined that preventive and predictive maintenance is beneficial in the long run and would result in money saved and therefore is seen as a benefit. A Benefit-Cost Ratio (BCR) is then calculated with Equation 6.3.1.

$$BCR = \frac{Total\ Accumulated\ Costs_{\text{benefits}}}{Total\ Accumulated\ Costs_{\text{costs}}} \tag{6.3.1}$$

where

$Total\ Accumulated\ Costs_{\text{costs}}$ = total accumulated costs associated with assets listed as corrective maintenance.

$Total\ Accumulated\ Costs_{\text{benefits}}$ = total accumulated costs associated with assets listed as preventive and predictive maintenance.

The analysis was done according to the MAT. All WOs listed as 001, 002 and 003 are grouped under Corrective Maintenance and all WOs associated with MAT 004, 005, 006, 007 and 008 are identified as proactive maintenance.

Table 6.11 shows the calculated BCR values of each of the assets and Figure 6.2 shows the graphical representation of the calculated BCR values.

TABLE 6.11: Calculating the BCR.

Asset Criticality	Ranking	Asset	BCR
Critical	1	10065636	0.102
	2	10124110	0.184
	3	10140410	0.075
	4	10151123	0.078
	5	10151163	0.046
	6	10053756	0.172
	7	10119090	0.083
	8	10124067	0.033
	9	10119134	0.067
	10	10115248	0.097
	11	10129614	0.157
	12	10145724	0.494
High	13	10060074	0.133
	14	10080067	0.098
	15	10033624	0.445
	16	10050776	0.335
	17	10129471	0.057
	18	10147020	0.195
	19	10150091	0.232
Moderate	20	10041582	0.408
	21	10079404	0.000
	22	10115346	0.068
	23	10132597	0.601
	24	10139585	0.031
	25	10069971	0.535
	26	10079848	0.170
	27	10079920	0.216
	28	10094093	0.336
	29	10104522	0.014
	30	10146939	0.122

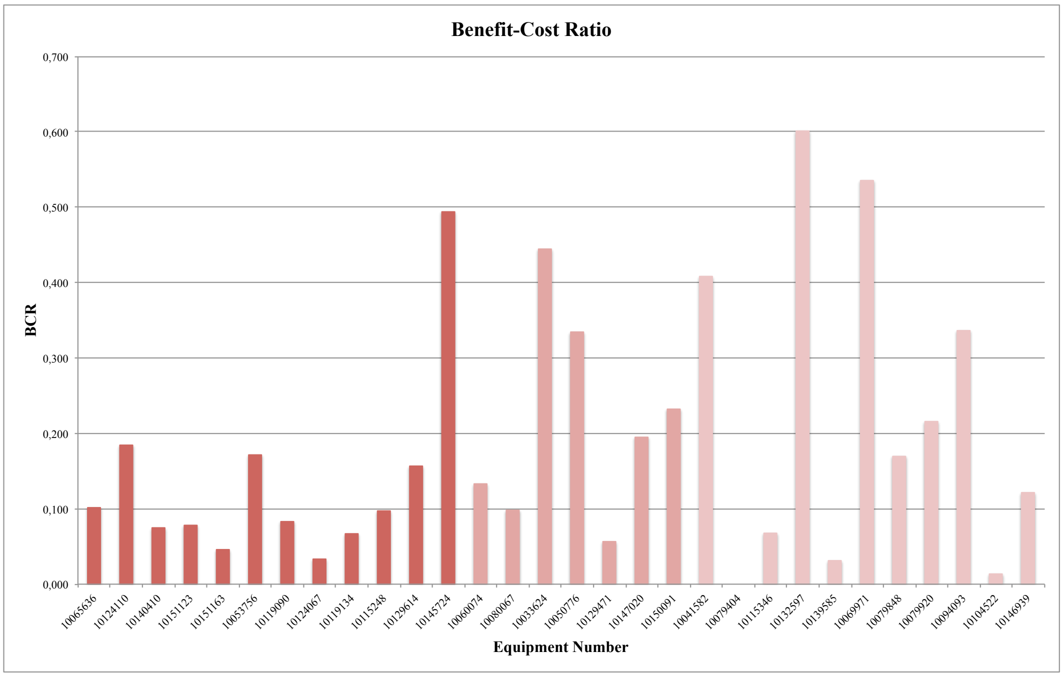


FIGURE 6.2: Calculated BCR of *Critical*, *High* and *Moderate* rated assets.

The BCR calculations shows that all the assets have a value below 1 meaning that the costs associated with corrective maintenance is higher. The mine should investigate the discrepancy and introduce further preventive and predictive maintenance techniques to improve the maintenance and asset management of the organization.

6.3.4 Failure Analysis

Failure Analysis is determining when an asset will fail as described in Chapter 5. The method most appropriate for this case study is MTBF. Although numerous literature has shown that MFOP is the superior method, it has not been intensely adopted by the mining industry and thus it should be considered for future improvements in the RMSF. The RMSF also states that if the Scale and Shape parameters as well as the surviving units of time are not available, MTBF is the natural option. Which is also true in this case. As the *Start Date* of each Work Order was included in the data, this was used to calculate the MTBF. Only the *Critical*, *High* and *Moderate* ranked assets were used for the Failure Analysis step. Table 6.12 shows the MTBF calculated for each of these assets. Figure 6.3 is the graphical representation of Table 6.12.

Table 6.12: Calculating the MTBF.

