Identifying and Quantifying Maintenance Improvement Opportunities in Physical Asset Management

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This thesis is dedicated to my father Giso, for always having a bright idea and a helpful suggestion, and for supporting and encouraging me along every step of my education.

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Declaration

I, the undersigned, hereby declare that the the work contained in this thesis is my own, original work and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

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Abstract

Asset Management initiatives suffer many barriers in implementation which hinder their influence and sustainability. One of these barriers is the lack of buy-in from all levels in the organisation, due to a lack of understanding of the perceived benefits of Asset Management. The relationship between throughput and the maturity of Asset Management implementation is usually felt throughout the organisation, but is difficult to prove or quantify. Furthermore, it is difficult to isolate the effects of maintenance using traditional methods.

Organisational alignment in an Asset Management project is achieved by aligning employees' views on what the deficient areas in the organisation are, and managing their expectations in what the perceived benefit of a good application of Asset Management would bring forth. However, the lack of a transparent method to convey the significance of critical areas in the system, and a clear way to communicate these problems creates a barrier in implementation. Without empirical evidence people rely on argumentative opinions to uncover problems, which tends to create friction as opinions from various factions may differ.

Typically, these initiatives are constrained by available resources, and the allocation of resources to the correct areas is thus vital. In order for Asset Management initiatives to be successful there first needs to be alignment in execution through a clear understanding of which assets are critical, so that resources can be allocated effectively.

In this study, this problem is thoroughly examined and solutions are sought in literature. A method is sought which seeks to isolate the effects of the maintenance function in an operation and uncover critical areas. A study is

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performed on methods which are typically used to create such understanding, which are shown to have shortcomings that limit their applicability. Thus a new methodology utilising simulation is created in order to overcome these problems.

The methodology is validated through a case study, where it is shown that the simulation, in the context of the methodology, is highly beneficial to uncovering critical areas and achieving organisational alignment through communication of results.

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Opsomming

Fisiese bate bestuursinitiatiewe het verskeie tekortkominge in hulle implementering wat hulle invloed en volhoubaarheid verhinder. Een van hierdie hindernisse is die tekort aan ondersteuning van alle vlakke in die organisasie, wat as gevolg van 'n gebrek aan begrip van die voordele van bate bestuur voorkom. Die verhouding tussen die volwassenheid van batebestuur en produksie deurset word gewoonlik reg deur die organisasie gevoel, maar hierdie verhouding is moeilik om te bewys of te kwantifiseer. Verder is dit moeilik om met huidige methodes die gevolge van instandhouding te isoleer, en dus deeglik te begryp.

Organisatoriese aanpassing by 'n bate bestuursprojek word bereik deur werknemers se siening te belyn oor wat die gebrekkige areas is, en om hulle verwagtinge te bestuur oor die voordele wat 'n goeie bate bestuursprojek kan voortbring. Daar is 'n gebrek aan metodes om in 'n deursigtige wyse die kritieke areas aan te dui en te komunikeer aan werknemers. Dít skep 'n hindernis in die uitvoer van projekte en, in die afwesigheid van empiriese bewyse van probleme, is werknemers afhanklik van argumentatiewe menings om probleme te ontbloot, en die menings van verskeie rolspelers kan verskil.

Enige inisiatiewe is tipies beperk deur die beskikbaarheid van hulpbronne daarvoor, en 'n effektiewe toedeling van beskikbare hulpbronne is dus noodsaaklik. Om 'n suksesvolle batebestuursprojek uit te voer, moet daar eers 'n duidelike begrip en ooreenstemming wees oor wat die verskeie kritieke areas is wat die meeste aandag verlang, sodat hulpbronne doeltreffend toegeken kan word.

In díe studie word hierdie probleem deeglik ondersoek deur oplossings na te vors in die literatuur. 'n Metode is gesoek wat daarop gemik is om die

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gevolge van instandhouding te isoleer in ‘n produksiestelsel en kritiese areas te ontbloot. ‘n Studie is uitgevoer op metodes wat gewoonlik gebruik word om sodanige analises uit te voer, en dit word gewys dat huidige metodes terkortkominge het wat hulle toepaslikheid beperk. Dus is ‘n nuwe metode geskep wat gebruik maak van simulasie om hierdie probleme te oorkom.

Die metode is gevalideer deur om ‘n gevallestudie uit te voer, waar dit bevestig is dat die metode voordelig is om op ‘n deursigtige wyse kritiese areas te ontbloot en om organisatoriese belyning te bewerkstellig deur effektiewe kommunikasie van die resultate.

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Abbreviations

AAPL	Anglo American Platinum Limited
ACRG	Asset Care Research Group
AM	Asset Management
AMS	Asset Management System
CA	Criticality Analysis
CBM	Condition-Based Maintenance
CMMS	Computerised Maintenance Management System
DES	Discrete Event Simulation
DOM	Design-out Maintenance
IID	independent or identically distributed
FMECA	Failure Modes Effects and Criticality Analysis
FMEA	Failure Modes and Effects Analysis
HPGR	High Pressure Grinding Roller
PC	Primary Crusher
ISO	International Organisation for Standardisation
JiT	Just-in-Time

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KPA	Key Performance Area
MFOP	Maintenance Free Operating Period
MNC	Mogalakwena North Concentrator
MOO	Multi-Objective Optimisation
MTBF	Mean Time Between Failures
MTTR	Mean Time To Repair
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
OR	Operations Research
PAM	Physical Asset Management
ERP	Enterprise Resource Planning
EAM	Enterprise Asset Management
PAS55	Publicly Available Specification 55
PM	Preventative Maintenance
RCA	Root Cause Analysis
RCM	Reliability Centered Maintenance
SA	Sensitivity Analysis
TOC	Theory of Constraints
TPM	Total Productive Maintenance
TQM	Total Quality Management
UBM	Use-Based Maintenance

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1 | Introduction

CHAPTER 1 serves as an introduction to the Physical Asset Management study conducted. The chapter introduces topics which are fundamental to understanding the basis of this thesis and provides an overview, intended aims, and structure of the study. A problem statement is put forth which describes current shortcomings in the area of maintenance prioritisation which the study aims to address. The chapter concludes with the central research question and the null hypothesis for the study.

INTRODUCTION
Evolution of PAM
PAM Optimisation
Maintenance Prioritisation
Problem Statement
Document Structure

PAM Landscape

PAM Prioritisation Techniques

Prioritisation Methodology

Case Study

Conclusion

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1.1 Evolution of Physical Asset Management

Physical assets include plant infrastructure, vehicles, machinery, spares, and other items which have a distinct value to the enterprise. Asset-centric organisations are those which can be described as having a performance dependency on the management of their physical assets, in terms of revenue generation. Most heavy industries rely on a built infrastructure as the primary means to create value, through operation and service delivery. The purpose of Physical Asset Management (PAM) is to ensure the optimised mix of cost, risk and performance over the asset's entire life-cycle, to ensure that the organisation derives the maximum value possible from its physical assets.

Maintenance is seen as an important facility of Physical Asset Management (PAM), as in manufacturing systems the profitability of the production process is directly linked to the availability of machinery. Maintenance is a dynamic service activity which seeks to maximise, over an intermediate time period, the availability of a component or system, and aims at smooth, cost effective operation of an enterprise. Non-performance of manufacturing systems is becoming less acceptable due to ever increasing demands on their functioning requirements in order to push profit and productivity, to improve the effectiveness of manufacturing within an integrated supply chain. The high stress which is placed on machinery in order to perform at these requirements needs to be offset by organisational and technological advances which improve the design, operation, and maintainability of production systems. The goal of PAM in this regard is to support the organisational strategic plan by ensuring the smooth and predictable operation of the production system while minimising cost, while being augmented by the use of available technology.

Maintenance has historically suffered from a "fix it when it breaks" mentality, where it is seen as a "necessary evil", in that planned or unplanned maintenance is always disruptive to production and causes conflict where monthly production targets are tight. Maintenance has undergone an evolution in recent decades from this reactive mindset to the point where it is rightfully seen as a vital and integral part of the production system and one of the enablers of the smooth operation of a production system. Figure 1.1 adapted from Mitchell (2007) presents a rough evolution of available maintenance practices.

Gaining insight into the operating functionality and in turn the criticality of indi-

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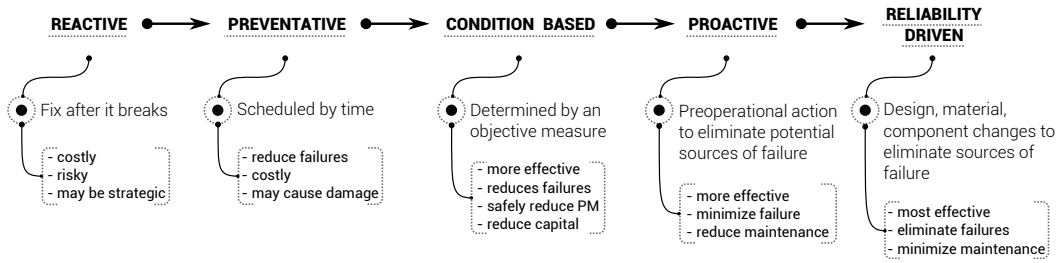

FIGURE 1.1: Evolution of Equipment Maintenance.
Adapted from Mitchell (2007)

vidual assets in the system is necessarily the first step in understanding the impact of downtime on profit. Many tools and management frameworks exist which seek to maximise the availability of the plant[1]. Under the consideration that the necessary resources to perform these functions, such as personnel, time, and money, are limited, emphasis should be placed on prioritising the interventions which enable the plant to continue running smoothly.

1.2 PAM Optimisation

Man-made systems are usually complex and, though they can operate satisfactorily, are by nature imperfect. Due to continually changing environments and constraints, any production system is constantly evolving and is always driven towards obsolescence. Engineers attempt to replace, adapt and improve systems in order to maintain satisfactory operation, and this continuous process is what is referred to as *optimisation*.

Many operations improvement projects focus on optimising the operation of one or many components within a system, while others seek to optimise the inter-operation of components using a system-wide analysis. Management paradigms such as TQM, Just-in-Time (JiT) and a host of others, seek to maximise performance in some way, but, argues McKone *et al.* (1999a), often the benefits of such programs are not fully realised due to failing and unreliable equipment. Therefore, PAM optimisation initiatives specifically seek to maximise the availability of the production system while accounting

[1]See for example Simatupang *et al.* (1997) and Cua *et al.* (2001) for an overview of Total Quality Management (TQM) and Total Productive Maintenance (TPM)

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for cost.

Typically, any system experiences a scarcity of resources, so that a necessary subsequent step is to assess and prioritise interventions in order to gauge which actions would provide the greatest benefit to the company's bottom line, while accounting for cost. In complex systems it may be difficult to assess quantitatively the impact of a potential decision, which limits the effectiveness of decision making in these situations.

PAM literature typically encourages uniform maintenance strategies, which provide the same level of care across the production system. Change initiatives may therefore be misdirected by inadequate prioritisation of maintenance efforts, which in an environment of scarce resources means that resources aren't allocated appropriately to the places they are most required. This misdirection of efforts may go completely unnoticed if there is not a sound understanding of production from a systems point of view, as it is generally difficult to gage and quantify exactly *how* maintenance affects the availability of the system. In addition, prioritisation of maintenance activities by gaining insight into the dynamic operation of the plant and its critical assets may be a further optimisation of an existing maintenance plan.

1.3 Prioritisation of Maintenance Interventions

Prioritisation of interventions is usually performed, if at all, by some function which compares and ranks available actions based on a function of their benefits, costs, and risk. The most widely used tools in industry focus on ranking potentially detrimental situations by risk, and their aim is thus to avoid negative situations from occurring[1].

Prioritisation is also used for project and investment appraisal. Models are generated to evaluate the impacts of available decisions in order to provide decision makers with the best possible information, so as to anticipate future events. Where multiple available scenarios exist, scenarios are compared and ranked by predetermined quantitative performance measurements and qualitative criteria. The models created may be as simple as brainstorming various scenarios, or may involve explicit models which seek to quantify various outcomes, depending on the nature of the operation. In the maintenance

[1] See for example the Criticality Analysis methods and their relevant references discussed in Section 3.5

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environment, prioritisation is seen where bottlenecks become obvious — for example in the case of recurring failures in one production area. This type of prioritisation is not the proactive approach sought by PAM and is akin to fire-fighting.

Criticality is defined as the potential impact that an action has on the business goals of the company. The goal of Criticality Analysis (CA) is to identify assets whose reliability has the greatest potential to negatively affect the profitability of the company. In a maintenance environment, critical assets are those that have the greatest negative effect, or greatest potential to negatively affect the operability of the system and incur production losses. CA typically assesses multiple assets and ranks them according to criticality.

In all available techniques it is important to be mindful of the value of quantitative information. Mitchell (2007) notes that initiatives that can provide some measure of quantitative benefit, or can accurately quantify risk, are far more likely to gain support and funding, as it can be shown directly how these projects will affect the company's bottom line.

Modelling is defined by White & Ingalls (2009) as creating and deploying an entity that is used to represent some other entity for some defined purpose. Models are an abstraction of reality and are employed when investigation of the actual system is impractical or prohibitive. *Abstraction* refers to the notion that models are a simplified view of reality, and are tailored to provide answers to specific questions about a system. Modelling approaches can provide an indication of the criticality of assets in the system, and can prioritise assets in order to direct focus on maintaining the most critical assets.

Other benefits of a modelling approach to maintenance may include investment appraisal for PAM, and supporting decision making by giving managers a quantitative indication of the cost/benefit of maintenance strategies, as well as aiding in the design of new systems for maintainability. The use and applicability of system-wide modelling approaches is limited, as models used are either too simplistic and rely to a large degree on guesswork and the intuition of operators, or where analytical approaches are taken, the models are typically either too abstracted to be applied in practice or too cumbersome to apply reasonably. Seila *et al.* (2003) state that with the advance in computer processing power and the evolution of available software, many modelling approaches have become more accessible to enterprises and may tip the appropriateness of quantified models to become a simple first-line analysis of component criticality in a

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system.

In this thesis, methods to analyse, prioritise and quantify maintenance opportunities are considered in detail, with a clear description of their potential roles within an integrated asset management system, and with emphasis on their capability to influence operational decision-making. In traditional CA prioritisation does not extend beyond assessing assets individually, thus the value of prioritisation based on an integrated systems approach is demonstrated. Finally, a case study will be performed to illustrate the method's application and viability in a real-world scenario, as part of an on-going PAM implementation project.

1.4 Problem Statement

PAS-55 is the current PAM industry standard framework created by the Institute for Asset Management, together with the British Standards Organisation and other collaborating organisations in 2004 as a standard specification for the optimised management of physical assets and infrastructure. A vital facet of asset management, according to PAS-55 (2010), is that it is constructed on accurate data and information. An accurate description of the status-quo is required, so that informed decisions can be made about the prioritisation of improvement opportunities.

In complex manufacturing and processing systems it may difficult to gain an understanding of the impact of per-machine downtime on system output, as there are counteracting factors such as buffers and feedback loops that can dampen or exacerbate the effects of a failure. Prioritising asset care decisions without considering the system in which the asset operates, or providing the same level of care for all assets regardless of their situation, may therefore induce wasted effort.

Employees dealing with operations in an organisation always seem to be aware of problems relating to their systems, but often fail to identify the root causes of these problems as they lack the necessary systems perspective. Furthermore, once problems are identified, these employees lack the technical means to translate what they are experiencing into empirical evidence of their problems.

The inability to be able to identify root causes of the problems in the system is a

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factor that hinders employees in suggesting improvements. Furthermore, employees are unable to explain the gravity of their problems to senior management because:

- They are unable to replicate specific problems;
- Problems lack definitive proof and can't be translated in such a way that they are universally understood;
- They are unable to identify critical factors in the system that lead to the problem.

By not having systems thinking engrained in analysis, employees struggle to correctly identify critical factors in the system such as bottlenecks, and may direct their focus in improving the system incorrectly. Furthermore, by not having a tool to evaluate the system in its entirety, employees are unable to anticipate or track changes to the system, creating a demoralising lack of feedback and promoting guesswork.

The abundance of data created by automated systems in today's industry is staggering, and there is a wealth of information that can be obtained from assessment of this data. However, the availability of analysis tools, imagination, and time to do analysis is often lacking in employees, and managers frequently fail to see how much credibility this empirical information can lend to their projects.

Even though many rating and optimisation approaches such as Reliability Centered Maintenance (RCM) and TPM have been developed, they still lack reliable quantitative measurements, which does not allow for cost-benefit calculations to be considered, and furthermore does not allow for the comparison of different investment strategies. Machine availability has a substantial impact on the profitability of asset-centric production systems, and thus state of the art maintenance strategy optimisation techniques should always be based on models which are able to quantify the benefits of such programs.

Achermann (2008) identifies some of the reasons why quantitative modelling techniques have not gained traction in practice as:

Cumbersome modelling: Transformation of the problem into a model is difficult and not necessarily intuitive and requires an understanding of the elements and dynamics of the system, as well as extensive knowledge of the modelling language itself.

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Inefficient modelling techniques: Modelling is time-consuming and the process is difficult to accelerate, as reuse of models and parts of models is not possible. Furthermore there is a trade-off in the usefulness of tools between efficient modelling and functionality.

Limited extendability: Models are impractical to use for anything other than analysis, as they are difficult to modify.

Inadequate modelling of preventative maintenance impact on availability: Only a few models exist that are able to represent the impact of preventative maintenance on system availability.

Loss of analytical solvability: Advanced models can generally only be analysed by means of simulation. Questions about the validity and sensitivity of abstract results will always appear.

Achermann (2008) argues that recently, JiT logistics and the pressure on costs and strict delivery times have dramatically gained importance and have urged companies to optimise their service level, and as a result this thinking has permeated into maintenance strategy as well. It indicates a tendency to move away from optimising system availability, to instead focussing on maximising the service level and overall profitability of the production system.

On a strategic level, it is well established that PAM projects which can provide some basis of quantitative benefit are far more likely to gain support and funding from the organisation. Neilson *et al.* (2008) notes that employees require the information they need to understand the bottom-line impact of their day to day choices. This is because rational decisions are always naturally bounded by the information available to employees. Also noted is that metrics that measure key drivers in the organisation need to be well-known to employees. Many organisations still have the mindset that maintenance is an expense, when it is really a contributing function. It is very difficult to attribute a value to an avoided cost, and therefore difficult to appraise the value of maintenance, where benefits are typically not noticed through traditional performance indicators. By giving definitive empirical evidence of the benefits that PAM improvement projects can bring to the company, these initiatives are far more likely to gain traction. Furthermore, it is far easier for the organisation to make investment decisions based on empirical evidence, and thus adequate resources can be supplied to these projects. It is therefore proposed in this project to create some quantitative basis by which these

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projects can be evaluated, such that strategic decisions regarding implementation of asset management can be economically justified in relation to competing projects, and can be fast-tracked and fully supported by the organisation.

Asset Management decisions vary greatly in complexity and criticality, so it is inappropriate to apply the same level of sophistication to all decisions. Typical quantitative models are analytical in nature and are either too complex to be reasonably applied, or their level of abstraction is too high and are therefore impractical. A model should be proportionate in effort to create the benefit it strives to give, and flexible analysis is thus sought, where any required level of abstraction is obtainable.

This project takes a systems approach in analysis. Systems thinking is the belief that component parts of a system can best be understood in the context of relationships with each other and with other systems, rather than in isolation. Systems thinking has been defined as an approach to problem solving, by viewing "problems" as parts of an overall system, rather than reacting to a specific part. A systems approach to problem solving is vital when considering complex systems. The project will thus consider the integrative nature of asset management and how its implementation can affect the entire system.

This leads to the central research question and null hypothesis statement for this thesis:

> *"Can an adequate modelling approach be found which can describe, to some level of abstraction, the production system as a whole, in order to gain insight into and prioritise critical assets, to gain quantitative information on maintenance interventions, and to rank available interventions and thus aid PAM decision making?"*

H_0 :	A modelling approach which isolates the effects of reliability related downtime can not be used to prioritise and quantify maintenance improvement opportunities in a production process.

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1.5 Research Objectives and Document Structure

This thesis builds upon a number of research objectives to ultimately achieve a comprehensive answer to the stated research question. The research objectives are structured into manageable sub-tasks which are logically presented in each subsequent chapter.

The first research objective is to present the fundamentals and key concepts of the domain of this thesis. In order to achieve this, Chapter 2 provides an exhaustive literature review to provide the reader with a thorough understanding of PAM, including the role of maintenance in an organisation and an overview of asset optimisation.

Chapter 3 examines potential solutions to the problems presented in Section 1.4 through further literature review, with an emphasis on methodology and case-studies, and concludes with a selection model to determine which method is most suitable for the required purpose.

A methodology for the use of Discrete Event Simulation (DES) to model maintenance prioritisation is presented in Chapter 4. Additionally, Chapter 4 provides an overview of the fundamentals of DES to guide the reader through the subsequent chapters.

Chapter 5 provides real-world evidence of the applicability of the modelling approach presented in the previous chapter through a thorough case study performed at Anglo American Platinum Limited (AAPL). The chapter details the entire modelling process, including data-collection, assumptions and simplifications, results obtained, and verification and validation of the model.

The thesis concludes with Chapter 6, in which a comprehensive evaluation of the central research question and the applicability of modelling to maintenance prioritisation, through the findings of Chapter 5, is argued. The defined null hypothesis is tested and consequently rejected of accepted. The chapter concludes with recommendations for further study.

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2 | Physical Asset Management Landscape

CHAPTER 2 endeavours to contextualise the topics in maintenance prioritisation introduced in Chapter 1 and serves to guide the reader through the remainder of the thesis by providing a sound background to the current and historic viewpoints in Physical Asset Management pertaining to these topics. The chapter also places focus on decision making in Physical Asset Management and introduces the reader to the role of models in the decision-making process.

Introduction

PAM LANDSCAPE
Physical Asset Management
ISO 55000 & PAS 55
Asset Management Definitions
Asset Optimisation
AM Strategy
Asset Contribution Modelling
Maintenance
PAM Decision Making
Conclusion

PAM Prioritisation Techniques

Prioritisation Methodology

Case Study

Conclusion

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2.1 Physical Asset Management

The Institute of Asset Management (2011) notes that as the discipline matures, Asset Management (AM) is not so much about *doing things to assets* but about *using* assets to deliver value and achieve the organisation's explicit purposes. Davis (2007) provides the view that the concept of asset management is not new, as people have been managing assets for thousands of years — yet recently the discipline was born out of a cumulative recognition for the need for optimising the mix of cost, risk and performance over the asset's entire life-cycle, and to do so in a governable and sustainable manner. The financial services sector was the first to use the term 'asset management' to describe the activity of managing risk, performance and long-term security from a mixed portfolio of investments.

ISO 55000 (2013) provides a general definition of AM as: "the coordinated activities of an organisation to realise value from assets". From this definition it is realised that AM is a set of disciplines, methods, procedures and tools to optimise the whole life business costs, performance and risk exposures of the company's physical assets.

The main objective of PAM according to Mitchell (2007) is to increase the value and return on physical assets which generate revenue and profitability within the production, manufacturing and process industries. In essence, notes The Institute of Asset Management (2011), PAM converts the fundamental aims of the organisation into practical implications for choosing, acquiring, utilising and maintaining assets, while seeking the best total value approach in terms of an optimal combination of costs, risks, performance and sustainability.

Due to ambiguous terminology, the term PAM is often used interchangeably with AM, though the latter is also commonly used to describe activities in finance, information technology, real estate, corporate management and many other areas. Ignoring these other contexts and usages of the term however, "asset management" is increasingly being used in industry to describe the holistic management of physical assets over their entire life cycles. This thesis acknowledges the importance of all assets a company holds (see Section 2.1.2) but due to the focus on the maintenance aspect and thus on physical assets, the term PAM is preferred throughout.

Hastings (2010) notes that historically asset management has not been a well defined

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activity, partly due to functional isolation in the disciplines surrounding the management of physical assets, and a lack of cross-functional integration of these activities. Hastings (2010) and Woodhouse (2007) further state that one of the most challenging areas in asset management is systems integration. Woodhouse (2007) states that physical assets have been managed for years, but that recently the scope of management has shifted considerably from a maintenance focussed view to a more holistic approach, which has been advocated strongly in past years and perpetuated by formal standards for asset management such as PAS-55 and ISO 55000. The mindset currently revolves around the view of using assets to deliver value in line with an organisation's needs. PAM therefore provides the competencies, processes, knowledge and tools to enable an organisation to effectively achieve a purpose with their chosen assets.

Through the preceding paragraphs, it can be argued that PAM has exceeded the simplistic traditional interpretations of a maintenance based activity, and has evolved into a multi-functional discipline which seeks the integrated, optimised, multi-disciplinary management of multiple asset types and systems.

2.1.1 Physical Asset Management: Definition

The definition of PAM has shifted to a broader view, with a stronger focus on organisational integration. Broader definitions imply that the discipline has an increasingly wide reach of influence, including general management, operations and production arenas, and financial and human capital aspects, notes Amadi-Echendu *et al.* (2010). Most recent definitions of PAM consistently acknowledge that it is an integral function in an organisation. Literature provides many definitions of PAM [1], however the one adopted for this thesis is given by PAS-55 (2010) framework.

The framework defines PAM as:
"systematic and coordinated activities and practices through which an organisation optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their whole life cycles for the purpose of achieving its organisational strategic plan."

[1] see for example Woodhouse (2007), Mitchell (2007), PAS-55 (2010), ISO 55000 (2013), The Institute of Asset Management (2011), Amadi-Echendu *et al.* (2010)

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2.1.2 Assets and Asset Types

The word "asset" may convey diverse interpretations and care should thus be taken to define the term within the context of PAM. Furthermore it is clear from PAM literature that there are asset subcategories of assets which, though distinctly different in many ways, should not be managed in isolation of each other. PAS-55 recognises five categories of assets, which should be considered holistically within a PAM framework. These categories are: Human assets, information assets, intangible assets, financial assets and physical assets. Figure 2.1 shows the interplay between these categories as identified by PAS-55 (2010).

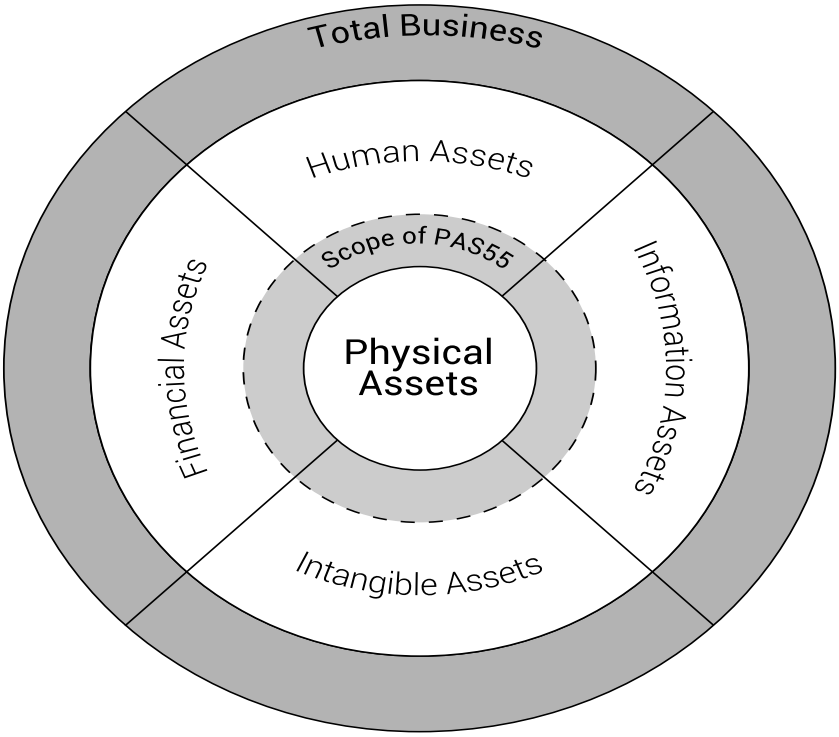

FIGURE 2.1: Key asset types identified by PAS 55
Adapted from PAS-55 (2010)

Definition of an Asset

Assets are defined by PAS-55 (2010) and ISO 55000 (2013) as *"Something that has potential or actual value to an organisation"*. This broad definition allows for the consideration of intangible assets. PAS-55 (2010) further defines *physical assets* as

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Table 2.1: PAS 55 Categories of Organisations. Adapted from PAS-55 (2010)

1.	Any physical asset intensive business, where significant expenditure, resources, performance dependency and/or risks are associated with the management of physical assets.
2.	Any organisation that has, or intends to manage or invest in, a significant portfolio of physical assets, or where the performance of asset systems and the management of physical assets are central to the effective achievement of business objectives.
3.	Organisations where there is a business or public accountability requirement to demonstrate best value in the safe management of physical assets and provision of associated services.

"plant, machinery, property, buildings, vehicles and other items that have a distinct value to the organisation", which is the definition adopted for this thesis.

2.1.3 Publicly Available Specification 55 for Asset Management

The current PAM industry standard framework, PAS-55 (2010), was defined by the Institute for Asset Management, together with the British Standards Organisation and other collaborating organisation in 2004 as a standard specification for the optimised management of physical assets and infrastructure. The standard received a review and update in 2008.

PAS-55 recognises multiple categories of assets, as discussed in Section 2.1.2 and Figure 2.1, but focusses primarily on the management of physical assets, and considers other assets only in terms of their impact on an organisations physical assets. PAS-55 (2010) provides three main categories of organisations which stand to benefit most from PAS-55, shown in Table 2.1. These organisations are frequently referred to as *asset-centric organisations*.

PAS 55 is published and subdivided into two parts: PAS 55-1 is the specification for the optimised managemet of physical assets and provides recommendations for establishing, documenting, implementing, maintaining and continually improving an asset management system. PAS 55-2 contains the guidelines for the implementation of PAS 55-1. These two sections are hereafter referred to as PAS 55 as a specification, rather than as two separate publications.

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2.1.4 ISO 55000 Specification for Asset Management

PAS-55 has been accepted by the International Organisation for Standardisation (ISO) as the basis for the development of the new ISO 55000 series of international standards.

Based on PAS-55, ISO 55000, could become the *de facto* standard for PAM. At the time of writing this publication was in draft form and to be published towards the end of 2013. This will bring even further credibility and more momentum to the field of asset management as well as to the PAS-55 standard. ISO 55000 (2013) provides the following rationale for Asset Management:

> *"Asset management involves a disciplined approach which enables an organisation to maximise value (or minimise liabilities) from the portfolio of assets for which it has a responsibility in delivering its strategic objectives. This includes determination of appropriate assets to create or acquire in the first place, how best to utilise and support them, and the adoption of optimal renewal or disposal actions, along with the ongoing management of any residual liabilities."*

The key concepts of ISO 55000 and their relationships are shown in Figure 2.2, which shows the integration of various elements of PAM and the Asset Management System (AMS) within the broader organisational context. To be noted is the broad range of functions which is to be included in the AMS, and the number of functions which a proper PAM framework seeks to integrate.

The standard consists of three documents: *ISO 55000* provides an overview of the benefits, principles, concepts and terminology relating to assets, asset management and asset management systems, *ISO 55001* specifies the requirements for the establishment, implementation, maintenance and improvement of an asset management system, while *55002* provides guidance for the application of an asset management system in accordance with the requirements of ISO 55001.

ISO 55000 ensures consistency with other related organisational standards such as ISO 9001 and 14001. ISO 9001 specifies the requirements for a quality management system, whereas ISO 14001 addresses various aspects of environmental management.

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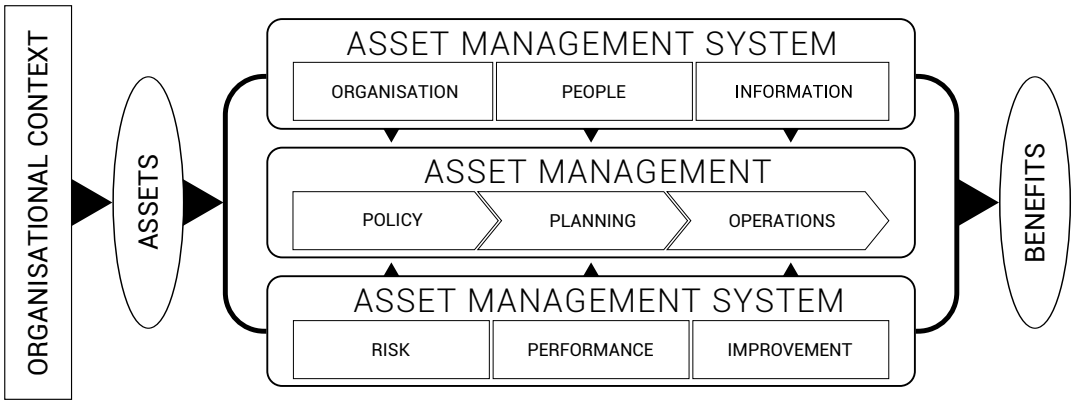

FIGURE 2.2: Key concepts covered in ISO 55000
Adapted from ISO 55000 (2013)

For the purpose of this thesis, the PAS 55 framework is preferred as a basis due to the fact that it is a published work, whereas ISO 55000 is still in draft form. Both are relatively interchangeable in ideology and execution, however.

2.1.5 Asset Optimisation

Mitchell (2007) gives a definition for Physical Asset Optimisation as:

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

A Physical Asset optimisation program is directed to:

- Establishing / maintaining full compliance with all safety, social and environmental best practices.
- Gaining greatest business value through optimum availability, technical integrity, operating performance, capital effectiveness and least sustainable cost for specific market, operating and business conditions.

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- Applying systematic, value driven prioritisation and opportunistic implementation of optimised improvements to the processes, practices and technology that determine the utilisation, effectiveness and reliability of physical assets.

ISO 55000 (2013) emphasises that asset management can only be effective if organisational objectives are understood and established within the operating context of the organisation. It is also stated that realisation of value from assets involves an optimisation of costs, risks, opportunities and performance benefits, and to this end it is noted that the measurement of asset and asset management performance is crucial, and that having risk-based, data driven planning and decision-making processes is the only way to realise the organisation's strategic intent. It should also be clear what the assets need to achieve, by when, and with what assurance.

2.1.6 Asset Management Strategy

A PAM strategy should define what the organisation intends to achieve from its specific AM activities and within what time frame. PAS-55 (2010) sets a list of requirements for an AM strategy which fall into seven broad categories:

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

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

The Institute of Asset Management (2011) states that one attribute of a functioning PAM framework is that it is systems oriented and looks at assets in their *systems context* rather than in isolation, for net, total value. Assets themselves have different levels of granularity — some organisations identify individual equipment items as discrete assets, towards which investment, maintenance and spares or other activities are directed. However such units generally yield functional performance and value only in a systems context — the network, production line, infrastructure facility or other larger entity and thus need to be considered within the environment that they inhabit.

Optimal, risk-based decision making is a vital element underpinning successful PAM, according to The Institute of Asset Management (2011). The goal is to determine the optimal *combination*, yielding the best net value, including risk exposures, indirect or intangible impacts and long-term effects. Accordingly, this involves understanding a range of quantification techniques, including how to evaluate risk and intangibles, and the real-life complexities of asset deterioration, reliability engineering and financial calculation methods. To consider these complexities in a disciplined and auditable manner, not just on a per-asset basis, but as a system with interdependent factors, requires sophisticated tools and experienced interpretation of the obtained information. Asset management is thus about deriving value from assets in a structured and predictable way.

According to Davis (2007), asset management strategy and planning contains the core PAM activities required to develop, implement and improve PAM within an organisation. PAM strategy typically produces an output which explains what the organisation plans to do with assets with respect to acquisition, maintenance, operation and disposal, and what level of service will be delivered as a result of these activities.

An integrated asset management strategy should not just apply to the maintenance department as it used to, but must involve the entire organisation by enhancing organisational strategic objectives. A simplified scope of AM strategy is shown in Figure 2.3 which presents an AMS hierarchy and shows the fundamental nature and intentions of the PAM field.

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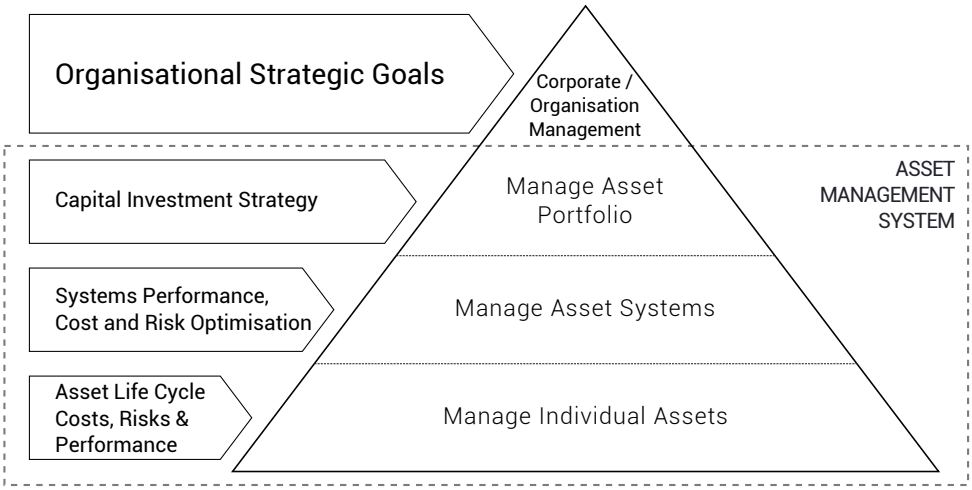

FIGURE 2.3: Priorities and concerns of a typical asset management framework
Adapted from ISO 55000 (2013)

2.1.7 Measuring Asset Contribution

Assets are defined by PAS-55 (2010) as *"Something that has potential or actual value to an organisation"*. Through this broad definition it becomes important to actually measure which assets add value, how they create value, and to put this asset contribution into perspective. Fogel & Vlok (2012) propose an Asset Contribution Model, which is based on the widely accepted DuPont model. This is presented in Figure 2.4.

The Institute of Asset Management (2011) emphasises that organisations need to understand the relationship between maintenance and capital expenditure and business output, and emphasises that appropriate asset data and information to support PAM decision making should be available. The implications of deferring maintenance should be understood and capital expenditure fully justified to stakeholders.

2.1.8 Maintenance

All man made structures require maintenance in order to remain fit for use. Dekker & Scarf (1998) highlight that maintenance expenditure will continue to grow as non-performance of systems becomes less acceptable and the functioning requirements

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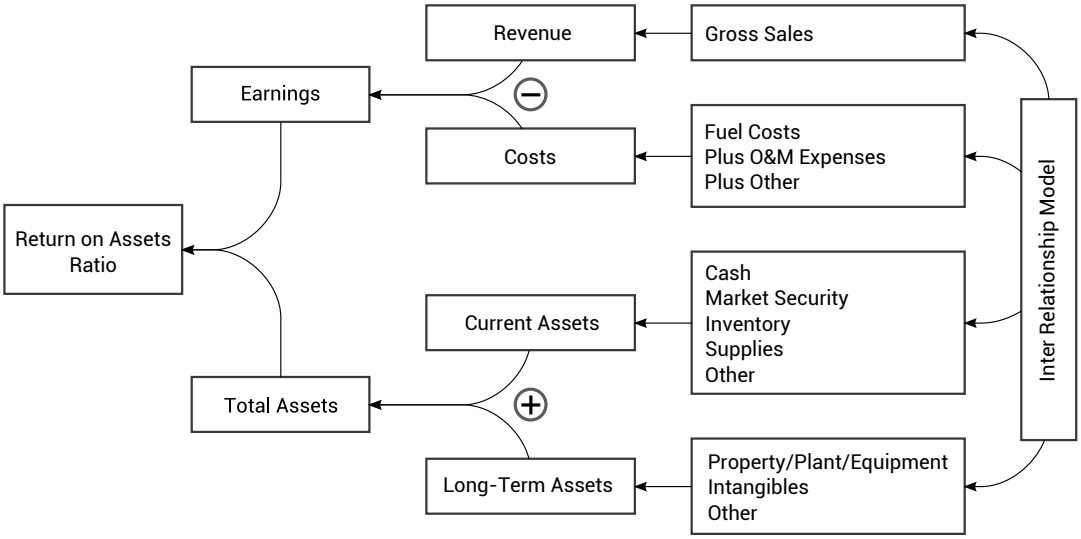

FIGURE 2.4: The Asset Contribution Model. Adaption of the classic DuPont Model
Adapted by Fogel & Vlok (2012)

increase, due to initiatives to improve the effectiveness of manufacturing systems such as supply chain integration and JiT philosophy. Sharma *et al.* (2011) provide the view that the role of maintenance in modern manufacturing systems is becoming even more important, with companies adopting maintenance as a profit-generating business element, and state further that the aim of the maintenance function is to contribute towards an organisations profit, thus bringing the need for maintenance operation to be in harmony with corporate objectives.

Breakdowns and holdups in production systems, notes Seiler (2000), inherently have a detrimental effect on system availability and put the profitability of a production system at risk. Idle production systems produce no profit and therefore any stoppages have a negative effect on the ratio of fixed costs to production output, which in combination with the reduced output of the production system has a compounding negative effect on the overall cost-effectiveness of the system. Furthermore, advanced production systems often require significant start-up time to resume operation after an interruption, and during this time scrap product is produced which does not contribute to profits. Efficient operation of a production system, according to Achermann (2008), therefore requires few interruptions and fast recovery from breakdown.

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Maintenance is defined by Mitchell (2007) as *"the act of causing to continue"* and depicts all the technical, technological, organisational, and economic actions to delay wear-out and/or achieve recovery of functional capability of a technical system. Deterioration of components has a negative effect on the operational capabilities of a system, and may cause the system to be unable to fulfil its intended function. The intended function of maintenance is therefore to counteract these effects in a effective and optimised manner. Sharma *et al.* (2011) agree, with the insight that maintenance is carried out through repairing at certain intervals, with the aim of extending the useful life of machinery.

Over the last 40 years, equipment management has evolved from a largely reactive "fix it when it breaks" approach to more modern strategies which view maintenance as a value-adding function. The Institute of Asset Management (2011) notes that historically, manufacturers and equipment suppliers have tended to provide a list of maintenance and inspection tasks and associated intervals for an asset, which are then adopted by the user without much consideration for the operating conditions in which the asset is being used. This is certainly not an optimised approach.

2.1.8.1 Maintenance Types

Most strategies in literature can be described as falling under one or more of the categories shown. Hastings (2010) notes that each step in the process has proclaimed to be the conclusive *end all* solution to maintenance that makes previous steps obsolete. In practice however, a recent survey showed that industry is still attempting to reduce the amount corrective maintenance performed, from a 65% of total mix to 30%. This is shown in Figure 2.5.

The following sections, inspired by Mitchell (2007), Achermann (2008), Sharma *et al.* (2011) and Hastings (2010) introduce the four categories of maintenance.

Corrective Maintenance (Run-to-Failure)
The old line "if it ain't broke, don't fix it" is the enduring and short-sighted "run-to-failure" argument for corrective maintenance. Run-to-failure is simplistic, requires no forethought, and appears to require the least amount of support, though only until the moment of failure. A large part of the reason that this mindset prevails is that the

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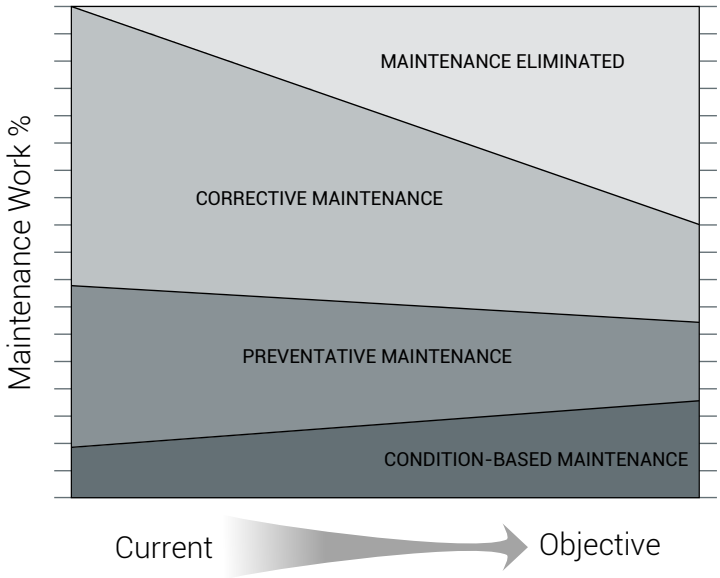

FIGURE 2.5: Proportion of maintenance work by classification—current practice and objective goals
Adapted from Mitchell (2007)

total costs that failures incur, including environmental, safety, lost production, repairs and logistics, are typically spread among various cost centres in the organisation, with manufacturing (typically in charge of maintenance) taking a smaller slice of the overall responsibility. As a result, the real costs may be hidden to the point of being invisible to management who see failure avoidance as an added expense. Mitchell (2007) suggests that reactive maintenance costs are typically two to four times greater than those for failure avoidance, though this can be far higher when human life or environmental damage are involved.

A further problem is that reactive maintenance pays little or no attention to machine operating conditions. As a result, this can have a seriously detrimental effect on the lifespan of equipment, not to mention product quality.

Corrective maintenance may make economic sense in certain cases — according to Nakagawa (2005), corrective maintenance is adopted in situations where units can be repaired and their failures do not have a detrimental effect on the entire system. An example of this is when replacing non-critical items with long life spans, e.g. light bulbs, where failure is neither costly nor dangerous, or for systems with built-in redundancy,

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where failures can be isolated and do not affect the system.

Maintenance should be based on a strategy which seeks the greatest economic benefit and reactive maintenance may well have its applicability in an optimised maintenance mix. Moreover, corrective maintenance is inherently part of any maintenance strategy as unplanned breakdowns can never be excluded.

Preventative Maintenance

Preventative Maintenance (PM) encompasses all activities geared towards reducing or preventing deteriorating tendencies by anticipating possible future failures.

Sarker & Haque (2000) provide the argument that preventative maintenance of operating components is based on the assumption that it costs more to undertake a repair or replacement at the time of failure than doing the same at some predetermined time.