Asset Criticality	Ranking	Asset	MTBF
Critical	1	10065636	1.494
	2	10124110	0.927
	3	10140410	0.696
	4	10151123	0.953
	5	10151163	1.275
	6	10053756	1.348
	7	10119090	1.454
	8	10124067	1.028
	9	10119134	1.488
	10	10115248	1.562
	11	10129614	2.085
	12	10145724	1.690
High	13	10060074	2.212
	14	10080067	2.204
	15	10033624	2.128
	16	10050776	2.532
	17	10129471	2.134
	18	10147020	2.549
	19	10150091	2.078
Moderate	20	10041582	2.457
	21	10079404	2.664
	22	10115346	2.005
	23	10132597	2.763
	24	10139585	2.719
	25	10069971	1.973
	26	10079848	2.524
	27	10079920	2.408
	28	10094093	2.303
	29	10104522	2.331
	30	10146939	2.170

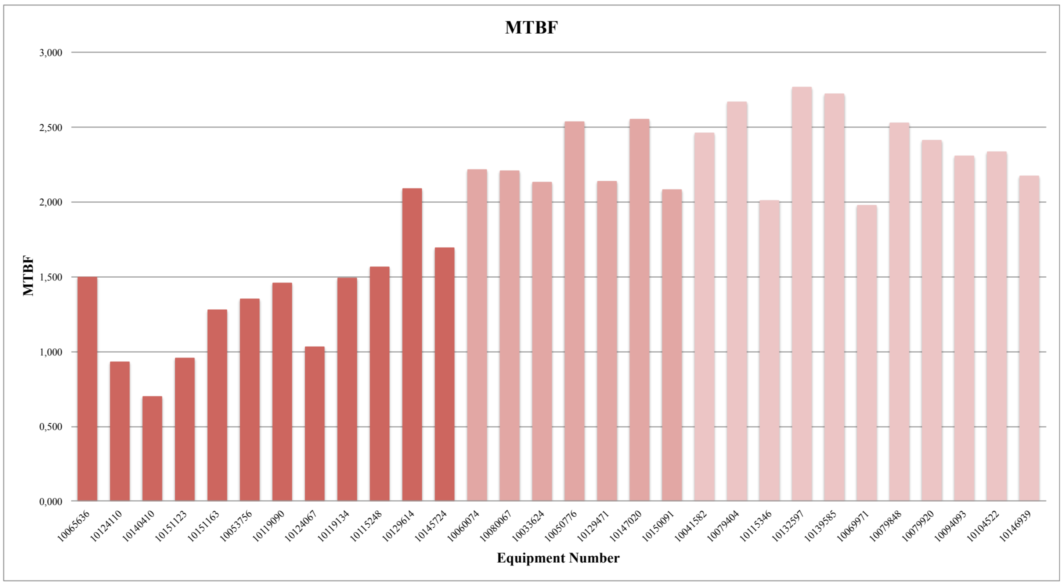


FIGURE 6.3: Calculated MTBF of *Critical*, *High* and *Moderate* rated assets.

It once again confirms the criticality of the assets identified. 11 of the 12 assets defined as *Critical* are once again on top with the lowest MTBF.

6.3.5 Comparison

The mine uses a basic risk matrix for determining the risk involved. The matrix is divided into seven areas of concern:

(1) Financial

(2) Safety (Harm to People)

(3) Occupational Health

(4) Environment

(5) Legal and Regulatory

(6) Social/Communities

(7) Reputation

Each area is associate with one of five severity rankings; Insignificant, Minor, Moderate, High and Major. Furthermore, the matrix helps determine the likelihood of a risk event occurring. These two values give a risk rating of Medium, Low, Significant or High.

The risk management matrix is not exclusively focused on the assets, but rather on risk events across the entire organization. Thus, a direct comparison with the RMSF is impossible. There is also no mention of any quantitative methods, but it is assumed that basic quantitative methods are used for, example the financial area of concern reads:

"Less than 1% loss of budgeted operating profit and listed assets."

Although there is not an existing risk management plan related to asset management, it is undeniable that there are some similarities between the traditional risk matrix and the RMSF:

– Both are focused on the financial aspects of risk management.

– Both uses numerical ratings to determine the degree of the risk.

Nonetheless, there are a vast number of differences between the two:

– No quantitative methods are explicitly mentioned in the original risk management matrix.

– The RMSF is focused on physical assets whereas the original risk management matrix is focused on risk in general.

– Health, Safety and Environmental Risk Impact was considered as an integral part of risk management for the RMSF, but after the research was done and through thoughtful consideration, it was decided that it is a much deeper field that should stand on its own. Therefore, it goes beyond the scope of this thesis.

– The traditional risk matrix is predominantly focused on health and safety.

– No specific attention is placed on the ISO 55000 requirements in the traditional risk matrix.

The fact that there is no risk management process with respect to the physical assets, makes it difficult to draw a complete comparison. Thus, any process implementation will most likely be an improvement in this regard.

6.3.6 Output

Concluding the process of applying the RMSF framework to the data received from the mine, final interpretations can be made to evaluate the results.

Criticality Analysis

The *Criticality Analysis* is the first step of *Risk Criteria*. Primarily, the Criticality Analysis exists to determine which assets are redeemed as critical in terms of

– probability or frequency of failure;

– severity of failure; and

– probability of not detecting failure.

A value between one and seven is assigned to each of the criteria for the top 50 critical assets as determined by the mine in a previous study. The values can be seen in Table 6.9 together with the calculations of the traditional RPN values. Using Fuzzy Logic RPN methods, the Z-value for each of the assets are calculated and ranked from high to low in Table 6.10. Furthermore, the assets are ranked as *Critical*, *High*, *Moderate*, *Low* and *Negligible* to indicate the risk ranking. Concluding the Criticality Analysis, 12 assets are labelled as *Critical*, seven assets are labelled as *High* and 11 assets as *Moderate*. These assets will be considered as the most important assets regarding risk management and will be scrutinized during the *Financial Risk Impact* phase and the *Failure Analysis* phase.

Financial Risk Impact

For the Financial Risk Impact part of the RMSF, the Benefit -Cost Ratio (BCR) was calculated for the *Critical*, *High* and *Moderate* rated assets (according to the RPN). In this case study all asset ratios are below 1, meaning that the costs outweighs the benefits. This shows that the organization is spending more money on corrective maintenance than preventive and predictive. Thus, it is important for the mine to pay attention to the over use of corrective maintenance and if some of these activities can be reduced by improving the PAM program and introducing more preventive maintenance techniques.