PM is generally invasive and requires outage of production and disassembly for visual inspection, repair or replacement, regardless of the condition of the machine. Nakagawa (2005) points out that every time a unit is repaired only after a failure, it requires large amounts of time and relatively higher cost to bring back into operation. The intervals between specific PM tasks are based on average life, and the measure which is quoted most often in industry is the Mean Time Between Failures (MTBF), which is an estimation of the interval between two successive failures.

A PM program can be cost effective when:

- Equipment operation is constant. That is, equipment runs continuously or is scheduled rigidly.
- Average life is predictable within a reasonable spread.
- Failures are well understood.
- Useful failure statistics are available.

The use of PM is contentious in industry, and many practitioners will report bad experiences or wastefulness as a result of doing PM. Advocates of PM recommend a

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highly structured, living, and well-documented PM plan, which should be phased out by new technology such as Condition-Based Maintenance where possible. A highly skilled workforce is required to constantly update plans, interpret analyses and perform quality checks on equipment. Salonen & Deleryd (2011) propose a model to measure the wastefulness of PM, shown in Figure 2.6. As noted by Sarker & Haque (2000), the total cost for this maintenance policy is the aggregate of the group replacements incurred after every replacement interval, and the cost for replacing those units that break down in spite of the preventative maintenance.

Mitchell (2007) contends that no more than 20% of total failures are time based, thus PM is an ineffective avoidance action for up to 80% of probable failures. Further concerns with PM include:

- Components can be replaced unnecessarily, while machines are still in good condition.
- Time based PM can introduce variation into an otherwise stable process. Intrusive inspections pose a real risk to equipment in good condition and should be avoided whenever possible.
- Generalised failure statistics (MTBF) never tell the whole story, and do not account for e.g. environmental conditions or the quality of maintenance performed at each interval.

Depending on the environment and operating conditions, extremely broad component failure distributions may result. Due to the extreme forces and operating conditions experienced by e.g. heavy machinery, the confidence intervals obtained from MTBF calculations may be so broad as to make the measure unusable due to lack of a meaningful confidence interval.

A possible benefit of PM is that it reduces the stochastic unplanned production hold-ups and therefore allows for simpler production planning. Downtime periods are reduced as preparation prior to maintenance can be performed, and spare parts procured etc. Although PM is used to prevent the system from failing, stochastic failures will still occur, which necessitates a maintenance strategy that includes corrective maintenance tasks.

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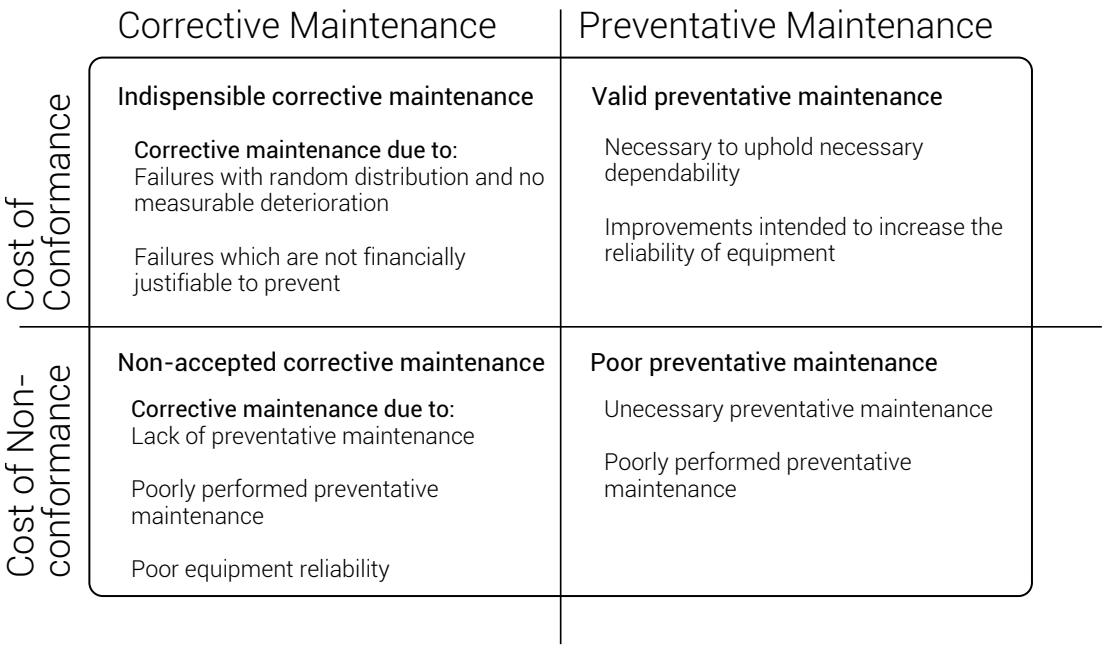

FIGURE 2.6: A model proposed by Salonen & Deleryd (2011) in which corrective and preventative maintenance are divided into cost of conformance and cost of non-conformance.

Condition-Based Maintenance (CBM)

Condition-Based Maintenance (CBM) incorporates inspections of the system in predetermined intervals to determine the condition of the system. Based on the result of this periodic or continuous inspection, a decision is made to perform a maintenance task. Thus a triggering event for a maintenance intervention is defined by the condition of the component. Accordingly, CBM is only applicable when wear-out reserve is available on the component. For a gradually deteriorating system, notes Grall *et al.* (2002), a condition-based policy is more effective than one based only on the system age.

In the experience of Mitchell (2007), condition monitoring and assessment technology, methods, and practise are proven beyond question. Applied correctly, all work well in a variety of situations for most facilities and people. CBM has proven capable of identifying anomalies for correction early enough to minimise the risk and impact of operational interruptions. In theory, there is an optimal maintenance point for each machine, which occurs when certain conditions are observed. This is shown in concept in Figure 2.7.

CBM is composed of at least three identifiable activities:

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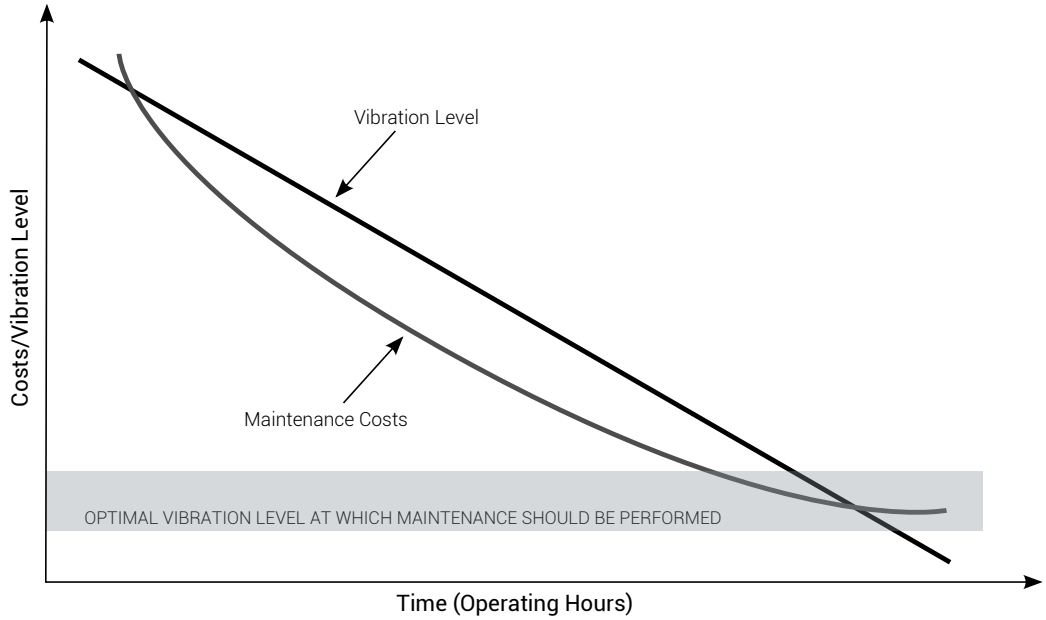

FIGURE 2.7: Maintenance costs as a function of vibration level
Adapted from Mitchell (2007)

1. *Condition measurement:* non-intrusive measurements that define mechanical and operating condition, e.g. vibration, fluid condition, operating performance, thermography and electrical characteristics. Measurements are recorded on-line from installed transducers.

2. *Condition monitoring and assessment:* a condition assessment system identifies mechanical and performance anomalies and diagnoses the nature and severity of the problem.

3. *Repair and maintenance actions:* based on condition monitoring and health assessment.

Root Cause Analysis (RCA) is an essential component of a functioning CBM program. RCA is called upon to ensure that CBM isn't limited to repeatedly identifying the same failure. Coupled with RCA within a comprehensive reliability program, CBM can prove to be a valuable tool to eliminate defects from a system. The value of CBM is estimated in industry by measuring the avoided cost calculations. However, avoided cost — taking credit for events that didn't happen — is often a difficult concept for management to

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accept.

A condition-based maintained system leads to higher system reliability, increased availability and lower production costs by lower utilisation of resources in comparison with PM and corrective maintenance.

Further benefits of CBM include:

- Predictive maintenance scheduling which smooths production and buffer levels, and anticipating operating interruptions in time to minimise the impact on production.
- Minimising the risk of failures, risk and safety hazards, and as a result the amount of Corrective Maintenance performed.
- Reducing the amount of time-based PM performed, which in turn reduces waste.
- Supplying knowledge of equipment operating problems and operator training requirements.
- Reducing the cost of maintenance in general.

2.1.8.2 Maintenance Optimisation

To succeed in the competitive global marketplace, it is vital for an organisation to optimise its operational costs, argues Moore & Starr (2006). The cost of maintaining complex industrial systems is one of the critical factors influencing the enterprise operating costs and hence it is easy to argue that the maintenance function should be optimised.

According to Dekker & Scarf (1998), maintenance optimisation consists of mathematical models aimed at finding either the optimum balance between costs and benefits of maintenance or the most appropriate moment to execute maintenance. Most mathematical models focus on this latter factor by attempting to determine the optimum interval for inspection or preventative maintenance, an almost ubiquitous method being Weibull analysis.

Mitchell (2007) provides a decision-making model, shown in Figure 2.8, which aids engineers in finding the best maintenance strategy for a production system.

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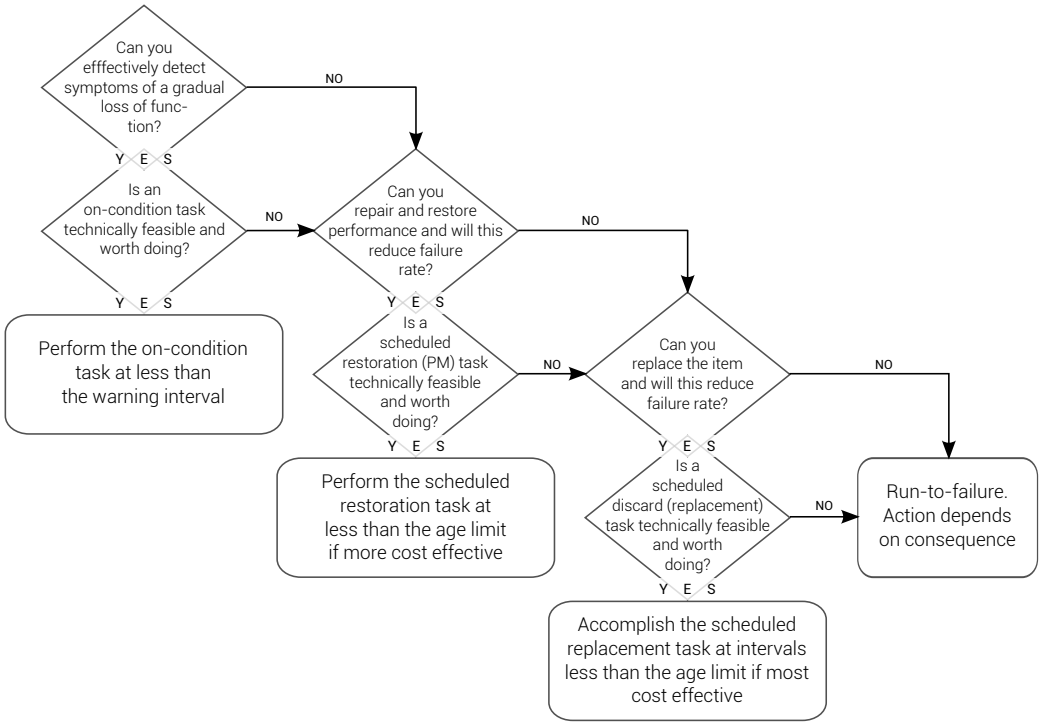

FIGURE 2.8: Task selection logic to arrive at the optimum plan for maintenance

Adapted from Mitchell (2007)

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Barata *et al.* (2002) note that detailed modelling is required for safety analysis of ageing and deteriorating systems posing high risk to the environment, and argues that such modelling can only be done analytically for systems with few components under simplifying conditions — when treating complex systems with more realistic behaviour simulation tools are needed. To this end it is stated that collecting detailed and accurate asset condition data is imperative to the effectiveness and success of the approach, so that estimation of simulation parameters is sound.

Dekker & Scarf (1998) notes that both mathematicians and engineers have contributed to the area, but that due to complexity, applications of maintenance optimisation have been slow, as data is often lacking and models are not easy to apply. This has been offset in recent years by the rapid performance improvement of computers, which is a big incentive to quantitative modelling approaches, and the availability of software aids. It is also mentioned by Dekker & Scarf (1998) and The Institute of Asset Management (2011) that the benefits of quantification and therefore optimisation should be proportionate to the amount of effort required to execute a model. PAM decisions have varying degrees of complexity and criticality and therefore do not require the same level of sophistication. Simple, non-critical decisions may be made with common sense, whereas higher impact decisions, with multiple influences, options, timings or inter-dependencies necessitate greater systematic, multi-disciplined and auditable optimisation methods.

Warrington *et al.* (2002) notes that maintenance of systems is both a technical and managerial challenge, and distinguishes technical challenges such as fault visibility and fault detection, and managerial challenges such as scheduling, identification of global priorities and objectives, forward planning, and individual task prioritisation. It is suggested that these tasks can be modelled and therefore optimised as follows:

Scheduling of Resources and Forward Planning Scheduling of resources is a common modelling task, and can be solved using a number of operations research techniques.

Maintenance Objectives and Overrides Often maintenance can be temporarily deferred without severe operational or safety implications. Models can be used to create heuristics for optimal or effective trade-offs between operational usefulness and continued maintenance.

Prognostic Anticipation Prognostics are the facility to identify impending system

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malfunction and being able to provide a reasonable prediction of the timing of that failure. Good CBM implementation and skilled technicians may be able to detect a prognostic indicator to a reasonable predicted time to failure. Failure predictions should be proportionate to the hazard that the potential failure poses. CBM maintenance prognostic models define a look-ahead — a time before which a prognostic indicator will never be detected, permissible risk of allowing failure before replacement, and maximum likelihood of a technician or CBM identifying the prognostic trigger.

In many cases, such as Dekker & Scarf (1998), Vatn *et al.* (1996), the term "optimisation" is applied too liberally and is used to describe a decision-making framework which minimises cost. Other authors have performed numerical optimisation on maintenance systems: Marseguerra & Zio (2000), Barata *et al.* (2002) and Marseguerra *et al.* (2002) use genetic algorithms and Monte Carlo simulation respectively to determine an optimal degradation level for multi-component CBM systems, but do not provide a case study.

Dekker & Scarf (1998) are quick to note the importance of qualitative maintenance efforts, such as TPM and RCM, as these should precede a maintenance optimisation problem. The optimisation of maintenance should already be considered in the design phase of the system by selecting equipment for reliability and designing the system with a level of redundancy. Warrington *et al.* (2002) note that multiple system malfunctions, across several assets, will result in many potential maintenance activities and that these activities require prioritisation and ordering.

Operational Excellence

Operational Excellence is a management system introduced by Chevron USA Inc (2010) which creates a culture of excellence in operations in an organisation. It is the systematic management of safety, health, environment, reliability and efficiency to achieve world-class performance. The key tenets of Operational Excellence are: leadership, continuous improvement, focus on customer, and optimising current processes. Simply put, Operational Excellence is executing operations in an efficient and effective manner across the value chain with a focus on delivering value to customers. Asset management programs rely on sound operations management to function, and Operational Excellence is thus very beneficial to their long-term sustainability. The ultimate goal of Operational Excellence is to drive an organisation to be World-Class through operations.

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American multinational energy corporation Chevron USA Inc (2010) reduces Operational Excellence to 5 key enabling processes:

1. ***Process in place*** to resolve issues that cause incidents or performance gaps.
2. ***Process in place*** to identify critical structures, equipment and work processes.
3. ***Process in place*** for condition monitoring.
4. ***Process in place*** to prioritise, plan, schedule and complete necessary maintenance.
5. ***Process in place*** to identify and resolve repetitive failures.

E. I. du Pont de Nemours and Company (2010) provides a plan to implement OE, which is presented in Figure 2.9

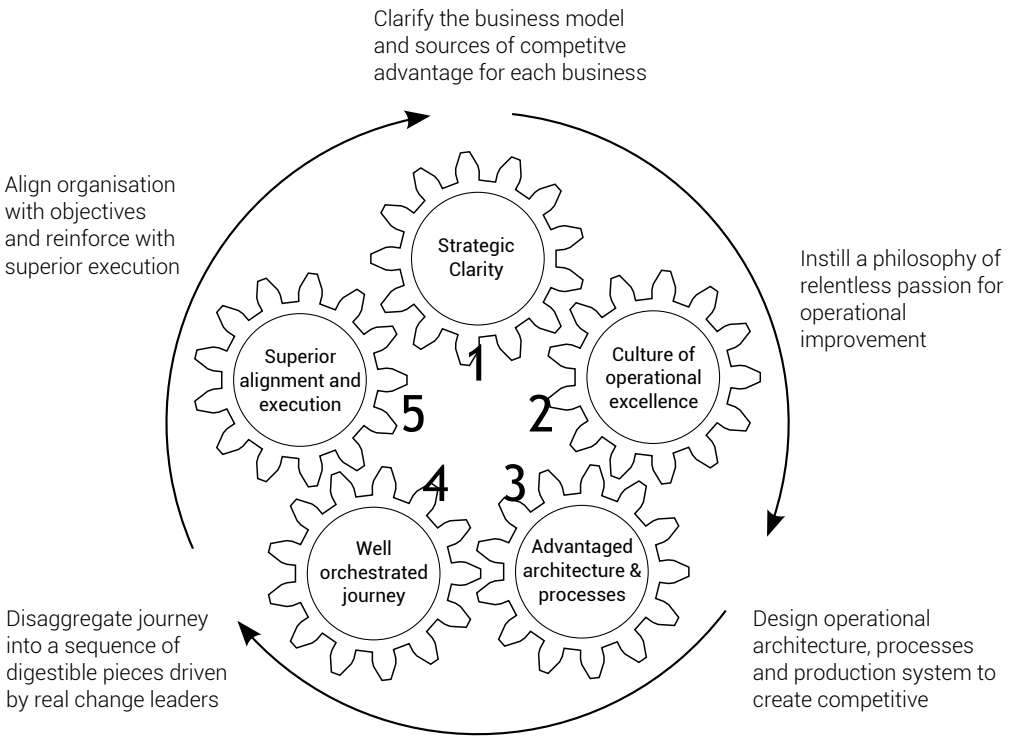

FIGURE 2.9: Operational Excellence implementation plan
Adapted from E. I. du Pont de Nemours and Company (2010)

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According to Mitchell (2007), physical assets utilised as a means of revenue generation usually represent the major percentage of an organisation's capital investment in productive resources and are subject to unprecedented operational demands. Virtually all production and operating companies must achieve significantly improved productivity from physical assets to meet business and mission requirements, and the tempo and intensity of operations are continuously being elevated. To this end, he notes that Operational Excellence has many benefits in Physical Asset Management implementation and should be considered as a core activity in executing sustainable asset management initiatives.

Total Productive Maintenance

TPM originated in Japan in 1971 as a method for improved machine availability through better utilisation of maintenance and production resources. According to Greasley (2006) and Cua *et al.* (2001) much of TPM's value lies in the fact that it combines and integrates the practise of preventative maintenance with employee involvement as focussed on by TQM and JiT philosophies. According to McKone *et al.* (1999a), TPM addresses equipment maintenance through a comprehensive productive-maintenance delivery system covering the entire life of the equipment and involving all employees from production and maintenance personnel to top management.

The TPM philosophy generally emphasises a system-wide improvement approach to PAM, through initiatives such as autonomous maintenance by operators, cleaning and lubrication standards, etc. but according to Achermann (2008) lacks the capacity to identify critical assets and assess available maintenance opportunities.

Reliability Centered Maintenance

RCM is a structured way to determine the maintenance requirements of complex systems. It was derived from approaches to structure aeroplane maintenance in the nineteen-sixties, but has been applied on a large scale in subsequent years. Maintenance is based on an analysis of failure modes, their effects and the ways to prevent them, states Dekker & Scarf (1998).

Balanced Scorecard Method

The Balanced Scorecard Method (BSC) is a management philosophy, management

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system, and method of measuring compliance to objectives, defined by its creators, Kaplan & Norton (1992) as follows:

> *"A method to translate an organisation's mission and strategy into tangible linkages, interrelationships, specific activities and measures necessary for successful implementation. Reliability and maintenance issues can be integrated into an overall business scorecard or identified in a stand-alone scorecard."*

According to Mitchell (2007) the BSC is intended to supplement financial measures with criteria that measure the performance from three additional perspectives: customers, internal business processes, and learning and growth. In a reliability environment, balanced scorecards are an attempt to monitor and control the effectiveness of different maintenance strategies by quantifying qualitative effects in maintenance.

2.2 PAM Decision Making

Decisions are constantly being made on both a strategic and an operational level in PAM and in maintenance. Decisions which should be of concern to managers and engineers include:

- Which assets are most critical to system availability?
- When can the next failure on this asset be expected?
- What is the probability of a failure at this specific point in time?
- What is the probability that a failure at any point in time will delay production?
- What is the optimal age at which this asset should be replaced or overhauled?

It is vital in PAM to make decisions relating to asset criticality based not simply on discussion and experience, but by employing fixed techniques and clearly stated methods. This is emphasised by ISO 55000 (2013) with the following statement, that an AMS shall:

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

It is important to retain consistency throughout the evaluation and decision-making process, according to The Institute of Asset Management (2011), and to ensure that methods used are understood and documented, with clearly stated boundaries. World class decision making involves stating confidence intervals and risks associated with the decisions made. Through modelling and understanding criticality and risk associated with decisions, implications of failure can be properly understood and optimally managed. Due to the fact that production systems often experience a shortage of resources, whether time, personnel, or capital, a necessary subsequent step is to prioritise the available interventions in such a way that the resources are always allocated in the most effective manner.

PAS 55-2 clause 4.3.3.2 corroborates this with the following statement:

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

In addition to explicit modelling, human judgement is needed to ensure good decision making. Very often, notes Neilson *et al.* (2008), sophisticated tools which remove human judgement from the decision-making process, become abstract and cause operators to accept solutions too readily. On the applicability of tools in PAM decision making, PAS 55-2 discusses various methods such as RCM, value engineering, risk based inspections etc. but states:

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

A variety of decision support tools are mentioned in clause 4.4.7.7 of PAS 55-2 that are available to support risk assessments. Maintenance decision making has a great

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influence on the successful operation of an organisation, by keeping physical assets in working condition, thus keeping production running, reducing unexpected downtime, and optimising asset utilisation.

2.2.1 Modelling Techniques in PAM Decision Making

Almost any time a decision is made, a model is used to aid the decision maker. Models may include ill-defined, implicit models which are as simple as a decision maker weighing up different scenarios, or may be advanced, explicit models involving mathematics, simulation and quantitative analysis, which use sophisticated techniques and tools to provide a decision maker with extensive information about a situation. Modelling is thus an integral part of problem solving and decision making in any discipline.

Sometimes one uses models implicitly (without being aware that one is doing so) at other times one consciously or explicitly constructs or uses a model. An explicit model is an indispensable tool for solving problems and for explaining and demonstrating the solution, note Starfield *et al.* (1993). A symbolic representation of a problem is clean and powerful, and communicates simply and clearly what the modeller believes is important, what information is needed and how that information will be used.

Models are used to represent reality, and offer an abstract, simplified representation of a system, which highlights certain features in order to better understand them. Starfield *et al.* (1993) state that a model is a partial, rather than a complete representation, and it can be likened to a 'caricature' of a system, where certain relevant parts are emphasised and elaborated upon. Seila *et al.* (2003) note that management sciences use models to make administrative or managerial decisions, and contrasts this to operations research, which uses explicit mathematical models.

Even a rudimentary answer is better than no answer at all. It may be found that due to modelling constraints, such as time, money, lack of data and available resources, a model is limited in its adequacy in representing a system, or that due to proportional effort, these constraints are induced or implied. Under these circumstances, though, it may be found that a model that is inadequate under one set of circumstances is the most effective under another set of circumstances, when considering the required resources and effort taken to build an improved model.

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2.2.1.1 Definition of a Model

White & Ingalls (2009) give the general definition of a model as *"an entity that is used to represent some other entity for some defined purpose,"* and provide the rationale that models are employed when investigation of the actual system is impractical or prohibitive. This might be because direct investigation is expensive, slow, disruptive, unsafe, or even illegal. Models can be used to study systems that exist only in concept.

Seila *et al.* (2003) describe a model as an abstract and simplified representation of a system, stating that a model is generally a specification of which system components are important and of the way in which they interact. A model is thus a simplified description of a system which specifies the assumed relationships between system components.

Seila *et al.* (2003) define a *stochastic* or *probabilistic* model as a model in which randomness or uncertainty is inherent — that is, variables that are random or uncertain are involved in an essential way.

Model Anatomy

Seila *et al.* (2003) define a *parameter* as any numerical characteristic of a model or system. An *input parameter* is any parameter whose value is required as part of the model specification. An *output parameter* on the other hand is any parameter whose value is defined by the system and its input parameter, and generally specifies some measure of the system's performance. This is shown succinctly in Figure 2.10

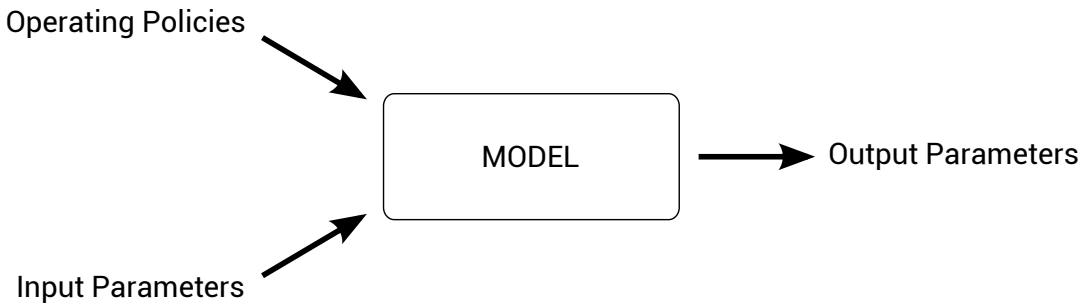

FIGURE 2.10: Model structure showing input and output parameters
Adapted from Seila et al. *(2003)*

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2.2.1.2 Model Validity

Validation, according to Kleijnen (1995) is concerned with determining whether the conceptual model is an accurate description of the system under study. Validity is often thought of as the degree to which a model faithfully represents its system counterpart. However, Robinson (2004) argues that it makes much more practical sense to require that the model faithfully captures the system behaviour only to the extent required by the objectives of the simulation study.

Modelling is severely constrained by complexity limitations, state Starfield *et al.* (1993). Successful modelling can be seen as *valid simplification*. We must *simplify* in order to enable our models to overcome resource constraints, but the simplified model must also be *valid* at some level, and within some experimental frame of interest. Depending on the frame of interest, a simple model may be just as capable as a complex one. It is vital to determine the "resolution" of the model — to establish the objective of the problem and ask whether detail is really necessary. The modeller should ask "What is the best answer we could give?" or according to Kleijnen (1995), "Is the model good enough?", rather than "What is the perfect solution?"

A further validation tool is including statistical information to describe a solution. For example, including upper and lower bounds with confidence intervals instead of stating a quantity provides the analyst with a measure of validity of the solution.

2.2.1.3 Modelling in PAM Literature

Achermann (2008) notes that off-the-shelf and best practice methods to select maintenance strategies, as well as spare parts stock keeping, are widely spread in manufacturing industries; they are mainly based on experience and production system manufacturer proposals. A further observation is made that improvements are normally done step-wise in a trial and error manner, and very rarely account for cost-effectiveness. A strict line of action is absent, which often originates from missing objectives and monitoring tools. Maintenance actions should always be aimed at optimising the profitability of a production system. Optimisation of maintenance implies finding an optimised role for maintenance within a production system, which encompasses factors such as demand forecasting and production planning. These complex interactions require sophisticated

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tools which facilitate the quantitative optimisation of maintenance actions. Achermann (2008) suggests that optimising the maintenance strategy under consideration of demand is a complex task and needs simulation to support decision making.

Mitchell (2007) notes the importance of having clear, specific, quantitative objectives, and measuring and monitoring these objectives accurately. Moore & Starr (2006) emphasise the need for maintenance information to be easily obtained and merged, so that optimal decisions can be made, and notes that enabling technologies such as the internet and Enterprise Resource Planning (ERP) software have made strides toward improving the quantity and quality of data that can be used for decision making.

Even though many rating and optimisation approaches such as RCM and TPM have been developed, they still lack reliable quantitative measurements, which does not allow for cost-benefit calculations to be considered, and furthermore does not allow for the comparison of different investment strategies. Machine availability has a substantial impact on the profitability of asset-centric production systems, note McKone *et al.* (1999b), and thus state of the art maintenance strategy optimisation techniques should always be based on models which are able to quantify the benefits of such programs.

Moore & Starr (2006) observe that there is a great deal of literature which concentrates on modelling for fault diagnosis and location, but there is less which deals with decision making in maintenance management.

Modelling Plant Reliability

Jaafari *et al.* (2006) describe a project which uses process simulation and optimisation for project-based strategic asset management. It is noted that strategic management decisions need to be made on a set of alternative scenarios, generated from a solution space defined by value chains and asset configurations, so that strategic business objectives are optimised. The project details the use of simulation for evaluating the alternative scenarios for feasibility and also for searching the solution space for alternatives.

Achermann (2008) notes that maintenance has a strong impact on production system availability and as such, performed a study focussing on simulating maintenance strategies and investigating optimisation techniques to achieve maximum service level. It was proved that a joint optimisation of logistic and maintenance strategy is useful

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and that financial objective functions tend to be the better optimisation criterion than production system availability.

2.2.1.4 Systems Analysis

A system is a set of interrelated objects that cooperate in order to achieve a common goal. A processing plant should be viewed as a system, where a set of machines cooperate in sequence and in parallel with one another in order to produce some output. Successful analysis of the system relies on having both an overview of the interrelationships between objects, as well as being able to isolate subsections and objects and analyse them at any level of detail.

The term *'system'* is used liberally throughout this thesis for a reason — no entity in a business environment exists in isolation, and it is therefore valuable to analyse as a constituent part of a greater activity.

In systems analysis, state Zeigler *et al.* (2000), the behaviour of an existing system is analysed based on its known structure. One form of systems analysis is computer simulation, which generates data through instructional logic provided by a simulation model. Although no new knowledge is generated, interesting properties of the system may be unveiled which we were not aware of before the analysis.

Systems Perspective in Asset Management Strategy Formulation
According to Whittle (2004) there are many tools and techniques for optimising various parts of physical asset systems in isolation, but the last frontier is to make these parts function properly as a system. Whittle (2004) suggests using business modelling and analytical techniques to model the system, and mathematical optimisation to maximise the value of the system.

2.3 Conclusion – Literature Study

Chapter 2 aimed to provide the reader with an understanding of the context of the problem introduced by the problem statement in Section 1.4, with the goal of introducing the various areas of influence which the thesis topic touches on.

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A thorough discussion of the field of PAM was provided and standards such as PAS-55 and ISO 55000 were recognised for their role in providing a solid framework for PAM. A brief evolution of maintenance practises was given, which uncovered the role of plant maintenance and the methods created to fulfill this role. An overview of the challenges and possibilities in maintenance optimisation was given, in order to discover the need for prioritisation of maintenance interventions.

The final section of this chapter aimed to glance over potential approaches which have been suggested by other authors to solve the problems related to the prioritisation of maintenance interventions. A number of projects were recognised that realised the same problem, though the approaches and needs recognised by other authors differed slightly in that they focussed on different aspects of the problem. The proceeding chapter examines the notion of prioritisation thoroughly and provides an overview of available methods which could potentially be used to fulfill the requirements of the problem statement.

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3 | Prioritisation Techniques in Physical Asset Management

CHAPTER 3 discusses the role of prioritisation methods in maintenance, and builds upon the arguments presented in the problem statement in Chapter 1, with the necessary additional PAM background gained from Chapter 2.
The chapter introduces a number of varied methods which could be used for maintenance prioritisation, and concludes with a comparative analysis and a selection of the most appropriate method.

Introduction

PAM Landscape

PAM PRIORITISATION TECHNIQUES
Requirements
Markov Chains
Weibull Analysis
Theory of Constraints
Simulation
FMEA/FMECA
Method Selection

Prioritisation Methodology

Case Study

Conclusion

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3.1 Summary of Project Requirements

It has been well established previously in Sections 1.4, 2.2, and 2.2.1 that there is both a need and a desire for quantitative decision making in PAM and in management in general. Moreover, as discussed, there is a need for these techniques to be accessible to employees and simple to apply on an operational level, in order to provide sustained support for PAM decision making. The aim of this chapter is to provide a thorough discussion of various techniques which may potentially address the issues mentioned in previous sections.

The idea behind criticality analysis is to identify the "vital few" factors which have the greatest effect on the operations at the plant. The purpose of prioritising is to differentiate these important factors from the rest, so that special focus can be given to improving them. Indeed, if too many factors are equally important in the eyes of management, none receive adequate focus.

Summary of Requirements

As a summary of the requirements mentioned in the problem statement of Section 1.4, and after subsequent considerations in Chapter 2 which highlight required features, the following criteria were identified which the technique should comply with:

Systems Based The selected method should view the system in its entirety and consider the complex interactions which exist between the machines and other internal and external factors.

Accessible The selected method should be able to communicate the problem in a manner which is understandable by plant management. The benefit gained from the method should be somewhat proportionate to the effort required to execute the analysis. Ideally, a flexible approach is sought, where any required level of abstraction is obtainable.

Objective The analysis should be based on objective information and real-world data as far as possible, and should be validated by an appropriate empirical method.

Quantitative A vital facet of the analysis should be to aid plant managers in budgeting by attributing costs to improved maintenance practices.

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The techniques presented here have all been identified as potential candidates which address some or all of the stated requirements, with varying degrees of adequacy and complexity. Some of the techniques may seem poor choices as they clearly fail to comply with certain requirements, however the most effective solution was sought with regards to potential benefit for induced effort. A broad range of techniques was considered, some (like Operations Research) take a hard approach and seek accuracy, while others (for example Theory of Constraints) take a softer approach and are more philosophical in nature. The techniques mentioned are well established in literature and practice, though generally for different roles to the ones that they fulfill here.

Numerical Decision Making

Lindley (1991) provides three basic principles to keep in mind to make effective numerical decisions:

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

An unwanted event represents any type of failure or fault that influences the operational capabilities of an asset. The probability of unwanted events goes hand in hand with the reliability of a system. If the system is reliable there is a low probability that unwanted events might occur, and vice versa. A basic paradigm of reliability modelling is that in order to maximise the expected utility of a production system, the reliability of the system needs to be maximised and the adverse consequences need to be minimised. Often multiple attributes are involved when balancing different objectives such as minimising consequences, maximising availability and reliability, amongst others.

Criticality/Priority Ranking Tools

As with many operations improvement projects, PAM maintenance opportunities are often selected using Pareto analysis by focusing on the resource with the most unscheduled down time, note Chakravorty & Atwater (1994). The logic of this approach is fairly straightforward in that the resource experiencing the most unscheduled down time is assumed to present the biggest potential to the system for improvement. However

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due to complex system interactions and constraints this is unlikely to paint the entire picture and may induce wasted effort.

A number of relevant projects and papers were consulted in addition to traditional sources of information about the techniques in this chapter, with the aim of finding the most suitable method to fulfill the requirements set by this study.

3.2 Analytical Modelling Using Markov Chains

History of Operations Research and Analytical Modelling
Operations Research (OR) is a termed coined during World War II when British scientists and engineers were tasked by military leaders to analyse several military problems relating to infrastructure, transportation, bombing and mining operations to aid decision making during the war.

OR is a scientific approach to decision making which usually involves one or more *mathematical models*, which create an abstract representation of a situation in order to better understand its operation. OR is therefore defined by Winston (2004)[1] simply as *"a scientific approach to decision making that seeks to best design and operate a system, usually under conditions requiring the allocation of scarce resources."* This definition allows for a broad interpretation of the term, as any *scientific* methods which are employed to optimise an operation. Most of the models used in OR are *prescriptive* or *optimisation* models. That is, they "prescribe" a certain behaviour using objective functions, decision variables and constraints as components, which are pre-defined in order to help an organisation best achieve its goals.

The extensibility of OR is virtually unlimited, as theoretically new techniques may be created to fit almost any situation, however the system under study may yield a model which is so complex that it cannot be described by a mathematical model. Seila *et al.* (2003) suggest that this leaves the analyst with the option of further simplifying the model to a level of abstraction which is "manageable" for an analytical approach — though this may perhaps make the model unrealistic or unusable in the process.

OR literature describes many such techniques, and indeed, following the broad

[1] Winston (2004) is a comprehensive introduction to OR and is referred to throughout this section.

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definition given, almost any quantitative method used to improve operations qualifies as an OR technique.[1] However, a technique is sought which can be used to model a production system and the effects of its components' downtime on the system in order to prioritise available maintenance interventions, and to this end two relevant modelling approaches, namely Markov chains and Weibull analysis, will be considered with the aim of shedding light on the available knowledge which can be applied by these methods to solve this particular problem.

3.2.1 Markov Chains

As an example of an analytical approach which may be considered for this project, Markov chains are described here specifically because they often provide the basis for modelling the stochastic production/failure process. A brief overview Markov chains is given in the following paragraphs.

A Markov chain is a special type of discrete-time stochastic process, and is defined by Hermanns (2002) as a stochastic process with the Markov property — that is, that the previous state is irrelevant to predict the probability of the subsequent state. In other words, the Markov chain is "memoryless", as the states have no causal connection with other states in the sequence. Markov chains have many applications as statistical models of real-world processes.

The mathematical definition of a Markov process is given by Winston (2004) as follows:

A discrete-time stochastic process is called a *Markov chain* if, for $t = 0, 1, 2, \ldots$ and all states $\mathbf{X}$,

$$P(\mathbf{X}_{t+1} = i_{t+1} | \mathbf{X}_t = i_t, \mathbf{X}_{t-1} = i_{t-1}, \ldots, \mathbf{X}_1 = i_1, \mathbf{X}_0 = i_0) = P(\mathbf{X}_{t+1} = i_{t+1} | \mathbf{X}_t = i_t)$$

A discrete-time random process involves a system which is in a certain state at each step, with the state changing randomly between steps. The steps are often thought of as moments in time, but they can equally well refer to physical distance or any other discrete measurement. Since the system changes randomly, it is generally impossible

[1] It should be noted that simulation, as described later in this chapter, is also classified as OR.

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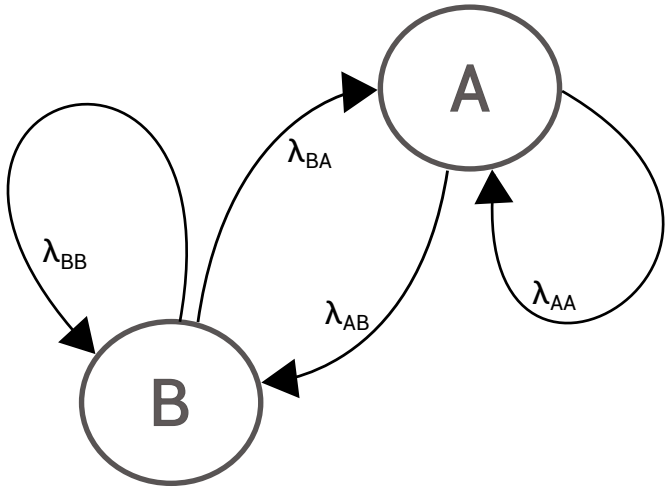

FIGURE 3.1: A basic Markov process with states A and B and transition probabilities λ_{ij}.

to predict with certainty the state of a Markov chain at a given point in the future. However, the statistical properties of the system's future can be predicted. In many applications, it is these statistical properties that are important. A basic Markov chain consisting of two states, A and B, with transition probabilities $\lambda_{t,t+1}$ is shown in Figure 3.1.

3.2.2 Markov Chains in Maintenance Prioritisation

Jardine *et al.* (2011) use a Markov chain to represent the behaviour of a physical system, and combine a number of condition indicators, coupled with failure cost data and life expectancy, however the approach does not deal with the prioritisation of a range of potential actions. Chan & Asgarpoor (2006) present a method to find the optimum maintenance policy for a specific component. Using state probabilities, the problem is set up as a Markov decision process and an optimum maintenance policy using a policy iteration algorithm is determined.

Gharbi & Kenne (2000) model multiple-identical-machine manufacturing systems with random breakdowns, repairs and preventative maintenance, with the objective of finding the production and preventative maintenance rates that minimise the total cost of inventory. This is performed by combining analytical formalism and simulation-based statistical tools and response surface methodology.

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Boukas & Haurie (1990) and Boukas *et al.* (1995) propose a model for planning production and maintenance in a flexible manufacturing system. The authors argue that machine failures depend mainly on usage, and that this dependance can be formulated by considering the machine state as a Markov process governed by production rates, and that can be affected by preventative maintenance. The model proposed is a stochastic control flow model which is used to compute the optimal control policy. The model makes many assumptions on the operation of a system and may be complex to adapt to larger systems.

Dimitrakos & Kyriakidis (2008) develop a semi-Markov decision algorithm to model the optimal preventative maintenance of a deteriorating installation. Grall *et al.* (2002) develop an analytical model for continuous-time predictive maintenance scheduling for a deteriorating system. The proposed decision model enables optimal inspection and replacement decision in order to balance the cost engaged by failure and unavailability. A mathematical model for the maintained system cost is developed using regenerative and semi-regenerative process theory.

Van der Duyn Schouten & Vanneste (1995) consider a finite-state Markov decision process for the optimal preventative maintenance of an installation in a production line with an immediate buffer. Kenn & Gharbi (2004) consider a production control problem in a manufacturing system with failure-prone machines and a constant demand rate, with the objective to minimise a discounted inventory holding and backlog cost over and infinite planning horizon. The machine capacities are described by a finite state Markov chain and the decision variables are input rates to the machines and their repair rates.

Abboud (2001) models a production-inventory system with constant production, random failure-rates and repair times as a Markov chain, and develops an efficient algorithm to compute the average system cost, which is in turn used to determine economic manufacturing quantities.

3.2.3 Conclusion – Markov Chains

Dimitrakos & Kyriakidis (2008) note that many papers have emerged dealing with Markov decision models for the optimal maintenance or replacement of a device, which operates in time and is subject to deterioration. Indeed, Kenn & Gharbi (2004) note that many authors contributed in the sphere of the production-planning problem of the

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flexible manufacturing systems, but that the problem becomes much more complicated with large flexible manufacturing systems involving multiple machines, multiple parts, random demands and breakdowns.

Analytical approaches are certainly more than capable of solving specific sub-problems in the field of maintenance optimisation and should not be overlooked, however it is duly noted that they often lack the scalability, simplicity and flexibility that other approaches can provide. Analytical approaches necessarily trade their pin-point accuracy for accessibility, which means that more accessible and easily understood models may be inadequate in their analysis.

Most analytical models in the maintenance sphere deal with specific sub-problems, where optimality of a solution is proportional to its accuracy. Many of these problems, as can be derived from the works mentioned in the previous section, seek to find optimal repair and replacement policies for single machines or at best small systems. While the formulation of such relatively simple sub-problems often requires an advanced understanding of mathematics, the extensibility of these problems to include larger systems is far from trivial. In order to reasonably apply these methods to fit the problem statement, concessions will therefore have to be made in the analyses' accuracy and validity, by improving the accessibility and extensibility of the model.

3.3 Weibull Analysis on Individual Components

The Weibull analysis uses historical failure data in order to characterise failure behaviour of system components by means of a Weibull distribution. This distribution is in turn used in different failure models that calculate failure occurrences. Indeed, Abernethy (2002) claims that Weibull analysis is the leading method for fitting life data to a distribution.

Abernethy (2002) names the scope of Weibull analysis to include:

- Plotting the data and interpreting the plot
- Failure forecasting and prediction
- Evaluating corrective action plans

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- Engineering change substantiation
- Maintenance planning and cost effective replacement strategies
- Spare parts forecasting

A Weibull distribution is often used to estimate lifetime. It can fit more failure patterns than an exponential distribution and flexibly describes increasing and decreasing failure rates.[1] Mitchell (2007:pp. 101) notes that the Weibull distribution may be used to analyse weakest link subsystems where the system fails with the first subsystem failure.

Although Moore & Starr (2006) maintain that the Weibull distribution is somewhat reliant on historical failure data, Abernethy (2002) argues that the primary advantage of Weibull analysis is the ability to provide reasonably accurate failure analysis and failure forecasts with relatively small samples compared to other analysis techniques.

The following example can demonstrate how Weibull analysis could be used for maintenance prioritisation[2]:

Example

A machine runs 24 hours a day for 7 days a week and it has been estimated through analysis of historical breakdown data that it fails according to a Weibull distribution with parameters $\beta = 1.2$ and $\eta = 240$ hours.

Using this distribution one can calculate the reliability of the machine at the current instant — for example if it is currently 70 hours since the last failure, then the reliability of the system can be calculated as $R(X) = 79.60\%$ and the value of the hazard function as $h_x(70) = 0.39\%$

These results tell us that the machine has a 79.60% chance of surviving to this moment, and that there is a 0.39% chance that a failure will occur in an infinitesimally short period into the future, provided that the system is still alive at time X. This information can be compared to other assets in the system and critical assets can thus be prioritised based on their reliability.