Specific assets should be considered in terms of the maintenance associated with it. Asset numbers 10080067 and 10129471 are rated as *High* by the RPN calculation, but show a BCR below 0.1. This also applies to asset numbers 10079404, 10115346, 10139585 and 10104522 rated as *Moderate*. Although these assets are rated as less critical, they should be reviewed as part of the costs associated to the maintenance activity type.

Failure Analysis

The MTBF associated with each of the assets are relatively on a par with the criticality of the asset as determined by the RPN. Figure 6.3 shows a steady increase in MTBF from *Critical* to *Moderate*. However, Asset 10115346 and 10069971 should be inspected as both of them have a lower MTBF than the rest of the assets in the *Moderate* range. Also, Asset 10129614 does not have such a low MTBF causing concern as with the other assets in the *Critical* range.

6.4 Results

The case study conducted in this chapter, enabled the validation of the RMSF. A real world problem with actually data from a mine proved the authenticity of the research conducted as well as the value of the RMSF. Conclusively, research objective nine and ten are accomplished. Table 6.13 shows *Before* and *After* the implementation of the RMSF.

TABLE 6.13: Comparison of *Before* and *After* the implementation of the RMSF.

Before the RMSF	**After the RMSF**
Critical assets identified according to the number of Corrective Maintenance WOs associated with each.	Critical assets identified according to Fuzzy Logic RPN with a parameter number of Corrective Maintenance WOs, total accumulative cost spent on WOs and number of Predictive/Proactive Maintenance WOs.
Assets only identified by criticality.	Assets identified by criticality, financial risk impact and failure analysis.
No risk management plan implemented associated with assets.	A proper Risk Management Solutions Flow.
No reference to quantitative methods regarding PAM and the risk management of assets.	Guidance for implementing quantitative methods regarding identification of critical assets, financial risk impact and failure analysis.
No specific focus on the ISO 55000 series.	Introduction to ISO 5500 and initiating the road to accreditation.
Very basic risk matrix.	Deeper analysis of risk management.

Concluding the case study, the validation of the RMSF is proven by means of the application of the framework to actual data from an existing mine. The *Before* and *After* table (Table 6.13), adds to the validity of the RMSF by showing a definitive improvement in a variety of aspects regarding risk management through quantitative methods for ISO 55000 and asset management.

6.5 Chapter Summary

Chapter 6 is the application of the Risk Management Solutions Flow (RMSF), designed and developed in Chapter 5, to a real world situation with actual data acquired from an iron ore mine. The research case study required the commitment of the research partners and the gathering of appropriate data. In regards to the initial introduction of the RMSF to the research partners, various modifications were suggested and implemented if seen as valuable to the case study and the RMSF.

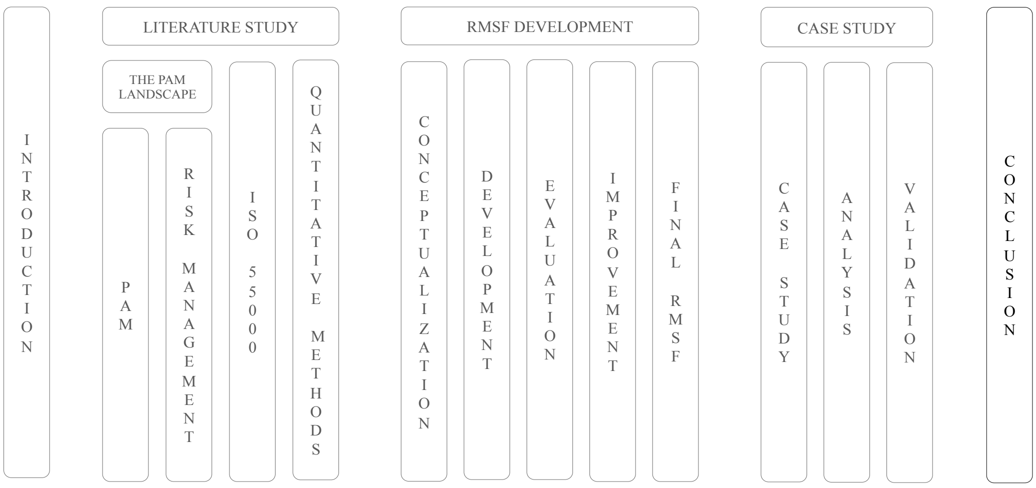
A brief background of the organization is provided in this chapter along with specification of the mine used for the case study. The case study is then conducted according to the sequence of events in the RMSF. Analyzing the data provided, brought up important information that can be used as the organization improves their asset management process and initiates the move towards ISO 55000 accreditation. The RMSF is thus a valuable framework for adhering to the quantitative requirements of ISO 55000.

Chapter 7

Conclusion

Chapter Aim:

Chapter 7 aims to consolidate the research findings into a final verdict. The limitations of the study, in addition to future research recommendations in the field of PAM and ISO 550000 are covered. Expansion of the RMSF is also appraised.



Chapter Outcomes:

- Limitations to the study.
- Future research recommendations.
- Expansion of the RMSF.
- Solution to the core problem statement.
- Final closure.

7.1 Limitations

The study of applying quantitative methods to risk management in the PAM environment primarily focused on the requirements stated in ISO 55000, is receptive to several limitations. The limitations are listed as follows:

(1) The study is limited by the data set obtained. Insufficient data prevented the RMSF to expand certain steps in the process such as calculating the MFOP and calculating the NPV. This however, did not prevent the validation of the RMSF or the value of the case study.

(2) The flow of the RMSF and the sequence of events eliminated certain assets during the *Criticality Analysis* that needed further analysis and be responsible for a higher risk than originally determined.