[1] A comprehensive look at using the Weibull distribution for failure forecasting and prediction is provided later in Section 4.3.2.5.

[2] See Section 4.3.2.5 for calculation methods and formulas

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3.3.1 Conclusion – Weibull Analysis

The method proposed of using Weibull analysis for the prioritisation of maintenance improvements overlooks an important aspect of the problem statement in that it isn't systems based. The method looks at each node or machine in a production system individually without considering the complex interactions which may exist between the machines, which may actually dampen or exacerbate the effects of a failure. Furthermore, while this method can be used rank the items, it makes no attempt to explain either the causes or effects of failures, unlike the other methods mentioned here. The ranking system is good in that it is analytical, accurate, and most importantly, based on actual data where it is available.

Weibull analysis can be incorporated into other types of modelling, as ultimately it is simply a probability distribution — one which is has proven very capable of describing failure occurrences.

3.4 Theory of Constraints

Developed by Goldratt *et al.* (1992) in the mid 1980s, Theory of Constraints (TOC) is a management paradigm that views any manageable system as being limited in achieving more of its goals by a very small number of constraints. There is always at least one constraint, and TOC uses a focusing process to identify the constraint and restructure the rest of the organisation around it. TOC adopts the common idiom *"a chain is no stronger than its weakest link"*. Nave (2002) explains that this means that sequential production systems and processes are vulnerable because the least reliable node in any sequence can adversely affect the outcome of the entire system. Thus TOC focuses on identifying these weakest links and elevating the constraints placed on them.

Rahman (1998) explains the basis of TOC thinking with the following two points:

1. *Every system must have at least one constraint.* If this were not true, the organisation would make infinite profit. A constraint is therefore defined by Goldratt *et al.* (1992) as *"anything that limits a system from achieving higher performance versus its goal."*

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2. *The existence of constraints represents opportunities for improvement.* Contrary to conventional thinking, TOC views constraints as positive, not negative. Because constraints determine the performance of a system, a gradual elevation of the system's constraints will improve its performance.

The philosophy's founder, Goldratt *et al.* (1992) provides the five steps in the TOC process, described below and depicted in Figure 3.2.

Identify the constraint the constraint is identified through various methods. The amount of work in process behind the component is a classic indicator according to Nave (2002)

Exploit the constraint Once the constraint is identified, the process is improved or otherwise supported to achieve its utmost capacity without major expensive upgrades or changes.

Subordinate other processes to the constraint When the constraining process is working at maximum capacity, the speeds of other subordinate processes are paced to the speed or the capacity of the constraint. Some processes will sacrifice individual productivity for the sake of the system. Processes after the constraint are not a major concern, as they are probably already producing under capacity because they have to wait for the constraining process.

Elevate the constraint If the output of the overall system is not satisfactory, further improvement is required. The organisation should now consider major changes to the constraint, which may involve capital expansion, major overhauling of equipment or outsourcing of certain operations.

Repeat the cycle Once the first constraint is broken, the system bottleneck shifts to another area of the chain. The performance of the entire system is re-evaluated by searching for the new constraint process and repeating the steps.

Nave (2002) notes that TOC has a strong focus on system improvement. Without making TOC sound like a magic bullet, Dettmer (1997) opines that these five tools, when effectively applied, empower the user to identify precisely and to execute the one or two focused changes that will produce maximum system improvement with the minimum investment of time, energy, and resources — and do it right the first time, without costly trial and error.

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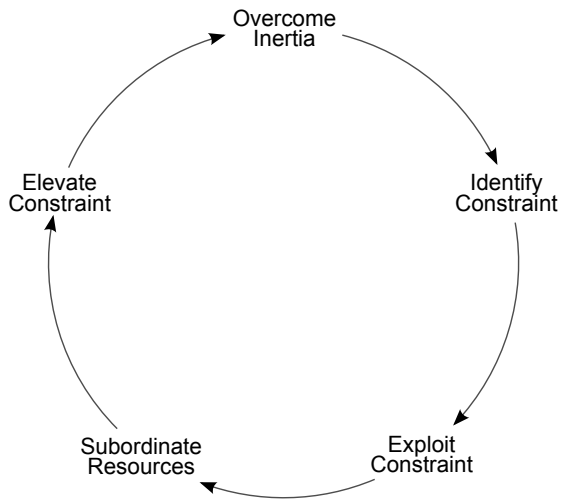

FIGURE 3.2: Theory of Constraints, major activities.

Nave (2002) states that TOC overcomes one criticism of most improvement programs: that many programs try to focus on improving every aspect of the organisation simultaneously by employing a one-size-fits-all approach, in the hope that improving processes individually will also improve the output of the system. This may induce much wasted effort, as processes which don't constrain output are improved, merely creating excess capacity at certain nodes but not affecting system output at all.

To address the policy constraints and effectively implement the process of on-going improvement, Goldratt *et al.* (1992) develop a generic approach called the "thinking process", which is the current paradigm of TOC. Experts such as Rahman (1998) believe that it is the thinking process of TOC which will ultimately have the most lasting impact on business.

3.4.1 TOC in PAM Literature

A good review of TOC literature in applications in literature is provided by Rahman (1998).

Ribeiro *et al.* (2007) use a mixed integer linear programming model and TOC philosophy to jointly optimise the maintenance, operation, and buffer size of a capacity constrained resource. Simatupang *et al.* (1997) propose a diagnosis of TQM using TOC, and using the philosophy to revitalise and direct TQM efforts in the firm, arguing that

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Goldratt *et al.* (1992)'s method for self-reflective diagnosis provides the basic principles to describe cyclic processes of perceiving, judging and acting.

Although it is not necessarily quantitative in nature, TOC is by its own nature a system-wide prioritisation technique. To this end, there is abundant literature on the application of TOC in a production environment, though not specifically focussed on PAM or maintenance.

3.4.2 Conclusion – TOC

The use of TOC to prioritise maintenance specifically is spare in literature, though this is somewhat expected as prioritisation of repairable components in the system would necessarily preclude maintenance activities. The crux of the problem though, lies in determining the bottleneck of the system. In simple cases, the methods provided by TOC literature may prove ample to determine system constraints, but as stated in previous chapters, in complex systems a more thorough modelling analysis may be needed. The presence of bottlenecks that are formed as a result of reliability and not through analysis of throughput, may be even more difficult to pinpoint. Furthermore, as stated by the problem statement, a method which is quantitative in nature is sought.

To its merit, TOC provides an excellent philosophy for the management and alleviation of these bottlenecks, and does so with continuous improvement in mind, which is certainly useful information post-analysis.

3.5 Failure Mode and Effects Analysis

Failure Modes and Effects Analysis (FMEA), according to Xiao *et al.* (2011) is a powerful and effective analytical too which is widely used in engineering projects to examine possible failure modes and eliminate potential failure during system designs. It provides engineers with appropriate quantitative and qualitative measures to guide the implementation of corrective actions by ranking and focussing on principle failure modes and their effect on productivity.

Usage of FMEA began in the US military in the 1950's as a formal technique to

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improve aviation reliability. During the 1970s, use of FMEA and related techniques spread to the automotive sector, and it is now used extensively in a large variety of industries.

Ben-Daya (2009) defines FMEA as a systematic analysis of potential failure modes aimed at preventing failures. It is intended to be a preventative action process carried out before implementing new changes in products or processes. The basic FMEA steps, as adapted from Ben-Daya (2009), are shown in Figure 3.3.

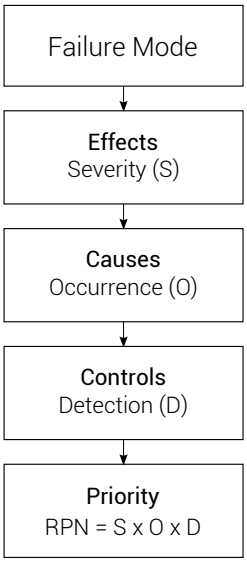

FIGURE 3.3: Important FMEA tasks.

In traditional FMEA, the Risk Priority Number (RPN) is used to prioritise interventions. An RPN is described by Xiao *et al.* (2011) as a number that measures the ranked importance of the items listed in the FMEA chart as calculated for each failure mode, and is nominally calculated as follows:

$$\text{RPN} = \text{Severity} \times \text{Occurrence} \times \text{Detection}$$

where Severity is the result generated from failure, Occurrence is the probability of a failure, and Detection is the opportunity for an unidentified failure due to difficulty in detection. The three factors are all scored from 1 (best) to 10 (worst) on a predetermined relational scale. Once all items have been analysed and assigned an RPN value, corrective actions are undertaken in descending order.

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Criticality criteria are usually identified by the probability of the failure mode and the severity of the effect. FMEA is used to assess the safety of various system components, and to identify design modifications and corrective actions required to reduce the effects of a failure on the system. It is thus a *pre-failure*, systems analysis technique which prioritises potential failures. Although FMEA is often thought of as a safety analysis, Kovacova & Janco (2008) argue that its main benefit is that the system designers learn more about the system while providing the analysis.

The value of FMEA lies in its simplicity, as in its least sophisticated forms it can almost be done as a "back of the napkin" calculation, and as a result of this simplicity it is very effective at prioritising work and giving operators an easy way to answer the basic question — *"What do we do next?"*. However, Kovacova & Janco (2008) also highlight that FMEA can become tedious and is prone to error as a result of its inherent subjectivity.

Achermann (2008) points out that FMEA falls short when assessing failures for their potential economic effects, as in complex systems it is difficult to ascribe quantitative values to a failure with far-reaching effects. In the execution of FMEA most criteria are measured subjectively and do not provide a quantitative basis for evaluation. It is therefore impossible to guarantee the viability of any action on an objective basis, or to provide a figure which gives an indication of the value of a project. For this, more sophisticated modelling techniques are required which attempt to analyse the system holistically.

3.5.1 Criticality Analysis

An FMEA that includes CA is referred to as a Failure Modes Effects and Criticality Analysis (FMECA). Moore & Starr (2006) defines criticality assessments as procedures which aim to identify those assets that could have the greatest effect on an operation if they were to fail. Criticality is usually described as a function of severity and rate of occurrence, typically using a formula such as $Criticality = Frequency\,of\,Failure \times Consequence\,of\,Failure$, and presenting results of a risk map, such as the one shown in Figure 3.4.

The goal of a CA in a maintenance environment, according to Smith & Mobley (2009), is to identify equipment with the largest contribution to the business goals

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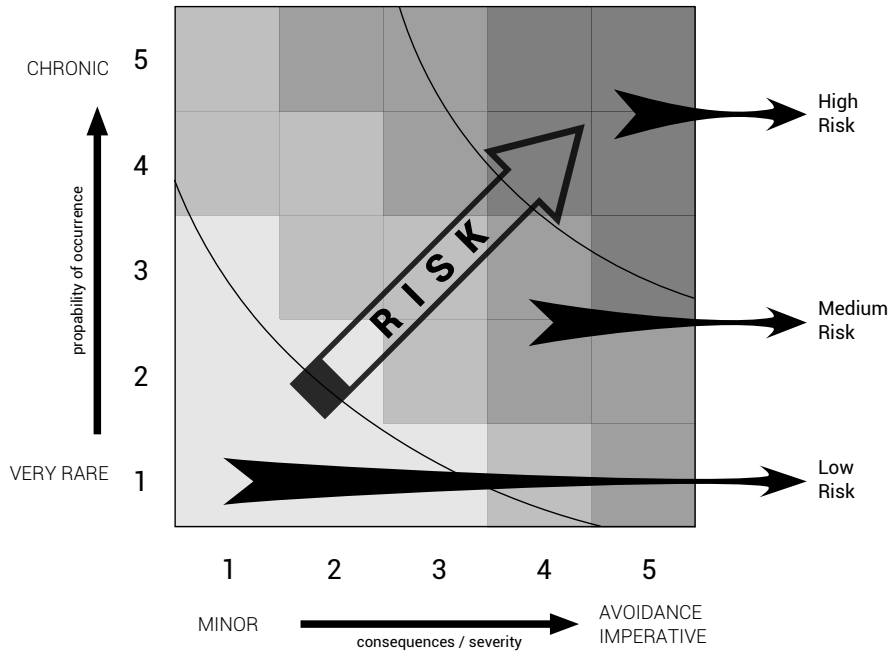

FIGURE 3.4: Risk Rank Matrix

in terms of physical asset reliability. Critical equipment can thus be defined as the equipment whose failure has the highest potential impact on the business goals of the company.

In a production environment this translates to identifying machines whose lack of reliability causes the greatest production losses. This ability to accurately link machine downtime to production throughput can be difficult to accomplish for complex systems, as these normally include advanced interactions between machines, such as parallel processing, reworking and storage buffers.

A ranking system usually accompanies a CA, which attempts to give operators an indication of where their efforts would best be spent. This system is relative in nature, and not quantitative. Although CA often includes financial consequences of failure, and these are absorbed into the ranking system, it must be emphasised that CA lacks the capacity to provide evidence of the *positive* effects of asset management which literature so unanimously advocates.

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Moore & Starr (2006) state that CA is usually a tacit part of an organisation's decision to select a maintenance strategy, carried out based on collected data or the experience of personnel. However it is noted that once the strategy is adopted it is unlikely to be used to prioritise activities on a regular basis. Moore & Starr (2006) also highlights the importance of on-line criticality, stating that once FMECA have been performed, they typically remain on paper and the knowledge gained is rarely integrated into ERP, Computerised Maintenance Management System (CMMS) and Enterprise Asset Management (EAM) strategy.

Moore & Starr (2006) illustrate the problems experienced by decision makers trying to cope with condition monitoring alarms and propose a method to focus attention automatically on alarms that pose the greatest risk to the organisation. The concept of condition based criticality is introduced, which basically alters a CA to use *cost* as the *consequence* metric. The cost metric is, however, not succinct enough to provide an objective measure, as it includes items which are either very difficult to quantify and/or are subjective, such as *'customer satisfaction'* and *'safety and environment'*.

3.5.2 Risk Analysis

Risk is defined by Jabiri *et al.* (2006) as the exposure to loss/gain, or the probability of occurrence of loss/gain multiplied by its respective magnitude.

Jabiri *et al.* (2006) classify three different categories of risk:

Strategy Risks: Risks associated with meeting market opportunities, defined for example by asset configurations or resource allocation. Identifies whether an existing asset is under-used or misaligned with expected operations.

Investment risk: Risks associated with investment decisions.

Conditional risks: Risk associated with the conditions that actually arise during the course of operation.

Jabiri *et al.* (2006) states that in the present dynamic business climate, asset-centric organisations are under increasing internal and external pressures, which can cause business discontinuities and may force the business into taking greater risks in order

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to remain competitive. In a PAM environment, risk analysis is therefore important in managing the risks associated with the production environment, including failures.

3.5.3 Conclusion – Failure Modes and Effects Analysis

In general practice, FMEA would classically be the most obvious choice for ranking the criticality of machinery in a production system, and therefore prioritising the amount of care that should be taken in dealing with each of the problem areas identified.

Perhaps the greatest issue with using FMEA for prioritisation is that in its rigid formulation, FMEA tends to be too reliant on human judgement in estimating the effects of an event occurring. There is little emphasis on accuracy or quantifying results — a trade-off that is happily made in favour of accessibility and speed to results. As with many of the techniques discussed in this chapter, when analysing large systems with complex interacting components the analyst may be overwhelmed by the complexity or misled into false interpretations of which areas are critical.

The methods employed by FMEA post prioritisation are useful in uncovering the root causes underlying a failing piece of equipment and should not be overlooked when seeking techniques for this purpose.

3.6 Simulation

Banks *et al.* (2005) gives a broad definition of simulation as *"the imitation of the operation of a real-world process or system over time."* For this purpose, it is required that a model is built of a real world system, which is an abstraction of the system, that has the required characteristics, data inputs and output parameters to be investigated. In the case of computer simulation, this model is then used to play out scenarios by mimicking the behaviour of the real-world system and observing the outcome.

The application of computer simulation is broad, and its use is increasing as it becomes more accessible due to the increasing accessibility of simulation software and the falling costs of computing. Simulation is often used as a substitute for or in parallel to modelling systems where analytical solutions are not possible due to complexity.

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Manufacturing represents one of the most important applications of simulation, stress Benedettini & Tjahjono (2009), and is a practical tool used by engineers when evaluating the effect of capital investment in physical facilities and equipment. Simulation is used to anticipate the operation of an existing or planned system, or to compare alternative scenarios for specific design alterations.

Simulation may be used to compare different maintenance plans and scenarios to optimise a system for cost or availability (as shown by Achermann (2008) and others). Sensitivity analysis may also be performed, as shown by Kleijnen (2005), in order to determine which changes to model inputs and parameters affect the system outputs. In this way, maintenance interventions can be prioritised according to what effect they will have on the system. A valid simulation model can give accurate quantitative data, so that a further prioritisation may be performed by comparing the cost to perform an intervention to the quantitative benefit that the intervention is likely procure.

3.6.1 History and Definition of Simulation

Simulation, according to Shannon (1975), is *"the process of designing a model of a real system and conducting experiments with this model for the purpose either of understanding the behaviour of the system or of evaluating various strategies (within the limits imposed by a criterion or a set of criteria) for the operation of the system."*

According to White & Ingalls (2009), simulation is a particular approach to studying models, which is fundamentally experiental or experimental, and is like running field tests, except that the system of interest is replaced by a physical or computational model. Simulation involves creating a model which imitates the behaviours of interest, experimenting with the models to generate observations of these behaviours, and attempting to understand, summarise or generalise these behaviours.

White & Ingalls (2009) state that simulation stands in contrast to analytical approaches to the solution of models. In an analytical approach, the model is expressed as a set of equations that describe how the system state changes over time, and these equations are solved using mathematical methods. The result gives the state of the system at any time as a function of the initial state, inputs, and model parameters. White & Ingalls (2009) note that for models that can be solved analytically this is always the preferred approach, but that for complex systems this is almost never the

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case. Chung (2003) states that an advantage of simulation is the ability to reduce the analytical requirements of modelling complex systems, and that simulation has encroached on the domains of mathematicians and operations research analysts.

The power of discrete-event simulation, according to Ingalls (2011), is the ability to mimic the dynamics of a real system. Ingalls (2011) further describes simulation as the process of designing a *dynamic* model of an actual *dynamic* system for the purpose either of understanding the behaviour of the system or of evaluating various strategies for the operation of the system.

Rohrer (2000) claims that visualisation has become a critical component of simulation technology as it reduces build time of the model and helps to communicate the results in an easily understood manner. Chung (2003:p7) notes regarding the use of animation in simulation, that many individuals have only the capacity to comment on the animation aspect of the simulation, and states that in addition to building a mathematically correct model, the simulationist should be able to demonstrate the significance of a model through animation. Animation is additionally a good tool for debugging and validating a model, and may be used to dynamically demonstrate how the model deals with different situations in real time, as opposed to the static nature of mathematical models.

Gaining insight into the operation of a system

Some systems are so complex that it is difficult to understand the operation of and interactions within the system without a dynamic model. In other words, it may be impossible to study the system by stopping it or by examining individual components in isolation. A typical example of this would be to try to understand how manufacturing process bottlenecks occur.

Testing new concepts and/or systems before implementation

A simulation model can help give an idea how well the proposed system will perform. The cost of modelling a new system can be very small in comparison to the capital investment involved in installing any significant manufacturing process. The effects of different levels and expenses of equipment can be evaluated.

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Sensitivity Analysis

The parameter values and assumptions of any model are subject to change and error. Pannell (1997) defines Sensitivity Analysis (SA) as the investigation of these potential changes and errors and their impacts on the conclusions to be drawn from the model. Saltelli *et al.* (2000) define sensitivity analysis as the study of how the uncertainty in the output of a system or model can be attributed to various sources of uncertainty in its inputs, and the degree to which variations in system inputs affect outputs.

There is a wide range of uses for SA. The following uses are adapted from Pannell (1997):

- Decision making or development of recommendations for decision maker
- Testing the robustness of an optimal solution
- Identifying critical values, thresholds or break-even values there the optimal strategy changes
- Investigating sub-optimal solutions
- Identifying sensitive or important variables
- Allowing decision makers to select assumptions
- Estimating relationships between input and output variables
- Model development, such as simplifying, validating and calibrating models

The simplest method for performing performing SA, according to Pannell (1997), is *One at a Time or One-factor-at-a-time (OAT/OFAT)*, which sequentially alters one parameter at a time while keeping all other parameters at a baseline, then returning parameter to its baseline and repeating for each of the other inputs.

In the context of quantitative modelling of PAM decision making and maintenance, SA can be used as a priority ranking tool, by comparing the sensitivity of certain inputs, such as maintenance interventions and unplanned failures, to relevant outputs, such as production output and system availability. Through mathematical modelling and SA an appreciation for the criticality of certain factors is obtained. This information is quantitative in nature and can be used to support decision making by prioritising

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Table 3.1: Drivers for a simulation project, based on Robinson (2004).

Evaluation	Comparing a system when evaluated against specific criteria.
Comparison	1. Comparing competing systems of similar functionality. 2. Comparing proposed alternatives.
Prediction	Estimate system performance under different operating conditions.
Sensitivity analysis	Determine which of one or several factors influence system performance
Systems improvement	Improving the performance of a system without obtaining guaranteed optimality.
Optimisation	Determing which combination of factor levels results in best overall system performance.
Functional relations	Determine the nature of relationships and the effects on the system's performance.

maintenance interventions and providing cost/benefit estimations for PAM related decisions.

3.6.2 Simulation Application

Seila *et al.* (2003) states that simulation is generally considered to be one of the most widely used tools in applied management science and operations research work, as it is applicable to a large number of models, and because computer equipment and methodology are widely available to implement models using these techniques. Robinson (2004) lists a number of drivers for completing a simulation project, shown in Table 3.1.

3.6.3 Conclusion – Simulation

Simulation is perhaps the most versatile of the techniques listed. Of all the techniques it is the best suited at modelling the operation of complex systems, and doing so from a system's perspective, which means that it can be used to quantitatively analyse the effects of maintenance if such scenarios can be created. Unlike other quantitative techniques, simulation doesn't suffer from a "state-space explosion", meaning that the level of complexity of the model is somewhat proportional to the effort required to create it, and not exponential as in the case of e.g. Markov chains.

Simulation may be prone to sensitivity to input data, so the availability of good historical data is generally a prerequisite. The expertise of the engineer performing the simulation is also vital, and the simulationist should ideally be an expert in the simulation software, the statistical analysis of data and the results obtained, and should

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have some experience in the field of application. As noted by Achermann (2008), questions about the validity and sensitivity of simulation results will always arise, and thus the experience and professionalism of the simulationist is vital in creating an acceptable model.

3.7 Comparison of Available Techniques

3.7.1 Summary of Available Techniques

The techniques introduced in this Chapter are succinctly summarised in Table 3.2.

3.7.2 Method Selection

In order to select an appropriate method for prioritising maintenance techniques, it is required to revise the Problem Statement in Section 1.4 in order to determine criteria by which the available methods can be ranked. Following this, a conformity evaluation matrix is used to select a viable method. A complete execution methodology is then presented in Chapter 4.

Summary of Requirements
For the benefit of the reader, the summary of requirements provided previously in Section 3.1, as deduced from the problem statement of 1.4, is repeated here:

Systems Based The selected method should view the system in its entirety and consider the complex interactions which exist between the machines and other internal and external factors.

Accessible The selected method should be able to communicate the problem in a manner which is understandable by plant management. The benefit gained from the method should be somewhat proportionate to the effort required to execute the analysis. Ideally, a flexible approach is sought, where any required level of abstraction is obtainable.

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TABLE 3.2: Comparison of available prioritisation techniques.

Method	Nature of Method	Description	Applicability
Analytical Modelling using Markov Chains	Analytical, Quantitative	Parts of the system can be modelled separately, or entire system can be modelled to a simple level of abstraction	Modelling approach is too complex, simple approaches inadequate
Theory of Constraints	Qualitative, ranking	System components are prioritised according to throughput rate. 'Bottleneck' component receives greatest attention until bottleneck shifts	Simple approach, good for continuous improvement, easy identification of bottleneck in a linear system complex system components (feedback loops and buffers) difficult to assess, not quantitative
FMEA/FMECA	Qualitative, ranking	Prioritises system components according to their perceived impact of failure	Complexity can range considerably depending on detail, tends to be subjective, only pseudo-quantitative due to subjectivity
Weibull analysis	Quantitative, statistical	Uses historical data to determine failure characteristics and failure trends of components	Not system-orientated so ranking can be misguided, relies heavily on accurate historical data
Simulation	Quantitative, qualitative	Mathematical emulation of real world system using best possible historical data and modelling insight	Level of complexity can be adjusted, multi-purpose evaluation, depends on availability of historical data

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Objective The analysis should be based on objective information and real-world data as far as possible, and should be validated by an appropriate empirical method.

Quantitative A vital facet of the analysis should be to aid plant managers in budgeting by attributing costs to improved maintenance practices.

Conformity Evaluation Matrix

The conformity evaluation matrix shown in Table 3.3 attempts to determine the adequacy of the proposed methods to meet the requirements for this project, as summarised in the previous section. Using this matrix, the available methods are critically examined and a viable solution selected. It is shown that simulation is the preferred method, as it conforms most adequately to all the selected criteria.

3.7.2.1 Conclusion

Boukas & Haurie (1990) note that in most of the manufacturing flow and control models considered yet, authors suppose that the jump disturbances affecting the system (e.g. machine failures) are described as a homogeneous Markov process, but that in practice, the probability of a failure depends on many factors, particularly its age.

Although it is an excellent management philosophy and a simple yet effective consideration of continuous system-wide improvement, which can be extended to PAM through its link with machine availability, the TOC approach of Goldratt *et al.* (1992) lacks the tools to natively provide an objective, quantitative measurement of system performance, especially when dealing with a large, complex system. The philosophy should not be overlooked by managers looking for a first-line system improvement analysis.

FMEA/FMECA's use in industry is ubiquitous for a good reason — it provides a simple and scalable analysis and prioritisation of the risks to system performance. This approach would likely have been most managers' first choice for the task proposed in this project, however it lacks the objectivity and quantitative nature that is sought by the problem statement, By its nature FMEA/FMECA isn't systems oriented, and isn't focussed on systems *improvement*, but rather focusses on *avoiding* negative situations.

Through deliberation of project requirements and an investigation of available

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TABLE 3.3: Conformity evaluation matrix of available prioritisation techniques.

	CRITERIA				
METHOD	**Systems Based**	**Accessible**	**Objective**	**Quantitative**	**SCORE (4)**
Analytical Methods	Parts of the system can be modelled separately, or entire system can be modelled to a simple level of abstraction **(0.5)**	Modelling approach is complex, simple approaches inadequate, abstract **(0.5)**	Yes, depending on availability of data and level of abstraction **(1)**	Yes, most methods **(1)**	**3**
Weibull on Individual Components	Analyses components in isolation **(0)**	Analysis based on collecting failure data from components **(1)**	Yes **(1)**	Yes **(1)**	**3.5**
TOC	Systems based by nature, systems analysis may be too simple for large systems **(0.5)**	Easily explained by Goldratt *et al.* (1992), does not need complex analysis to be effective tool **(1)**	Would require additional tools during analysis to ensure objectivity **(0.5)**	Not inherently **(0)**	**2**
FMEA/FMECA	Not inherently, could be extended **(0)**	Yes **(1)**	Tends to be subjective and reliant on subjective information **(0.5)**	Not inherently **(0)**	**1.5**
Simulation	Yes **(1)**	Close representation of reality, theory requires knowledge of statistics**(1)**	Yes, depending on availability of data and validity of model**(1)**	Yes**(1)**	**4**

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modelling and prioritisation techniques, it was shown that simulation is the only method which conforms to all criteria adequately. Object oriented simulation, which is currently the norm in simulation modelling through commercial packages like Arena™ and Simio™, gives the possibility to model very complex systems.

The other quantitative, systems-based methods mentioned, Markov chains, suffer from *state space explosions*, note Bolch *et al.* (2006), which refers to the notion that every possible state combination has to be modelled to depict system characteristics with Markov chains. Therefore, state space exhibits an exponential growth with every additional component. Object oriented simulation on the other hand, as explained by Kindler & Krivy (2011), is a careful top-down application of abstractions and subdivision of problems into smaller and less complex subtasks that are assigned to "objects". This hierarchical approach gives rise to the possibility of modelling object characteristics independently from the interplay between those objects on the same hierarchy. Modelling is thus simplified as possible "state combinations" arising from higher level states don't have to be modelled explicitly but rather just emerge as a result of this interplay.

This section served to compare simulation to other approaches. Many other advantages of simulation, and a detailed approach to use simulation for this project are provided in Chapter 4.

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4 | Maintenance Prioritisation Methodology Using Simulation

CHAPTER 4 introduces the proposed methodology with which maintenance prioritisation is undertaken in this study. The chapter also aims to provide the reader with a background in simulation modelling so that the case study in the proceeding chapter may be fully appreciated and understood.

Introduction

PAM Landscape

PAM Prioritisation Techniques

PRIORITISATION METHODOLOGY

Simulation Concepts
Prioritisation Methodology
Validation

Case Study

Conclusion

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4.1 Maintenance Prioritisation Project Design

Through the problem statement and subsequent discussion of relevant areas in Chapter 2, a thorough understanding for the need for maintenance prioritisation was realised. In Chapter 3, various solutions to the problem were considered, of which computer simulation was chosen as the most adequate tool. In this chapter, a methodology is presented which demonstrates the use of simulation to meet the ends of the problem statement. The various interacting elements of this project, which were discussed in previous chapters, are displayed in Figure 4.1, while a summary of intended objectives of the methodology is once again shown in Figure 4.2.

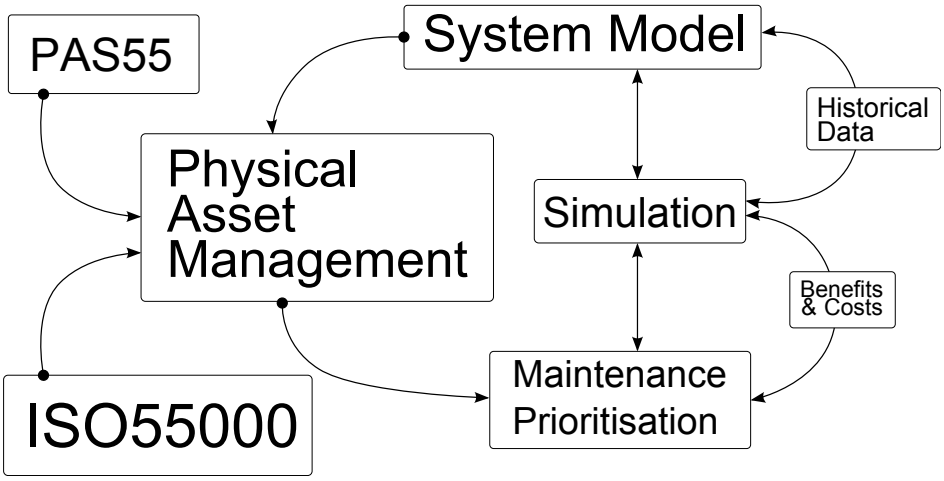

FIGURE 4.1: Project methodology overview showing the application of simulation to prioritise maintenance interventions in the wider context of asset management.

There are very few examples in literature of where simulation has been specifically applied to maintenance prioritisation. Therefore, this methodology relies on the success of other applications of simulation. Most notably the maintenance optimisation project of Achermann (2008), and the simulation for sensitivity analysis of Kleijnen (2005) where used as guides.

Despite the choice of using simulation to form the core of the analysis over other methods discussed in Chapter 3, remaining elements of these methods may be found in this methodology. For example, the philosophy of TOC is essentially followed as bottlenecks are sought and focussed on; FMEA methods are kept in mind when seeking the root causes of machine downtime after specific bottlenecks have been found; Weibull

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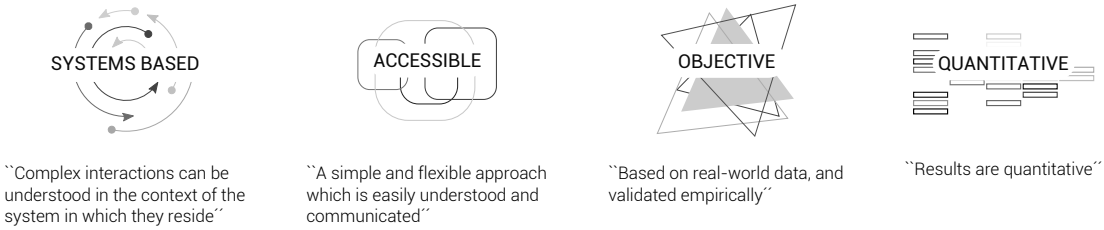

FIGURE 4.2: Project objectives.

analysis is used to determine the failure characteristics of machinery and forms an integral part of the simulation model.

4.1.1 Field of Project Application

An asset-centric environment was sought to execute this study — one where physical assets are the primary source of revenue generation, and where asset reliability thus has a large impact on system output. Generally it would be beneficial if the plant to be studied historically has been experiencing problems with reliability, as reliability improvements to such a system would have a greater effect on output, leading to more conclusive findings. It may even be applicable in such systems to make the assumption that maintenance costs are negligible when compared to the profitability of the system, thus removing the need for maintenance costs to be factored into modelling.

A system of sufficient complexity was needed, to ensure that the simulation model could provide a greater insight to plant operation over simpler analyses, and to eliminate the possibility of evaluating the system analytically.

A simulation always represents a simplification of a real-world system. The versatility of simulation is such that virtually any system can be modelled to some level of complexity, but it needs to be ensured that the level of abstraction which can be reached will provide meaningful conclusions. Added complexity in a simulation inherently increases the possibility of modelling errors, increases development and validation time, and furthermore increases the actual computation time. A simulation engineer thus tries to emulate the system at the most meaningful level, which is the simplest effective model, and not necessarily the most complex. Bekker (2011) recommends that the smallest and least detailed model which provides the required information be used, and that models should be developed from the top down.

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The availability of historical information relating to machine uptime and maintenance records is absolutely vital, as the reliability and operational data is formed from on past events. Thus a plant with an integrated condition monitoring system which collects accurate reliability data is sought.

4.1.2 Steps in Methodology Execution

The execution methodology for this project is shown visually in Figure 4.3. The corresponding items will be explained in the following sections. To be noted is that the case study for this thesis only includes the *modelling* portion of the outline, but that the other sections have been included here and will be described in order to place the project in context.

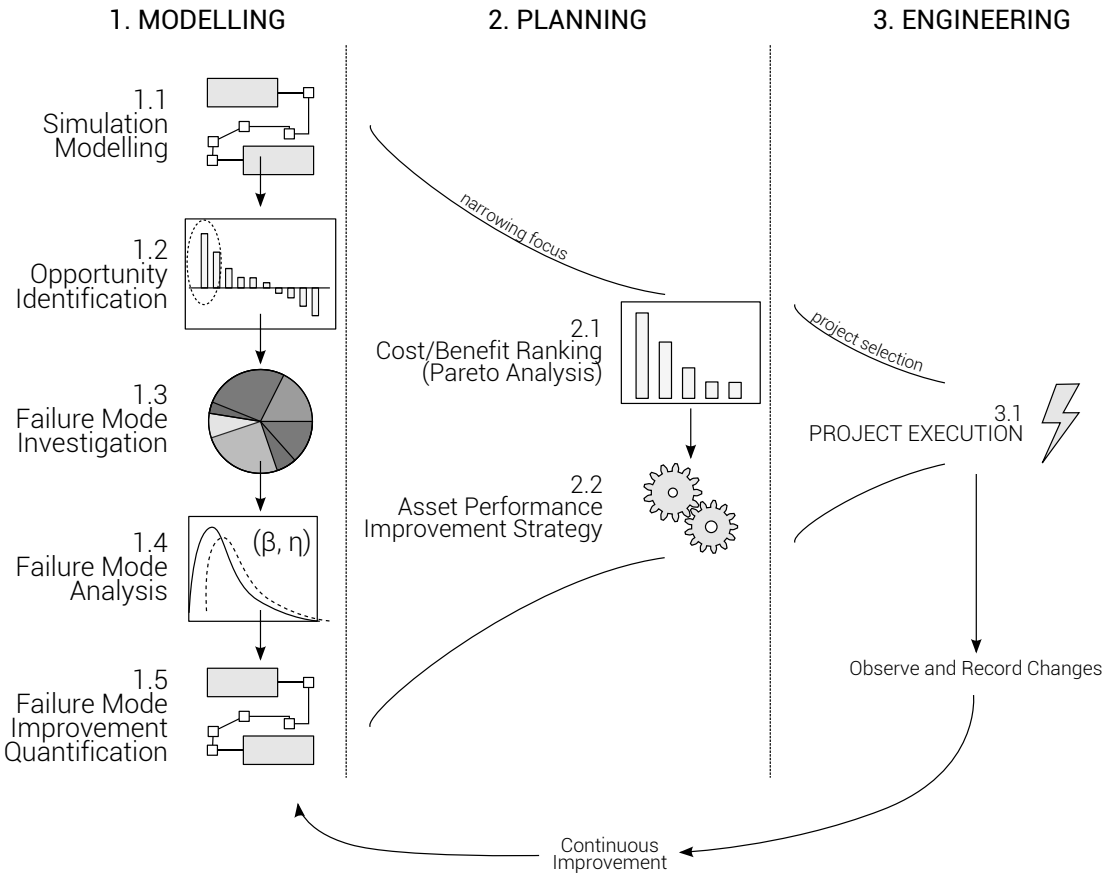

FIGURE 4.3: Steps in the proposed methodology execution.

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1. Modelling

This phase details the use modelling to represent a real-world production system, and the analysis and virtual manipulation of this system using the built model. The philosophy and application of modelling, types of modelling, and the use of modelling within an PAM framework were discussed in detail in Section 2.2.1. The modelling phase is the responsibility of the simulation analyst.

1.1 Simulation Modelling

Simulation modelling is described in detail in Section 4.2. This stage includes all the activities required to build a simulation model including data-collection and model validation. This phase, along with all the steps in creating a simulation model, is described in detail in this chapter.

1.2 Opportunity Identification

Once a valid model of the system is built, a series of tests are performed in order to determine which elements in the simulation have the greatest influence on system downtime, as well as which uptime improvements yield the greatest throughput benefits.

1.3 Failure Mode Investigation

The opportunity identification stage will yield a list of elements, prioritised according to the system throughput benefit of uptime improvement. The strongest elements are now analysed in order to determine which failure modes cause the element to experience the most downtime.

1.4 Failure Mode Analysis

Simulation model data is updated, considering that the alleviation of failure modes on a machine will alter the downtime distributions in the model[1].

1.5 Failure Mode Improvement Quantification

In this step, the effects of failure mode improvement are quantified using the updated simulation model. That is, simulation analysis is performed with the updated model parameters.

[1] More specifically, the *Weibull parameters* α and β will change as the element's MTBF improves.

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2. Planning

The planning phase is the responsibility of plant management, or of the plant asset manager if this title exists. The modelling phase will yield a list of available maintenance interventions, prioritised according to the throughput benefit that can be attained by alleviating or eradicating failure modes, and the purpose of the planning phase is to use this information to rank available interventions according to a cost/benefit ratio, and to create maintenance plans to ultimately carry out the maintenance improvements.

2.1 Cost/Benefit Ranking (Pareto Analysis)

Management needs to determine the intervention costs for improving an elements' performance. This may include performing a detailed analysis on the component in order to determine what exactly the problem is, followed by obtaining quotes from Original Equipment Manufacturer (OEM)s and otherwise determining or estimating the costs which would be incurred by improving the functioning of an element.

2.2 Asset Performance Improvement Strategy

The output of this step is a detailed recommendation which can be passed on to engineering management. The document should include all details from the analyses performed, as well as a strategy recommendation on which actions should be performed in order to most effectively improve maintenance at the plant.

3. Engineering

The role of engineering is firstly to liaise with the simulation analysis project team for the purpose of model validation, and secondly to carry out the asset performance improvement plans as prescribed by 2.2.

3.1 Project Execution

One or many projects are selected after careful consideration of the recommendations proposed by the simulation team. These projects are then executed by the engineering team.

Continuous Improvement

Many aspects of this project enable it to be used in a sustainable continuous improvement

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application. As certain areas of the plant improve due to focussed interventions, the reliability characteristics of the plant's components can be re-examined and the simulation periodically updated and rerun in order to observe changes to the system [1]. The simulation model of the plant may be reused indefinitely, and changing parameters in the model is trivial. A drawback of this approach is that sufficient time must pass in order for enough data to be generated for an updated analysis.

4.2 Simulation as a Problem Solving Technique

Simulation in the context of this project is defined as the mathematical imitation of the operation of real-world processes or systems over time. According to Bekker (2011), simulation can be defined as the experimentation with a model of a real-world system in order to study the behaviour of the model, given certain starting conditions. It is assumed that the model is a sufficient predictor of the real system's behaviour. When a system is of such a complex nature that it cannot be analysed analytically, simulation is strongly considered. In addition, if the system is of complex stochastic nature, then simulation is again indicated. Simulation allows for *"what-if?"* questions when systems are studied, i.e. an existing system's behaviour is studied when certain parameters are changed.

Plant simulation represents one of the most important and valuable applications of the field of simulation according to Ferreira *et al.* (2009), Emun *et al.* (2010) and Sewring & Nilsson (2012). It is a valuable tool when evaluating the effect of capital investment in equipment and facilities or to predict the performance of an existing or planned system and to compare alternative solutions for a particular design problem, as changes to a system can be investigated without disrupting the operations of the system. Common measures of system performance include the following:

- Throughput under average and peak loads;
- System cycle time;
- Utilisation of resource, labour and machines;
- Bottlenecks and choke points;

[1] The TOC of Goldratt *et al.* (1992) as explained in Section 3.4 may be useful in this regard.

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- Queuing at work locations;
- Queuing and delays caused by material-handling devices and systems;
- Storage needs;
- Staffing requirements;
- Effectiveness of scheduling systems;
- Effectiveness of control systems.

Simulation has many uses within the manufacturing environment. For the case of this project, simulation is used in a facilities- design context, by providing assistance to planners in determining the throughput capabilities of competing designs, and by animating the operations to provide planners with information regarding the limitations, constraints and bottlenecks of the system. Simulation is introduced thoroughly in the following sections as it plays a pivotal role in the developed prioritisation methodology.

General Definition of Simulation

Since the early 1970s, simulation has been increasingly used for the solution of problems in business, engineering and science. Simulation been applied extensively in the private sector in many fields of application.

Seila *et al.* (2003) state that over the past 30 years, the use of simulation as a problem solving technique has improved dramatically due to the advent of fast and accessible computing power, as well as the availability of efficient software which allows simulation models to be created quickly and easily. It is also noted that the number of practitioners of simulation is dramatically increasing, due to the prevalence of courses being offered at university in engineering and science degrees.

The following definition of simulation from Seila *et al.* (2003) is used: *"A set of numerical and programming techniques for representing stochastic models and conducting sampling experiments on those models using a digital computer."* Simulation is therefore a technique that extracts information from a *simulation model* by "observing" the behaviour of the model using a digital computer.

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4.3 Fundamental Concepts of Simulation

The following section provides a background in simulation which introduces the reader to fundamental concepts in simulation.

4.3.1 Simulation Classification

Seila *et al.* (2003) differentiates between *static* and *dynamic* simulations. Static simulations operate by sampling observations and transforming them according to the rules that compose the model, and repeating this process independently many times to produce independent or identically distributed (IID) observations that are then used to study the characteristics of the transformed random variable.

Dynamic simulations on the other hand observe the behaviour of systems over time, and constitute the bulk of simulation work in management, as problems such as inventory, queueing, production and transportation are easily modeled this way. Dynamic simulations are further classified as either *discrete simulations* or *continuous simulations*. Continuous simulations, as described by Kelton & Law (2000), involve models in which quantities are represented as variables in differential equations which change over time, whereas discrete simulations allow system variables to change only at discrete points in time, called *events*. Discrete-event simulations represent the majority of simulations, as most models deal with discrete entities which flow through the system, and because discrete-event simulations are more natural to program. Furthermore, continuous systems may be approximated by DES.

Kelton & Law (2000) introduce the concept of *combined discrete-continuous simulation*, which contains aspects of both discrete and continuous systems. In these simulations, discrete events can affect the continuous state variables at a particular time.

4.3.2 The Simulation Mechanism

The Transaction-Flow World View

According to Schriber & Brunner (2011), the "transaction-flow world view" often provides

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the basis for discrete-event simulation. In this world view a system is conceptualised as consisting of discrete units of traffic that move through the system, from point to point, and compete for the use of scarce resources along the way. Many real world systems fit this description, including manufacturing, health-care, communication, material handling and queueing systems in general.

An important principle in the transaction-flow world view, as noted by Bekker (2011), is that an entity proceeds through a model until it encounters a delay or is disposed of. Travelling from one point to another also implies a delay.

A representation of a typical transaction-flow world view is presented in Figure 4.4.

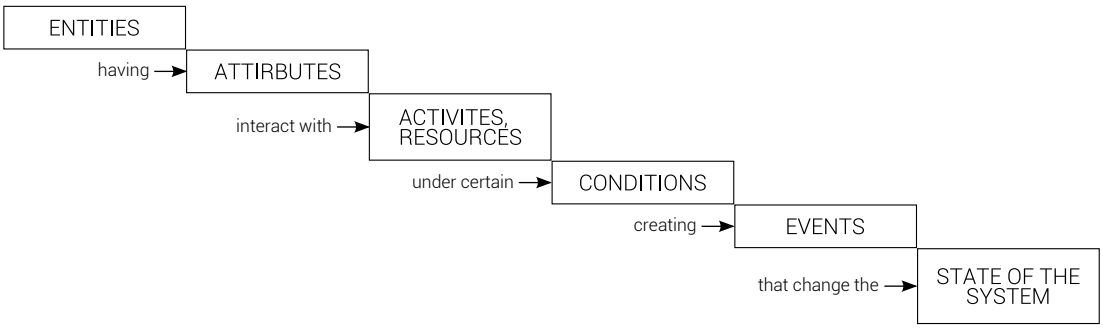

FIGURE 4.4: A typical transaction-based simulation world view
As presented by Shannon (1975)

The term *entity* is used to designate a unit of traffic. Entities have physical and logical attributes, or *properties* and can respond to and instigate *events*. An event is any occurrence that changes the state of the system. The term *resource* is used to designate an element that provides a service and which can be seized by one or more entities. For example, machines, buffers and conveyors are considered resources.