(3) ISO 55000 was officially launched about two years ago and the novelty of this document means that many organizations are not aware of the content and implications of the series.

(4) The person responsible for conducting the RMSF process needs a basic knowledge of the quantitative methods and the assets being evaluated. If this person has no knowledge about these two important factors, the RMSF may become inconsistent and unreliable.

(5) Another critical part of the RMSF is that the process is continuous. Thus, the RMSF should be repeated regularly to keep the output generated from the RMSF up to date. Data required for the RMSF should be kept contemporary to adhere to the requirements of the RMSF.

Finalizing the limitations of the study leads to the final closure of the thesis. The following section surmises the research and advances towards a conclusion.

7.2 Closure

Chapter 1 introduced the research domain and summarized the problem statement of this thesis. The various elements that are core values to this research are raised. These include the PAM environment, PAS 55, ISO 55000, traditional maintenance techniques and risk management. Providing a rigorous context to the research, enables Chapter 1 to diverge in to the problem regarding the need for quantitative methods in ISO 55000 with the focus on risk management. A list of research objectives is provided and the chapter concludes with a project roadmap and the methodologies used throughout the research process.

The literature review is proliferated across Chapter 2, Chapter 3 and Chapter 4. Each chapter approaches a singular theme that is fundamental to the growth of the thesis. Chapter 2 dives into the PAM landscape and focus on the move from traditional maintenance techniques to asset management and life cycle management.

The focus is placed on risk management and as an added benefit, the ISO 31000 series is scrutinized. Table 2.1 is fundamental to the research and compares the different areas that are important in PAM, ISO 55000, PAS 55, the research in general and for quantitative methods. The most important areas are identified and discussed in more detail.

Chapter 3 is a concise study of the ISO 55000 series. All three of the ISO 55000 documents are analyzed and summarized to give the reader an overview of ISO 55000. Risk management and quantitative requirements in ISO 55000 are emphasized and the most valuable areas are further contemplated. Concluding the literature review, a thorough investigation into the different quantitative methods is brought together in Chapter 4. The methods are classified according to the critical areas as identified in previous chapters: *Criticality Analysis*, *Financial Impact* and *Failure Analysis*.

Developing the Risk Management Solutions Flow (RMSF) in full, forms Chapter 5. Conceptualization of the RMSF commences the chapter and the structure follows the flow of the RMSF. The final RMSF framework is determined and displayed in Figure 5.2 and 5.3 (or Appendix 2). The detailed version of the RMSF is revealed in Figure 5.4 and 5.5 (or Appendix 3).

A case study is conducted in Chapter 6 and applies the constructed RMSF to the identified mine. The developed RMSF framework was executed successfully as part of the case study on the data acquired from the mine. The RMSF adheres to the main objective of the research as mentioned numerous time throughout the research:

> *"The goal is to introduce organizations to the newly launched ISO 55000 series and start the process of becoming accredited."*

The RMSF provides a framework or solutions flow that focus on risk management and PAM by introducing quantitative methods to initiated the process of becoming ISO 55000 compliant. Quantitative methods used are easy to understand and quick to implement. The RMSF is also user friendly and the ready-to-use versions of the framework are practical and elegant. However, it is necessary to mention that the RMSF was not applied to industries beyond the mining industry, but due to the generic nature of the RMSF, it is assumed that complications would be few once a different industry is subjected to the RMSF.

All eleven objectives listed in Table 1.1 have been addressed and met throughout the research of which ten have been achieved in Chapter 2 to Chapter 6. Finally, the last research objective is attained in this chapter. Throughout the progression of the research, the eleven research objectives were accomplished leading to a comprehensive solution to the research problem. The thesis comes to a final conclusion with recommendation for future research in the last section.

7.3 Future Research

During the research process certain aspects were revealed that may require further investigation. The recommendations for future research opportunities includes:

(1) The most notable design improvement is one that was initially included in the preliminary design of the RMSF. *Health, Safety and Environmental Impact* was identified as one of the primary areas of concern in regards to risk management, PAM and the ISO 55000 series. After thoughtful consideration, it was excluded from the research as it was determined to be a very broad field. Expanding the RMSF to include the *Health, Safety and Environmental Impact* of the assets could improve the process of evaluating the risk related to specific assets.

(2) The RMSF is designed for a variety of organization types. Over time it will be beneficial to apply the RMSF to a broader range of industries to see how the focus differs from the mining industry.

(3) Throughout the research, it was determined that employees or people related to the organization, can be viewed as an asset. Modifying the RMSF to apply it to people can provide a valuable contribution to the field of asset management. Managing people is a significant problem in PAM and they propose a great risk to any organization.

(4) Currently, this research only introduces the concept of becoming ISO 55000 accredited and facilitates the adherence to specific guidelines in the series. To enable an organization to become fully accredited, focus should be placed on all areas in the ISO 55000 documents. Thus, an extensive study into the full process of becoming ISO 55000 accredited can lead to further research.

Appendices

Appendix A

Completed FMECA Worksheet

Failure Modes and Effects Criticality Analysis

Project No. 82
Subsystem:
System: Continuous Miner
Probability Interval: 25-year/Continuous use
Operational Phase: Mining

Sheet 1 **of** 2
Date: 11 September 1990
Prep. by: Yvette Nichol
Rev. by: Jean-Guy Beauvoir
Approved by: Armand Gamache

Item Function	Potential Failure Mode	Potential Effects of Failure	SEV	Potential Cause(s) of Failure	OCC	Current Controls	DET	RPN	Recommended Actions	Responsibility & Target Dates	Action Results				
											Actions Taken	SEV	OCC	DET	RPN
CMPG001 - Pressure Gage	False high reading	Catastrophic engine failure; reduction in engine life; engine wear; higher oil consumption	I	Low oil level; oil not flowing to pump; pump runs too slow; oil too hot; worn pump and/or bearings	2	None	7	14	External oil pressure measures; weekly maintenance and repair	Isabelle Lacoste - 19 March 2000	Weekly maintenance	I	1	7	7
	False low reading	Exploding or damaged oil filter; catastrophic engine failure; reduction engine life	I	Oil does not flow through oil galleries; oil thickened by soot and/or oxidation; viscosity to high; filter blocked; oil too cold	4	None	7	28	External oil pressure measures; weekly maintenance and repair	Isabelle Lacoste - 21 December 2017					

Appendix B

Risk Management Solutions Flow

The RMSF

RISK MANAGEMENT SOLUTIONS FLOW

by

wilandri basson

Risk Management Solutions Flow to Implement Quantitative Methods as Part of ISO 55000 for Physical Asset Management

ESTABLISH CONTEXT

1

1. Industry Type
2. Asset Register
3. Current Risk Management Plan
4. Requirements Regarding ISO 55000

Questions

to the organization

~ What type of industry?