4.3.2.1 Simulation World Views

According to Pegden (2010), simulation models are built using one or more "world views" that provide the underlying framework for defining the system of interest in sufficient detail, such that the behaviour of the system can be simulated.

A simulation model executes on a computer to dynamically act out the behaviour of a real-world system over time. A simulation is a set of variables and a mechanism for

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changing those variables over time. A simulation world view provides the framework and underlying logic for the execution of a simulation, and must provide a definitive set of rules for advancing time and changing the state of the model. Bekker (2011) notes that the world view governs how a real world system is conceptualised in a computer language.

Pegden (2010) discusses three distinct simulation world views which have been developed over the last 50 years, namely: 1) Event Modelling, 2) Process Modelling and 3) Object modelling — which have distinctly different approaches to programming. These will be described in the proceeding paragraphs, with an emphasis on Object Modelling, which is the world view used in this project.

Event Modelling

Pegden (2010) describes event modelling as a series of instantaneous events that change the state of the system over time. The modeller defines the events in the system and models the state changes that take place when those events occur.

Event modelling tools are highly efficient and flexible, but are a relatively abstract view of a system and are thus difficult to conceptualise, program and debug. According to Pegden (2010) these models were widely used during the first 20 years of simulation but are no longer popular, owing to the release of more friendly world views, however the underlying internal logic for all discrete event simulation software is still event based, regardless of which world view is presented to the user.

Process Modelling

In the process view, entities' movement through the system is described as a process flow, given by a series of steps which model the state changes to the system. At each process step, various operations affect the entities' movement — it may be delayed, re-routed, destroyed, duplicated, etc., and it may seize resources, like servers or buffers, along the way.

Process models are typically defined in the form of a flowchart, which gives simulationists a practical overview of the model. According to Pegden (2010) process modelling displaced event orientation as the dominant discrete event simulation method in the 1980's, as it allowed for graphical model building and animation and thus provided

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practitioners with a simplified model building and debugging process.

Object Modelling

In object orientated modelling one models the system by describing the objects that make up the system. For example, one models the machines, conveyors, buffers, entities, and workers in a processing plant and describes the operation of the system as an interaction of these objects. By Pegden (2010)'s definition, an object-based simulation tool uses modelling constructs that directly relate to the physical system that they represent, as opposed to logical processes. This allows for a more logical modelling process, enhanced opportunity for animation and reduced complexity in debugging, while maintaining the flexibility and speed of the process modelling approach.

Pegden (2010) posits that object oriented models are increasingly replacing process modelling as the primary simulation world view.

4.3.2.2 Analysis of Simulation Data

According to Law (2010), one of the most important but neglected aspects of a simulation study is the proper design and analysis of simulation experiments. A simulation of a stochastic process yields results which require an understanding of statistics to understand and interpret.

The following section provides a brief review of the statistical knowledge required to interpret simulation results. For further information see Bekker (2011), Law (2010), Vlok (2012) and W. David Kelton (2011).

Analysis of Output Data

There are many describers of output data which can be analysed, but these require different approaches. Bekker (2011) identifies the following descriptors:

- Expected Values
- Minimums
- Maximums

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- n-th percentile — i.e. "How long do 95% of my materials spend at a particular buffer?"
- Proportions — i.e. "What proportion of breakdowns last longer than three hours?"

Only the *Expected Value* output describer is used, as the theory presented in this section does not apply to the other describers, primarily due the fact that the Central Limit Theorem does not (directly) apply and this forms the basis of analysis.

The outputs of a stochastic process from a *single* simulation replication are generally not IID, and thus many of the formulas from classical statistics do not *directly* apply. However a series of replications which use the same initial starting conditions but draw random variables from random number generators can be shown to be IID. This is explained by a summary of Law (2010) in the proceeding paragraphs.

Let $y_{11}, y_{12}, \ldots, y_{1m}$ be the realisation of the random variables $Y_1, Y_2, \ldots, Y_m$ resulting from running the simulation with a particular set of random numbers $u_{11}, u_{12}, \ldots$. If we run the simulation with a different set of random numbers $u_{21}, u_{22}, \ldots$, then we will obtain a different realisation $y_{21}, y_{22}, \ldots, y_{2m}$ of the random variables $Y_1, Y_2, \ldots, Y_m$. In general, suppose we make n independent replications of the simulation, that is each run uses different random numbers but the same initial conditions, each of length m, resulting in the observations:

$$\begin{array}{ccccc} y_{11} & \cdots & y_{1i} & \cdots & y_{1m} \\ y_{21} & \cdots & y_{2i} & \cdots & y_{2m} \\ \vdots & & \vdots & & \vdots \\ y_{n1} & \cdots & y_{ni} & \cdots & y_{nm} \end{array}$$

Then observations from the ith column are IID observations of the random variable Y_i, for $i = 1, 2, \ldots, m$. That is, the observations y_{ij} may be used to draw inferences about the characteristics of the random variables $Y_1, Y_1, \ldots, Y_m$.

Experiments, Replications, and Runs

Schriber & Brunner (2011) provides the rationale that simulation projects are comprised of *experiments*, which are differentiated by the use of alternatives in the model's data and/or logic. In optimisation or sensitivity analysis problems these parameters are

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tweaked per experiment in order to maximise, minimise, or determine the effects on model results.

Each experiment consists of one or more *replications*. A replication is defined by Schriber & Brunner (2011) as a simulation that uses the experiment's model, but employs its own set of random numbers, and so produces a unique statistical result that can be analysed in a set of such replications. The actual process of running the model until a run-end condition is met is referred to as a *simulation run*.

Confidence Intervals

Suppose that $X_1, X_2, \ldots, X_m$ are IID random variables and are normal distributed, which fortunately in simulation output analysis is a useful result of the Central Limit Theorem, with a population mean and variance μ and σ^2, respectively. Then unbiased point estimators for μ and σ^2 are respectively given by

$$\overline{X}(n) = \frac{\sum_{i=1}^{n} X_i}{n}$$

and

$$S^2(n) = \frac{\sum_{i=1}^{n} X_i}{n-1}$$

Where n is the number of replications executed (and thus the number of observations). Furthermore, an approximate $100(1-\alpha)$ per cent $(0 < \alpha < 1)$ confidence interval for μ is given by

$$\overline{X}(n) \pm t_{n-1,\,1-\alpha/2}\sqrt{S^2(n)/n}$$

where $t_{n-1,\,1-\alpha/2}$ is the upper $1-\alpha/2$ critical point for a t distribution with $n-1$ edges of freedom.

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Initialisation Bias

The aim of a simulation is to obtain data about a system when it is operating "normally", that is, average performance data are obtained from a simulation that is running in *steady-state*. In this steady-state, model output data are centered around a mean and have some predictable distribution. Initialisation bias is caused by the analyst using data for which the system was not in a steady-state. For instance, many models begin empty, with no work-in-progress in the system — that is as if to say the factory begins with empty stores on a Monday morning. Most of the time this is obviously an incorrect assumption, and thus the analyst needs to allow the simulation to reach realistic operating conditions.

Robinson (2004) suggests that initialisation bias is overcome by either specifying starting conditions for the model or by discarding initial outputs of the model until a steady-state has been reached. This period of discarded results is referred to as the 'warm-up period'. Robinson (2004:145) provides an exhaustive list of methods to determining warm-up period length, but advocates a graphical approach and general overcompensation in favour of more rigid statistical methods. The graphical approach basically consists of viewing a time-series of output data and inspecting for abnormal results in the early phases of the model. This concept is demonstrated in Figure 4.5

Terminating and Non-terminating Systems

A *terminating system* is defined by Bekker (2011) as a system that starts in the empty state with operations idle, and after a logical event, ends in the empty state with operations idle again. As defined by Law (2010), a *terminating simulation* is one for which there is a "natural" event E that specifies the length of each run (replication). A simple example of a terminating system would be a restaurant that opens at 8am with no customers, and closes again at 10pm when all customers have left. In this simple example each simulation run is naturally bounded by the opening time and the closing time, E.

A *non-terminating* system on the other hand is one for which there is no natural event E to specify the length of a run. This occurs when we are interested in the behaviour of a system in the long run, when it is operating "normally." In a non-terminating simulation, Robinson (2004) suggests performing either one long run or multiple replications with set warm-up periods.

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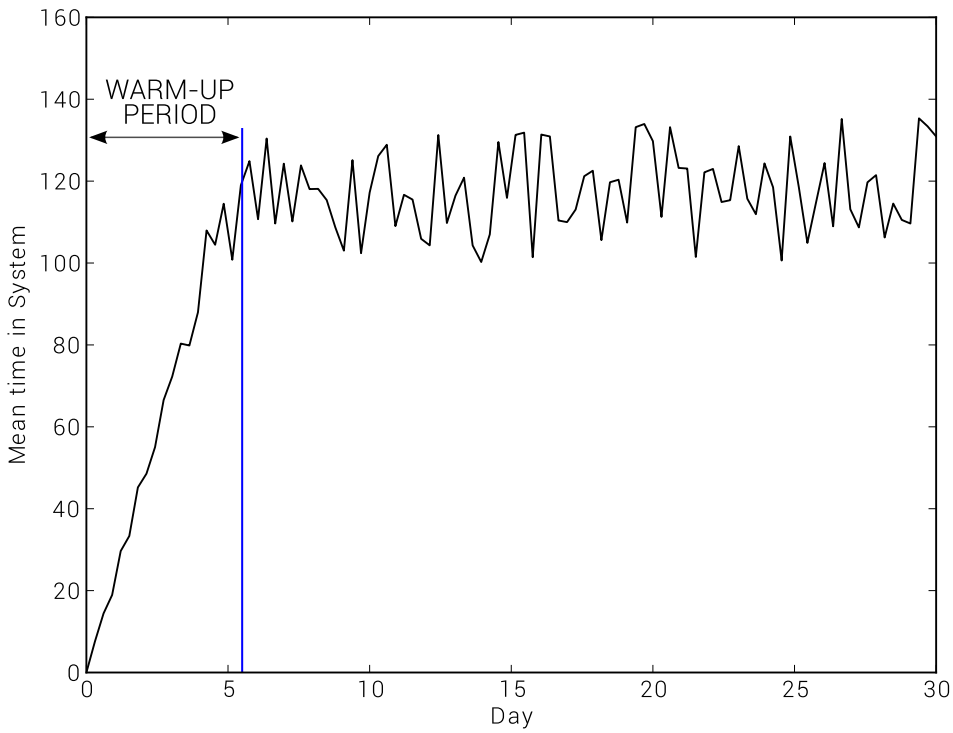

FIGURE 4.5: Example of using a visual representation of a time-series to discard data in order to overcome initialisation bias

Determining Simulation Run Length

In simulation analysis, a run usually supplies the analyst with an observation (per output parameter), which may be considered statistically independent of the observations from other runs during the same simulation run. In simulation terminology a model run that results in such an observation is referred to as a *replication*. Because of the stochastic nature of the simulation study a number of replications are required, and the mean observation is taken as the result. In terminating systems, each replication results in one observation, so that the ultimate objective is to determine how many replications are required to achieve a certain confidence level for a given output parameter. Law (2010) proposes the following method to determine the number of runs required:

An initial run of $n = 10$ replications is performed, and the half-width h calculated. An estimation of the number of runs n^* required for a desired confidence half width h^* is then given by

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$$n^* = n\left(\frac{h}{h^*}\right)^2$$

4.3.2.3 Steps in Simulation Execution

Figure 4.6 shows typical simulation activities and logical work flow used for this project, and highlights the ultimate goal of computer simulation — to build and use a model which converts data, both quantitative and structural, into some understanding of a real-world system. This understanding is quantitative in nature through the statistical analysis of results, but in addition provides softer feedback through model development and animation. The following 7 steps, adapted from Kelton & Law (2000), were used in this simulation study:

1. Problem formulation
2. Objective setting and overall project plan
3. Model conceptualisation
4. Data collection
5. Translation of concept to computer model
6. Verification and validation
7. Experimental design and analysis

4.3.2.4 Data Requirements

Historical data of the system will be required to create a valid model. Simulation is very prone to the "Garbage In, Garbage Out" effect, so careful validation of the model must be performed to ensure its accuracy. As with any project of this nature, the quality and quantity of the data used is somewhat proportional to the accuracy of the results, so data that is complete and accurate is beneficial. The availability of all required data is important, as any assumptions made necessarily detract from the applicability of

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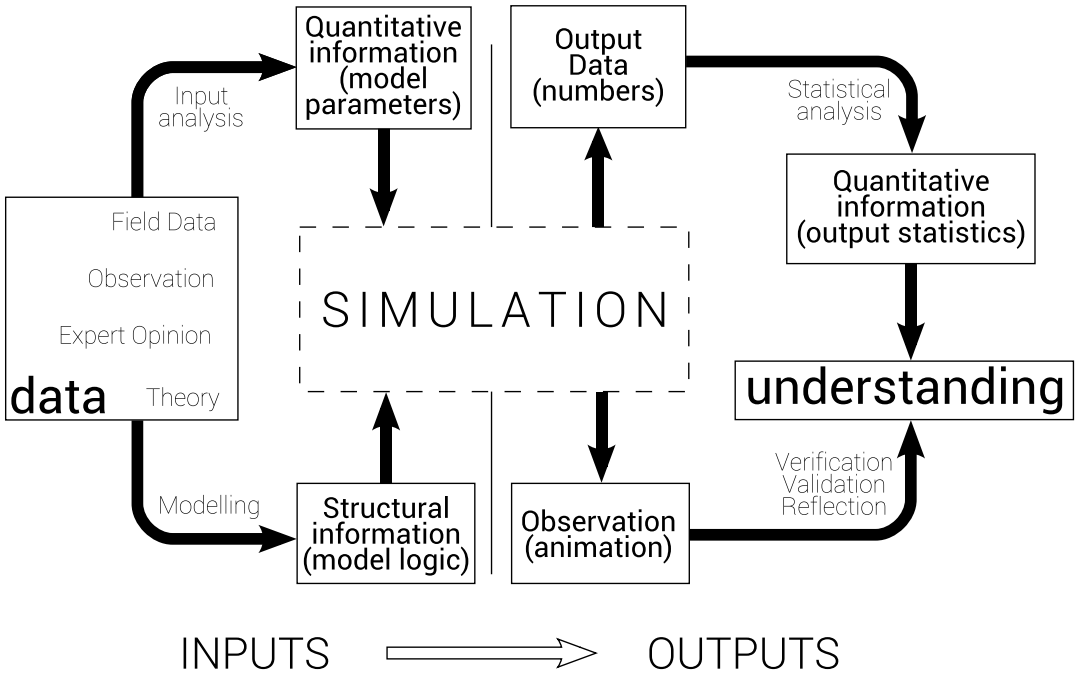

FIGURE 4.6: Simulation activities and work flow showing modelling inputs and outputs
As adapted from White & Ingalls (2009)

the results. This is corroborated by Chung (2003) — simulation cannot give accurate results where the input data are inaccurate.

Data requirements for the simulation are shown in Table 4.1.

Item	**Data Required**
System inputs	Batch size, frequency, delimitations
Physical characteristics of machines	Observed throughput, stated capacity
Failure data of all machines	Failure frequency and downtime distribution
Failure information	Failure modes for all breakdowns
Maintenance data for each machine	Date, unplanned/planned, time
Buffer and stockpile information	Size, throughput
Conveyor/transport information	Velocity, capacity

TABLE 4.1: Data Requirements for case study

Chung (2003) notes that historical data should be treated with caution, as it is often not known what the nature of the conditions were at the time of recording. Often, where human intervention is required in the data collection process, inconsistency is found due to improper recording and negligence on the operators behalf. Data collected from condition monitoring software should in theory be free from these vices, but should

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be calibrated and checked for consistency nonetheless.

Trends in reliability data

In order to create the most accurate representation of the current operating conditions of the plant, it was important to be mindful of trends of improving or declining improvement that occur in the data. That is, all data is necessarily historic by definition, but a snapshot of *current* operating conditions is required, thus a time period needs to be selected which provides this. Care was thus taken to select data that is an accurate representation of the current reliability of the system.

The *Laplace Trend Test*, as described by Vlok (2012) was used to determine whether a trend was present in the data. The Laplace trend test, note Tobias & Trindade (2011), tests if an observed series of events (i.e. failure occurrences) can be identified as a Homogeneous Poisson Process (HPP) or Non-Homogeneous Poisson Process (NHPP). An HPP is characterised by a series in which events have a consistent rate of occurrence, whereas an HPP describes a series with an either decreasing or increasing trend in the frequency of events. The test is conducted by considering r as the total number of failure event arrivals with arrival times: $T_1, T_2, \ldots, T_{r-1}, T_r$. The Laplace trend test makes use of the fact that the first $r-1$ arrival times are the order statistics from a uniform distribution on $(0, T_r)$. The Laplace value for identifying the presence of a trend is calculated by:

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

Where T_i is the interarrival time elapsed from the $(i-1)$th arrival to the ith arrival, $i = 1, 2, 3, \ldots, r$. The result of the Laplace test can be interpreted as by Figure 4.7. A value of $-1 < L < 1$ indicates that there is no underlying trend. $1 < |L| < 2$ is the result of an inconclusive test, in that there may or may not be a trend present, while $L > 2$ and $L < -2$ indicate decreasing and increasing trends respectively.

4.3.2.5 Using Weibull Analysis to Model Failures

Dodson (2006) provides the following notation and form for the Weibull distribution,

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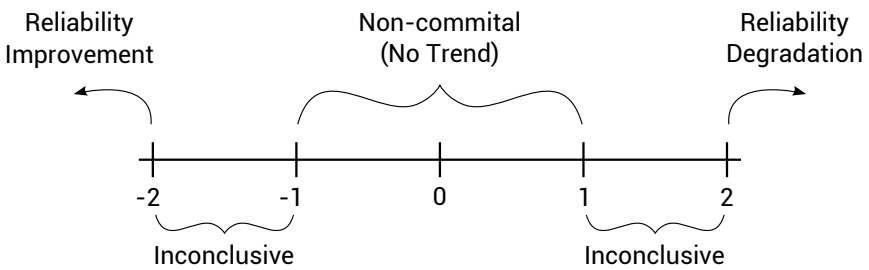

FIGURE 4.7: Interpreting the results of the Laplace Trend Test
Adapted from Vlok (2012)

which is used throughout:

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

The probability of system failure at instant x is then given by f_x as follows:

$$f_x(x) = \frac{\beta}{\eta}\left(\frac{x}{\eta}\right)^{(\beta-1)} . \exp(-(x/\eta)^{\beta})$$

The cumulative failure distribution, up to time x, illustrates the probability that a failure will occur within the interval $(0; x)$. Thus if $f_x(x)$ is integrated with respect to time (x), we obtain the probability of system failure *before* a certain instant, x, that is:

$$F_x(x) = \int_0^x f(\tau)d\tau = 1 - \exp(-(x/\eta)^{\beta})$$

Analogous to $F_x(x)$ is the relation for the probability of system survival up to a certain instant x, given by $R_x(x)$ as follows:

$$R_x(x) = \exp(-(x/\eta)^{\beta})$$

Furthermore, the ratio of $f_x(x) : R_x(x)$ yields a conditional probability referred to as the Force of Mortality (FOM) or *conditional intensity* of a non-repairable system, and is used to characterise failures and measure the tendency to fail. This *hazard function* is given by:

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$$h_x(x) = \frac{f_x(x)}{R_x(x)} = \frac{\beta}{\eta}\left(\frac{x}{\eta}\right)^{\beta-1}$$

It is noted that for $\beta < 1$ the hazard function decreases as x increases. This means that the instantaneous failure rate reduces as time progresses, also known as *infant mortality*, as described with the bathtub curve, shown in Figure 4.8[1]. For $\beta = 1$ the failure rate remains constant for all x, implying that the failure behaviour is totally random. This can also be referred to as the behaviour of a non-repairable system. When $\beta > 1$ the instantaneous failure rate increases with x and is referred to as the *wear out period*, as portrayed by the bathtub curve.

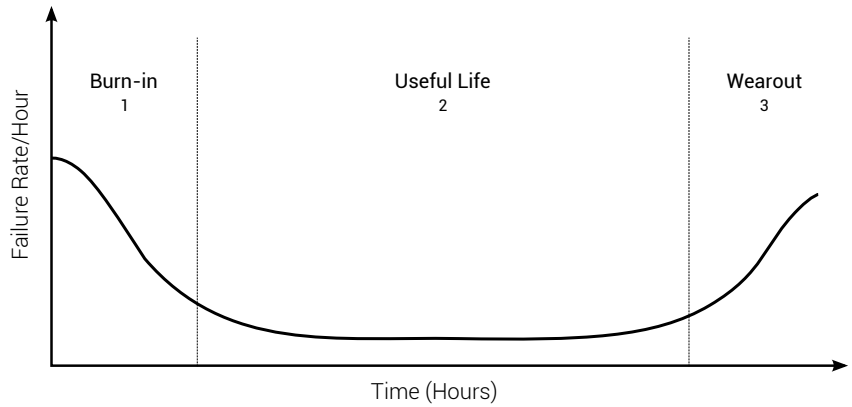

FIGURE 4.8: The "Bathtub Curve" failure rate graph
Adapted from Vlok (2012)

The flexibility of the Weibull distribution enables it to take on the characteristics of other distribution types by altering the shape parameter β. This is demonstrated in the following section and shown in Figure 4.9.

Flexibility of Weibull Distribution

The Weibull distribution is able to take on the shape of many other well known distributions by altering the shape parameter β. Dodson (2006) lists a few such distributions:

[1] The bathtub curve is widely used in reliability engineering and is generated by combining the rate of early "infant mortality" failures when an item is first introduced, the rate of random failures with constant failure rate during its "useful life", and finally the rate of "wear out" failures as the product exceeds its design lifetime. The bathtub curve is discussed in more detail in Section 5.2.3

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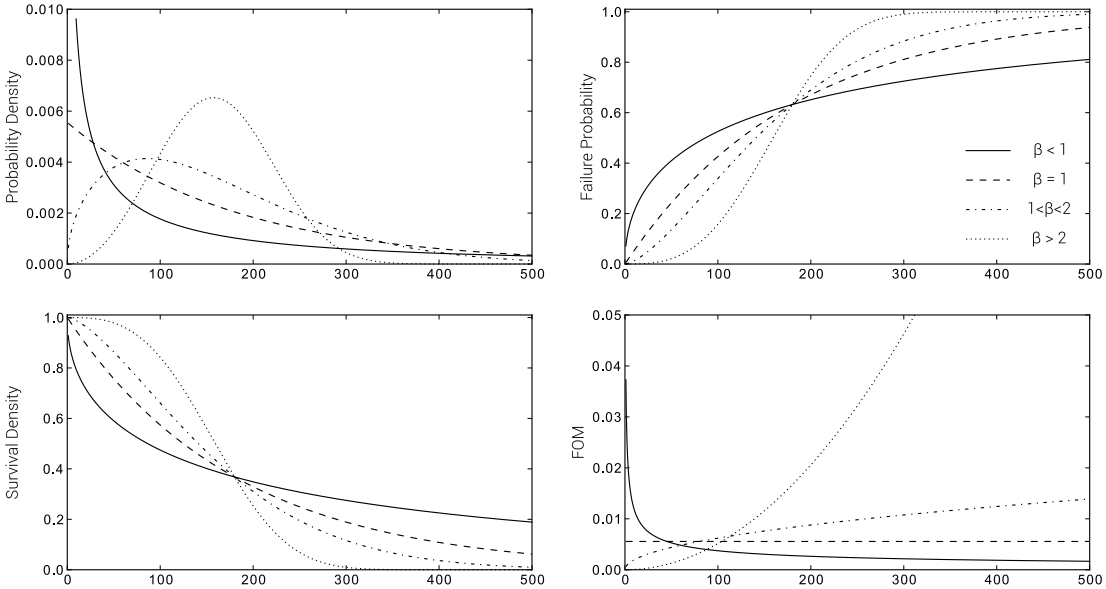

FIGURE 4.9: Reliability functions for different values of β.