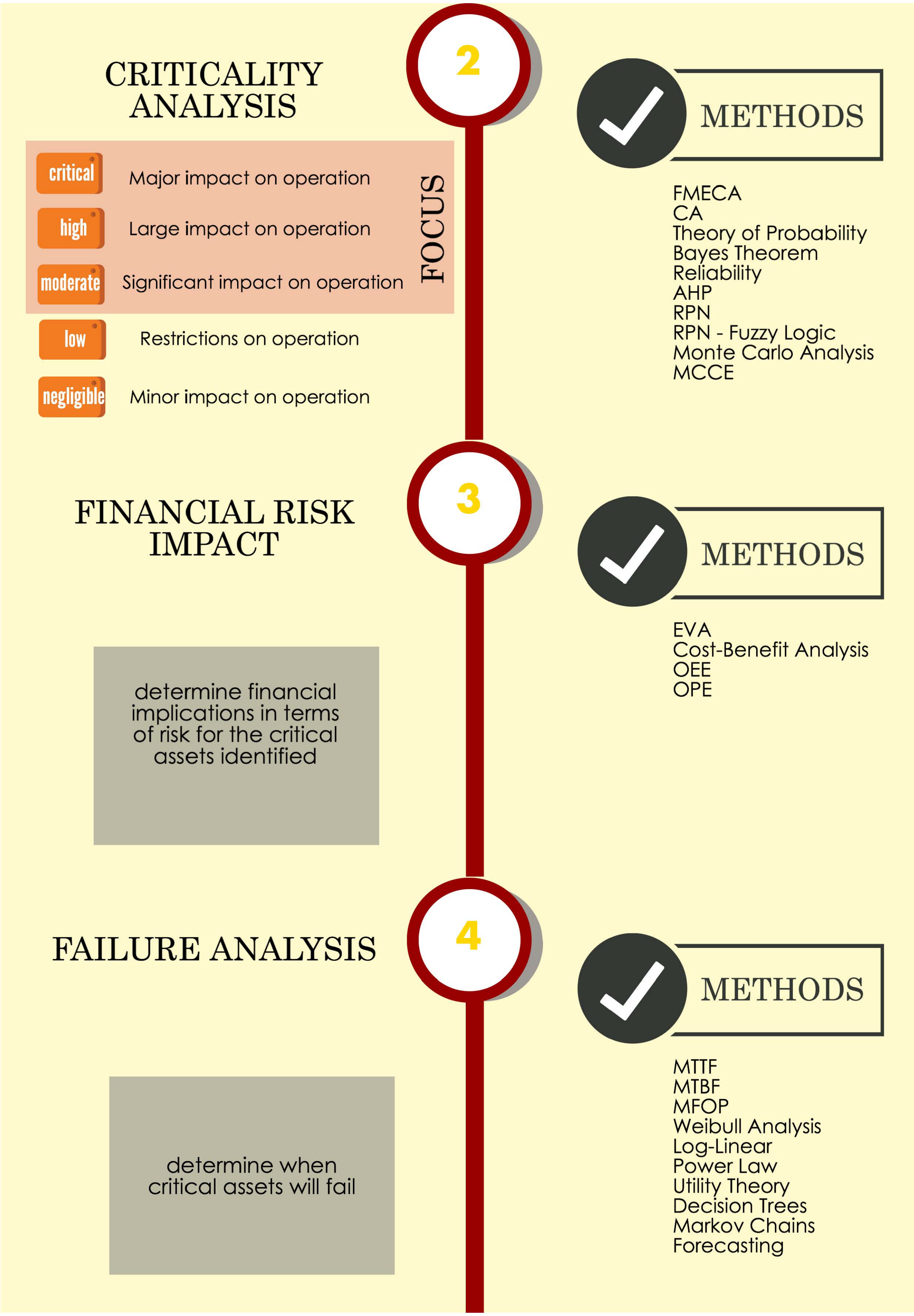
~ Is there an asset register?

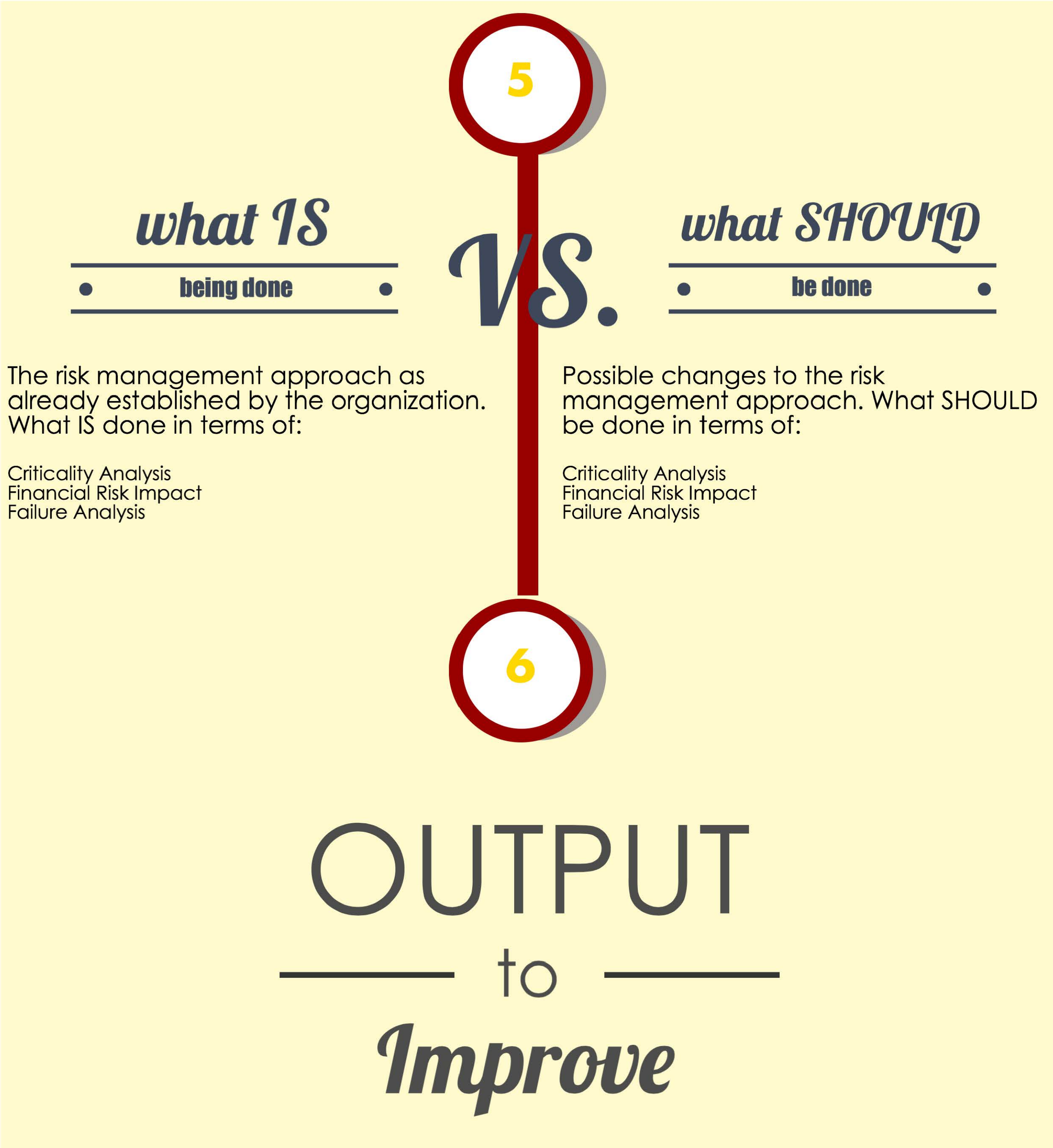
~ How complete is the register? And in what format is the asset register?

~What assets are listed and what assets are identified as important?

~ What is the risk management plan? What methods are used? Quantitative?

~ Are there any attention paid to the ISO 55000 series? Requirements in ISO 55000 established.


2
CRITICALITY ANALYSIS
critical
Major impact on operation
high
Large impact on operation
moderate
Significant impact on operation
FOCUS
low
Restrictions on operation
negligible
Minor impact on operation
METHODS
FMECA
CA
Theory of Probability
Bayes Theorem
Reliability
AHP
RPN
RPN - Fuzzy Logic
Monte Carlo Analysis
MCCE
3
FINANCIAL RISK IMPACT
determine financial implications in terms of risk for the critical assets identified
METHODS
EVA
Cost-Benefit Analysis
OEE
OPE
4
FAILURE ANALYSIS
determine when critical assets will fail
METHODS
MTTF
MTBF
MFOP
Weibull Analysis
Log-Linear
Power Law
Utility Theory
Decision Trees
Markov Chains
Forecasting


5
what IS
being done
VS.
what SHOULD
be done
The risk management approach as already established by the organization. What IS done in terms of:
Criticality Analysis
Financial Risk Impact
Failure Analysis
Possible changes to the risk management approach. What SHOULD be done in terms of:
Criticality Analysis
Financial Risk Impact
Failure Analysis
6
OUTPUT
to
Improve

Appendix C

Detailed Risk Management Solutions Flow (RMSF)

The RMSF

RISK MANAGEMENT
SOLUTIONS FLOW

by
wilandri basson

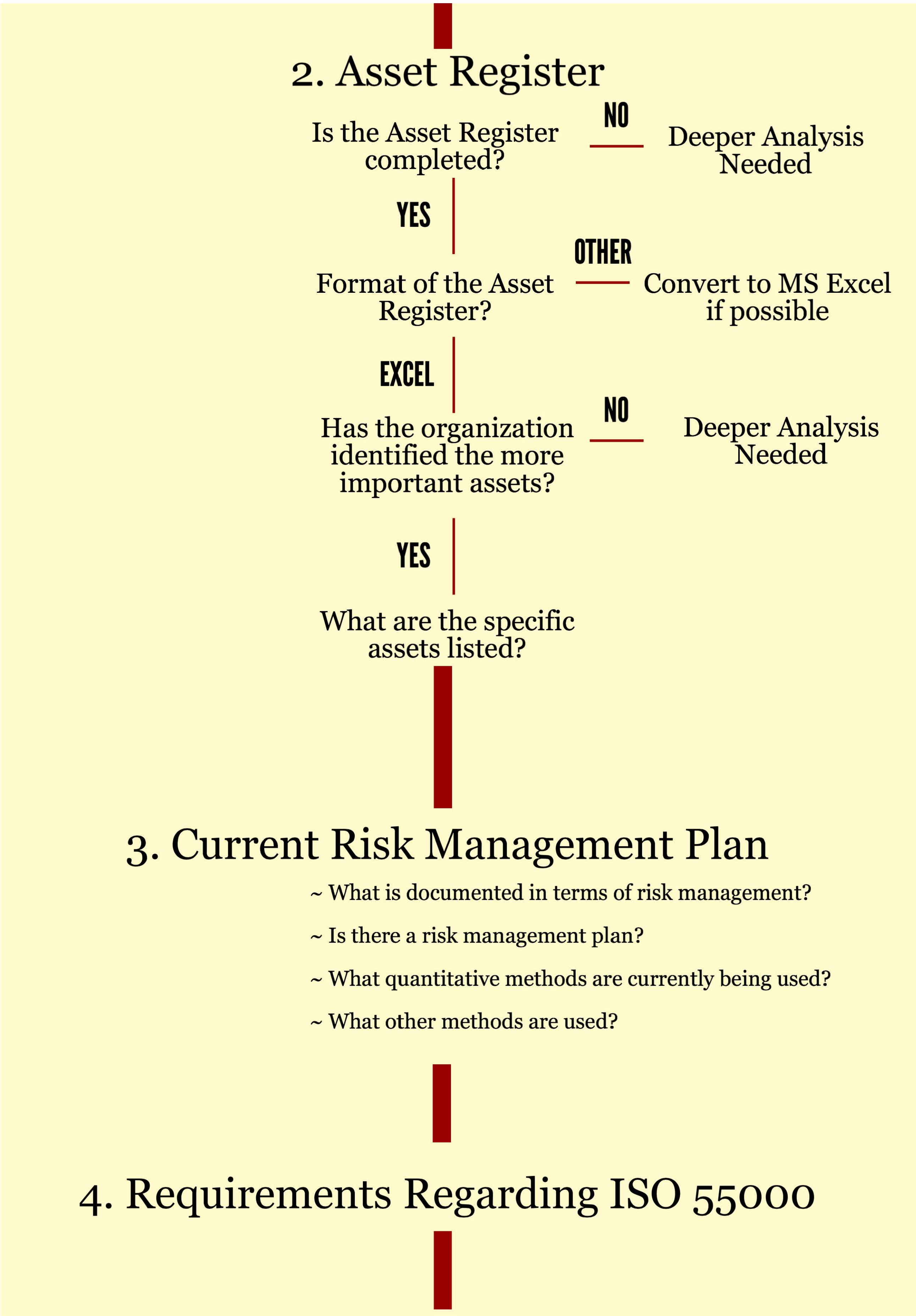
Risk Management Solutions Flow to Implement Quantitative Methods as Part of ISO 55000 for Physical Asset Management

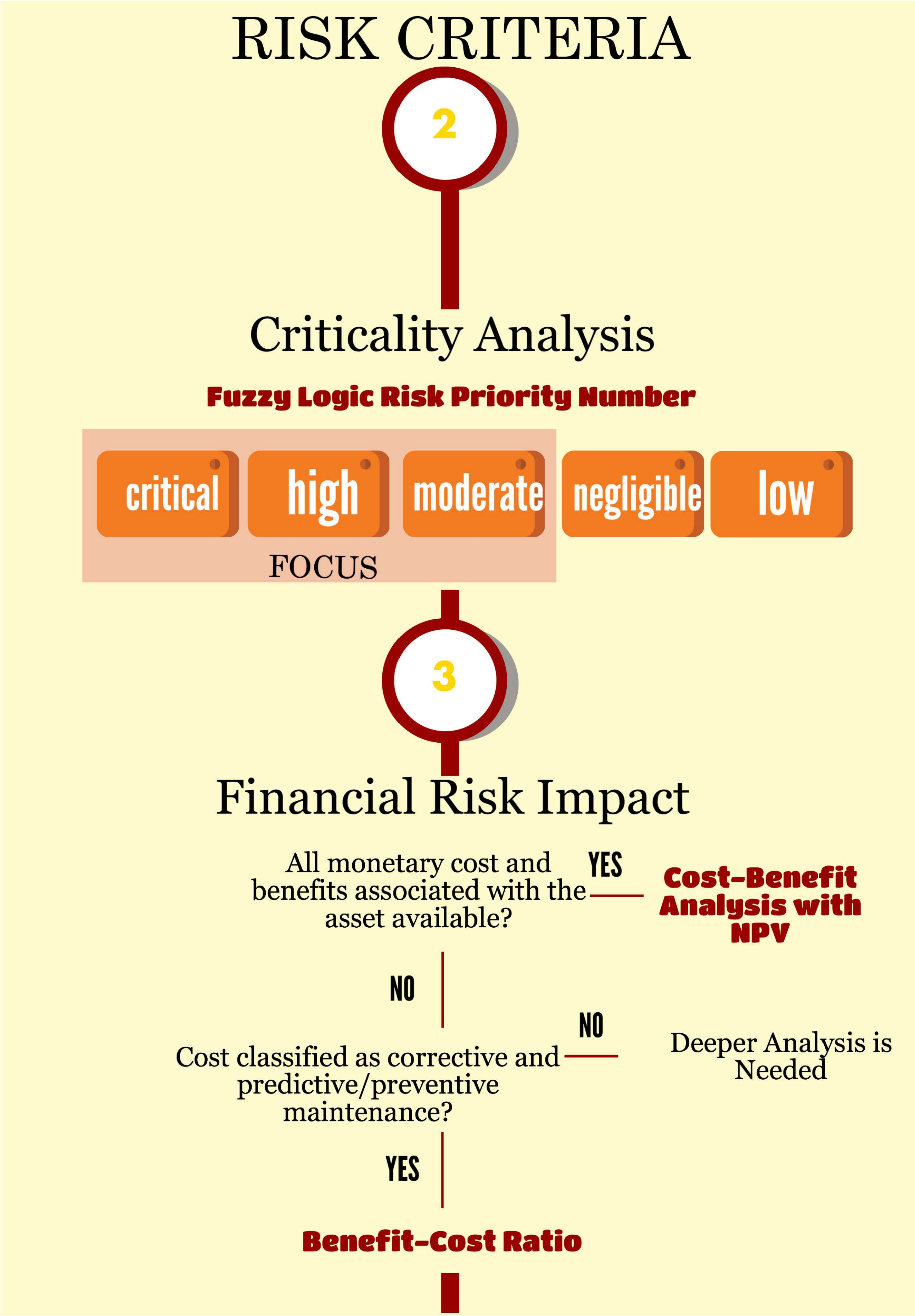
ESTABLISH CONTEXT

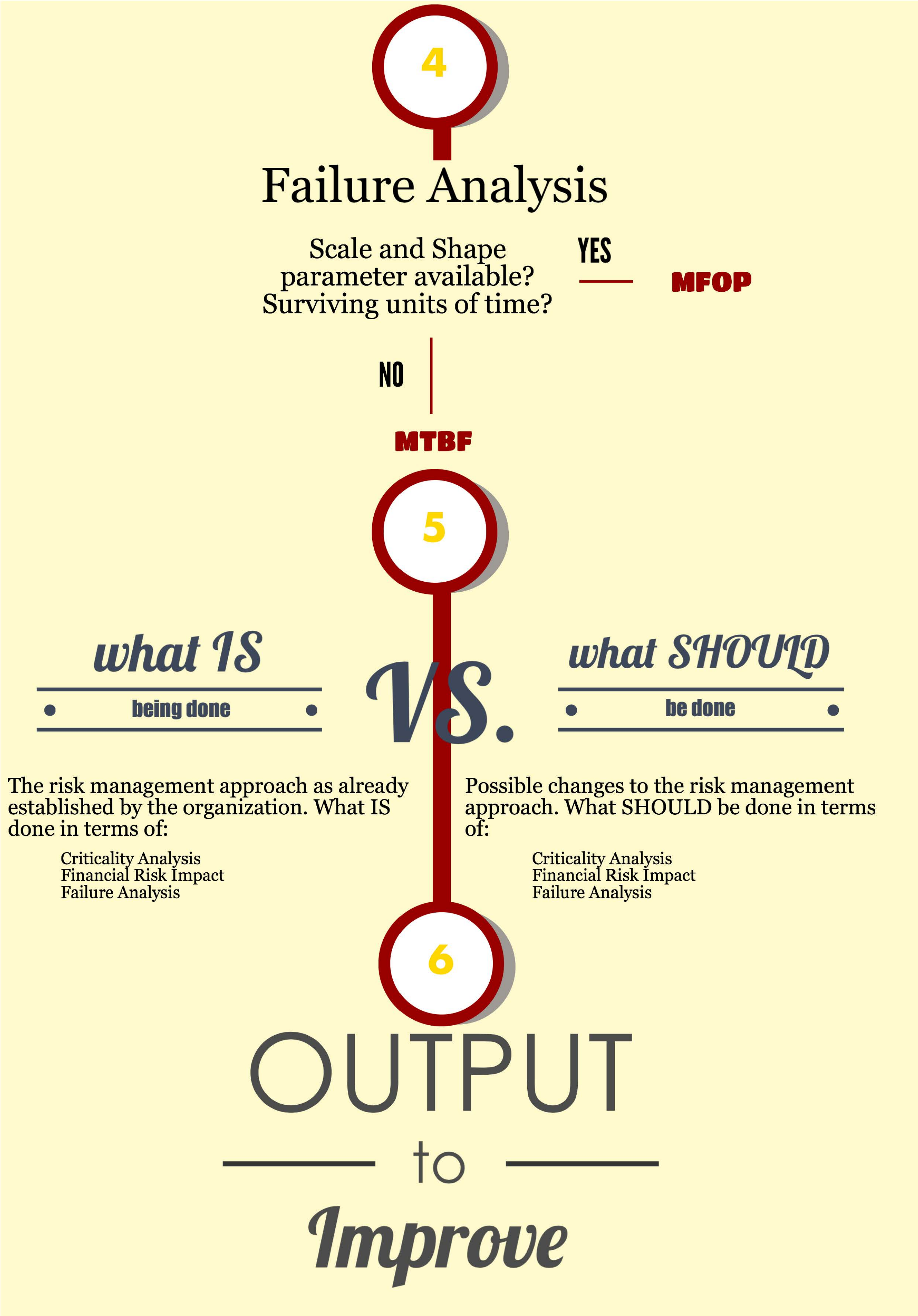
1

1. Industry Type

~ Agriculture
~ Mining
~ Energy
~ Health Care
~ Manufacturing


2. Asset Register
Is the Asset Register completed?
NO
Deeper Analysis Needed
YES
Format of the Asset Register?
OTHER
Convert to MS Excel if possible
EXCEL
Has the organization identified the more important assets?
NO
Deeper Analysis Needed
YES
What are the specific assets listed?
3. Current Risk Management Plan
~ What is documented in terms of risk management?
~ Is there a risk management plan?
~ What quantitative methods are currently being used?
~ What other methods are used?
4. Requirements Regarding ISO 55000


RISK CRITERIA
2
Criticality Analysis
Fuzzy Logic Risk Priority Number
critical
high
moderate
negligible
low
FOCUS
3
Financial Risk Impact
All monetary cost and benefits associated with the asset available?
YES
Cost-Benefit Analysis with NPV
NO
Cost classified as corrective and predictive/preventive maintenance?
NO
Deeper Analysis is Needed
YES
Benefit-Cost Ratio


4
Failure Analysis
Scale and Shape parameter available? Surviving units of time?
YES
MFOP
NO
MTBF
5
what IS
being done
VS.
what SHOULD
be done
The risk management approach as already established by the organization. What IS done in terms of:
Criticality Analysis
Financial Risk Impact
Failure Analysis
Possible changes to the risk management approach. What SHOULD be done in terms of:
Criticality Analysis
Financial Risk Impact
Failure Analysis
6
OUTPUT
to
Improve

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