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

Mean Time Between Failure (MTBF) and Residual Life Estimation

As described by Vlok (2012:9.3), if the underlying failure process is described by a Weibull distribution, then it is possible to predict the arrival time of the next event. Suppose a system has been in operation for x time units and a maintenance policy exists where the system is replaced preventively at time X_p or at failure, whichever comes first. The conditional expectation of X_{r+1} (where $X_{r+1} \leq X_p$) is given by

$$E\left[X_{r+1}|X_{r+1} \leq X_p\right] = \frac{\int_x^{X_p} x \cdot f_X(x)dx}{\int_x^{X_p} f_X(x)dx}$$

In the case where there is no preventative maintenance rule, i.e. $X_p = \infty$, and we

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would like to calculate the residual life shortly after X_r, i.e. $x \approx 0$, the equation becomes

$$E\left[X_{r+1}\right] = \frac{\int_0^\infty x \cdot f_X(x)dx}{\int_0^\infty f_X(x)dx}$$

This is also what is referred to as a non-repairable system's MTBF.

Parameter Estimation

The Weibull parameters β and η are estimated analytically by using methods such as Maximum Likelihood, Method of Moments and Least Squares Method. In a comparison of these methods, Al-Fawzan (2000) finds that the Least Squares Method delivers fast and accurate results. Although the Method of Moments gives a slightly more accurate estimation, it is more time-consuming. Vlok (2012) suggests using a the Maximum Likelihood Method, which is relatively easily performed by maximising the likelihood given by:

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

where X_i, X_j are the interarrival times of failures or events that caused downtime. Maximising the function is performed numerically using Microsoft Excel's solver or some equivalent.

Using Weibull Distribution in the Simulation Model

Using the method described above, parameters for the Weibull distribution can be obtained to model the failure characteristics of each relevant component in the simulation model. In the context of DES this introduces a probability for each component, based on the respective Weibull distribution, that the component may fail at any time in the simulation, and be unavailable for some duration while it is being 'repaired'. Important to note is that the Weibull distribution is 'clipped' to disallow extreme values for repair times and failure rates.

Using this approach has the advantage that it is completely unbiased, as it is based solely on historical information from the operating conditions of the plant machinery.

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However, a drawback is that it relies heavily on said data, and where data is unavailable or unreliable the analysis loses some credibility.

4.3.2.6 Validation and Verification of Simulation Model

In order to ensure that the model is a realistic representation of the real world scenario, it must be verified and validated. Verification of the model is performed by asking *"Was the model built correctly?"* The verification process entails ensuring that model logic is sound, that all syntax errors are corrected and that run-time errors are eliminated from the simulation. Kleijnen (1995) elaborates, that verification aims at a 'perfect' computer program in the sense that the computer code has no programming errors. Validation of a simulation on the other hand can not be assumed to result in a perfect model, since it is the process of questioning whether the the model is a sufficient representation of the actual system, or in other words, answering the question: *"Was the correct model built?"* Validation is therefore the process of ensuring that the model is sufficiently accurate for the purpose at hand. Kleijnen (1995) states that there are unfortunately no perfect solutions for the process of validation and verification in simulation, and that the whole process has elements of art as well as science. Validation and verification are important steps in the modelling process and are usually integral to the build and performed concurrently — that is, the model has to be built right in order to test whether it is realistic.

Kleijnen (1995) presents a comprehensive set of statistical and tacit steps for verification and validation. Robinson (2004) provides a conceptual and philosophical view of validation which emphasises its indeterminate nature, and presents a method for validation known as *black box validation*. Rohrer (2000) emphasises the value of visualisation in simulation modelling, noting that validation of a model can be aided by visualising the system. W. David Kelton (2011) and Bekker (2011) note the iterative nature of model development, where validation of the model is a constant process of improvement through communication between the simulationist and the client.

Robinson (2004) suggests the following paradigms of validity which can be used to guide the simulationist to create a valid model:

Replicative validity – For all experiments possible within the experimental frame, the behaviour of the model and system agree within acceptable tolerance.

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Predictive validity – Ability to predict yet unseen system behaviour.

Structural validity – The model is capable of mimicking step-by-step the way in which the system does its transitions.

In black-box validation the overall behaviour of the model is considered. The basic broad approach performing this form of validation is to compare the simulation model to the real world model. The premise is that if confidence is to be placed in a model then, when it is run under the same conditions (inputs) as the real world system, the outputs of both models should be sufficiently similar. Historic data collected from the real system, such as production throughput, can be compared with the results of the simulation when it is run under the same conditions. This hypothesis is shown visually in Figure 4.10.

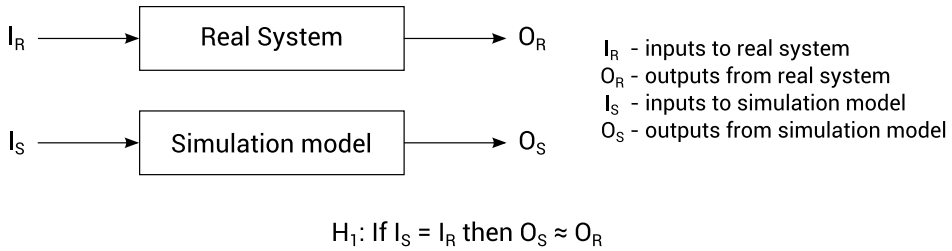

FIGURE 4.10: Black-Box validation: Comparison with the real system
Adapted from Robinson (2004)

4.4 Prioritisation Methodology

In the previous section, the inner workings of computer simulation were examined, as well as all the relevant aspects of the modelling process which are used to fulfill the requirements of this study. The following section describes the application of simulation specifically to prioritise maintenance improvement opportunities. This is done in the context of the methodology depicted earlier in this chapter by Figure 4.3.

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4.4.1 Maintenance Improvement Opportunity Identification

An output parameter is selected by which to compare different scenarios. In most production systems, the most ubiquitous metric to use would be system throughput, given as throughput $= \frac{\text{production units}}{\text{time}}$.

A sensitivity analysis is set up in order to determine which factors in the system, when tweaked, yield the greatest potential to positively affect the throughput of the system. It is assumed that maintenance interventions will have the effect of reducing the MTBFs of machinery. Different maintenance scenarios are mimicked by improving the failure characteristics of system components and running simulations to test the effects of these tweaks.

Kelton & Law (2000) provides an excellent overview of statistical output analyses for single systems and addresses how a simulationist should analyse and compare the outputs from multiple simulations. Several methods are given, but for simplicity it is assumed that outputs from each simulation scenario are IID, normally distributed and are simply compared by the value of their mean. The components are thus ranked by their *criticality*, that is, according to their capability to affect the system.

Choosing Components and Maintenance Scenarios

As explained in Section 2.2.1, any model is necessarily a simplification of a real-world system, which enables the analyst to focus on certain aspects of a process. To this end, modelling is an art as well as a science — the simulationist must to some degree use intuition to decide which factors are most important in order to build the simplest model which still performs its function adequately.

A possible simplification of the system is a sub-grouping of certain components or functions in the production system. When looking at failures especially, it may make sense from a modelling point of view to aggregate the failures in a particular sub-area according to what data is available. Where more detail is needed, that is, when looking at the effects of certain failure modes on a certain component, this logic can be built into the simulation. This top-down approach of simulation model building — building a model and then adding detail to it — is a big advantage of object based simulation.

Maintenance scenarios are mimicked by adjusting the MTBFs and repair durations for

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components. The MTBFs are adjusted incrementally and the effect on the throughput observed. A sensitivity analysis is performed by linear least-squares regression in MATLAB using the method described in Chapra (2005:ch 13.2):

The mathematical expression for a straight line is:

$$y = a_0 + a_1 x$$

When fitting a straight line to a set of paired observations: $(x_1, y_1), (x_2, y_2), \ldots, (x_n, y_n)$ the least squares fit of the linear expression can be determined by:

$$a_1 = \frac{n \sum x_i y_i - \sum x_i \sum y_i}{n \sum x_i^2 - \left(\sum x_i\right)^2}$$

and

$$a_0 = \overline{y} - a_1 \overline{x}$$

where $\overline{y}$ and $\overline{x}$ are the means of y and x, respectively.

The results can then be compared by the gradients of these least squares regression lines. This is shown in Figure 4.11. Kleijnen (2005) and Kelton & Law (2000:ch 12) provide further insight into experimental design for sensitivity analysis.

4.4.2 Investigation of Failure Modes

Figure 4.12 shows how failure modes and simulation results are consolidated by using the linear regression to estimate the value of intermediate results. Using this information, the analyst may interpolate the value of any improvement to the component and if possible, compare this to the cost of performing the improvement. If the data set acquired contains failure mode information, the analyst may proceed with investigation into possible improvement projects by analysing failures and using the results obtained from the simulation to quantify the value of these projects. Components where improved maintenance has the greatest effect on system output will be analysed further.

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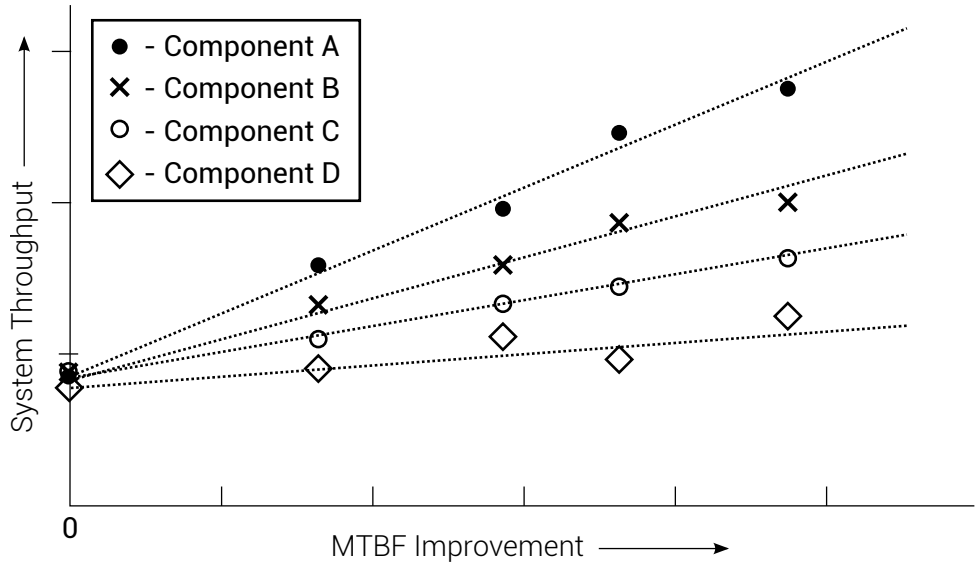

FIGURE 4.11: Visual comparison of different simulation scenarios using linear regression.

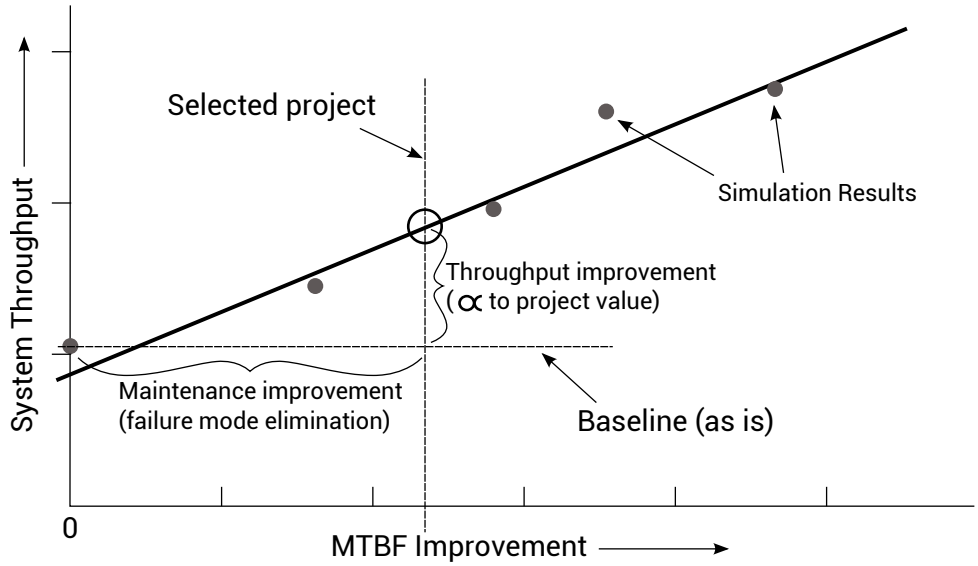

FIGURE 4.12: Consolidation of failure mode analysis and simulation results for one component.

4.4.3 Selecting Projects

Projects are selected for comparison based on availability — the plant's engineering department will need to suggest interventions and give an estimate on their cost. The

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project selection process is shown by means of example in the following paragraph.

Example: Comparing available interventions

A maintenance prioritisation project is performed at a plant. Simulation analysis has shown that Component A is the most sensitive to maintenance improvements. Subsequent analysis of Component A's failure modes has shown that a blocked feeder causes the most downtime in this component. The engineering department has identified three projects, X, Y, Z which address different issues, have different costs, and each respectively reduce Component A's downtime by some degree. The analyst may now use this information, as shown in Figure 4.13, to determine which project yields the greatest output per unit of cost.

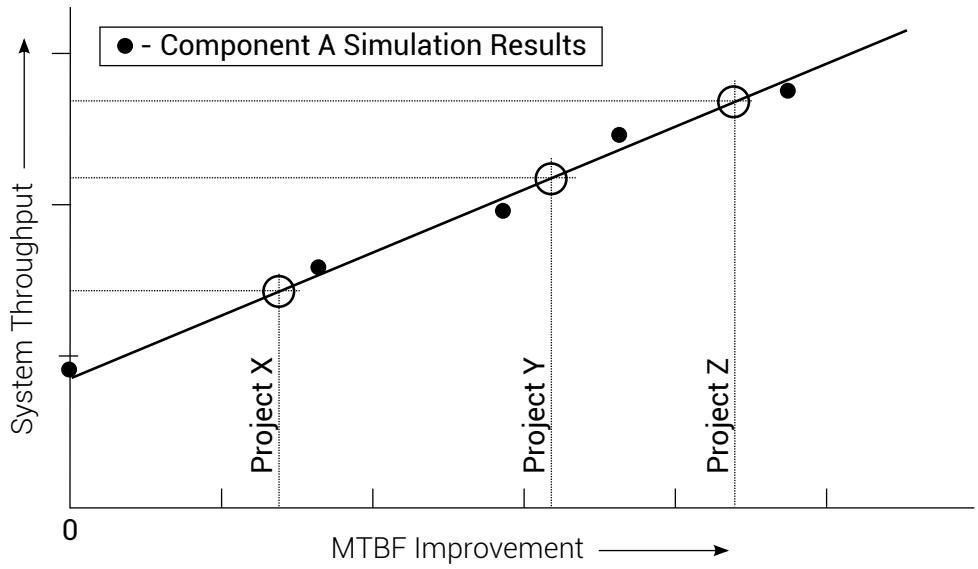

FIGURE 4.13: Example: Comparing available interventions.

The process depends somewhat on the amount and quality of data available to the engineering team, though in the absence of data, estimations may be made by operators. The scope of this study concludes with the selection of the most viable, cost-effective projects. Only the planning and execution phases remain, which are functions of the engineering department.

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4.5 Validation of Proposed Methodology

According to the problem statement, a method for prioritising maintenance interventions was sought. It was determined that the methodology should have certain characteristics as discussed in Chapter 3. The selected methodology will now be assessed to determine whether these criteria have been met:

Systems Based – The simulation model mimics the operation of a real-world production system and is systems based. Boundaries for the study are created and certain simplifications are made, and all interactions between nodes in the system are modelled. Prioritisation is based on this systems view. This criteria is therefore adequately met.

Accessible – The simulation model is a visual representation of the system, which makes it less abstract and therefore more accessible, as personnel can easily infer parallels between the model and the real system. Personnel are involved in the validation process and are therefore more likely to accept the model results. Creating a valid simulation model requires knowledge of statistics and practical experience. Once a valid model has been built, altering it to test different scenarios is trivial if the model has been built correctly. This criteria is met.

Objective – The simulation model collates failure data which is collected from the real world system. It is the simulationist's responsibility to ensure that this data is accurate. The model can be empirically validated to ensure that it adequately mimics the real world system. Where the required information is available, the input data to the model is not reliant on human judgement, and therefore this criteria is met.

Quantitative A vital facet of the analysis should be to aid plant managers in budgeting by attributing costs to improved maintenance practices. This is achieved through this methodology, as results are quantitative and describe the relationship between machine reliability improvement and throughput.

This purpose of this section is to discuss and ensure the appropriateness of the proposed methodology presented in this chapter in its intended function of satisfying the problem statement. Methods to validate the simulation model itself have been discussed

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in this chapter and will not be included here. Further validation is provided by means of a case study in Chapter 5.

4.6 Conclusion

In this chapter a methodology was proposed which may enable an analyst to successfully prioritise maintenance interventions in a complex system by the modelling of the system using object-based discrete event simulation and proper analysis of the results. The purpose of this technique is to satisfy the requirements presented in the problem statement in Section 1.4

The reader was introduced to the modelling and prioritisation process, which includes a discussion of where such techniques may be applicable. The field of simulation and its related functions was thoroughly reviewed, including its role in optimisation and problem solving in production environments.

The remaining chapters attempt to validate the methodology further by applying it to a real-world scenario.

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5 | Case Study: Mogalakwena North Concentrator

CHAPTER 5 aims to validate the methodology described in Chapter 4 through the rigourous application of the methodology in a real-world situation. The chapter describes the application in detail, with a thorough investigation of the operation of the plant, the data analysis process, the simulation process, as well as the results obtained.

Introduction

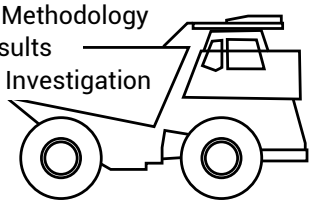
PAM Landscape

PAM Prioritisation Techniques

Prioritisation Methodology

CASE STUDY

Overview MNC
Description of Operations
Implementing Methodology
Simulation Results
Failure Modes Investigation
Summary



Conclusion

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5.1 Introduction

In previous chapters, the need for maintenance prioritisation was explored, and a methodology proposed which aims to overcome the challenges proposed by this problem. The purpose of this case study is to evaluate the adequacy of the methodology proposed in Chapter 4 to fulfill the requirements of the project as discussed in previous chapters.

The case study was performed at a large platinum ore crushing plant in Limpopo Province, South Africa. This chapter gives a detailed description of the operations of the plant, including a thorough background on the problems the plant was experiencing. The case study is a detailed application of the prioritisation portion of the methodology in the previous chapter, and includes data collection, data processing, model building, simulation, interpretation of results, and maintenance prioritisation. The chapter concludes with an evaluation of the efficacy of the method.

5.1.1 Case Study Overview

Anglo American Platinum Ltd.
The case study was conducted in cooperation with Anglo American Platinum Ltd. (AAPL). AAPL is a subsidiary of the British multinational mining company Anglo American PLC, and is the world's leading primary producer of platinum group metals and accounts for approximately 40% of the worlds newly mined platinum. The company is listed on the Johannesburg Stock Exchange and has its headquarters in Johannesburg, South Africa.

Anglo American Platinums wholly owned South African mining operations in the Bushveld Complex include the Bathopele, Dishaba, Khomanani, Khuseleka, Mogalakwena, Siphumelele, Thembelani and Tumela mines. Various Platinum Group Metals (PGM) are mined such as palladium, rhodium, iridium and osmium, with platinum being the main product. Smelting and refining operations are wholly located at a plant in Rustenburg.

Mogalakwena Mine
The case study was undertaken at Mogalakwena mine, which is situated 30 kilometres

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north-west of the town of Mokopane in the province of Limpopo. It operates under a mining right covering a total area of 137 square kilometres.

The current infrastructure of the plant consists of four open pit mines and two ore concentrators, namely the older South Concentrator, and the new North Concentrator, which was fully commissioned in 2008. The mining method is open-pit truck and shovel, and the current pit depths vary from 110 metres to 245 metres. Mogalakwena's life-of-mine extends well beyond 2060.

The operation is highly dependent on the availability of mining machinery and process infrastructure: the performance of physical assets is indispensable for achieving the operational targets. Despite the current economic challenges owing to the lingering decline in platinum demand due to the 2008 economic crisis, the plant under investigation is determined to expand its operations and production output. One such initiative is a major *de-bottlenecking* project, which aims to relieve production constraints caused by the operation of a crusher in the North Concentrator and improve plant output.

The plant does not have a formal, departmentalised PAM function, though discussions to introduce a formal PAM to the entire AAPL group were in progress at the time of the study.

5.2 Description of Operations at Mogalakwena North Concentrator

In order to gain an understanding of the need for maintenance prioritisation, the operation of the plant and its current problems are discussed in detail in the proceeding section.

5.2.1 Production Processes

Mogalakwena North Concentrator (MNC) is an ore concentrating plant. The study performed focussed on modelling the *dry section* of the plant, which is the section starting at the Primary Crusher, which receives material from the open pit mines, and ending at the Primary Mill, from where the ore is transferred to a floatation process.

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The purpose of a crushing/refining plant is to reduce the size of ore-containing rock to a fine dust, so that platinum particles may be separated from the ore body by means of a chemical floatation process.

To this end, the dry section of the plant consists of a series of crushing units, which use mechanical advantage to crush rocks, conveyors to transport rocks, and screens or *grizzlies* to sort undersize and oversize rocks at various points in the process. The secondary and tertiary crushers operate in a closed loop. That is, often the ore requires multiple passes through a crusher in order to reach an acceptable diameter, after which it may exit the loop and proceed.

The following paragraphs and diagrams introduce the various components in the production process flow of the plant.

Mining and Primary Crushing

Platreef ore from the mining pit is transported by truck to a feed bin, and is fed to a gyratory crusher referred to as the *Primary Crusher* or *PC*. The primary crusher is sized to receive rocks up to Ø0.5m and operates with a nominal setting of Ø175mm. The primary crusher is designed to operate at a peak crusher feed rate of 2850 tons per hour.

A crusher discharge apron feeder transfers crushed ore onto a conveyor, which transports it to a 3000 ton transfer silo. An apron feeder withdraws crushed ore from the transfer silo and discharges onto the stockpile feed conveyor, which feeds a 45000 ton capacity conical ore stockpile, known as the *primary stockpile*. The primary crushing process is shown in Figure 5.1.

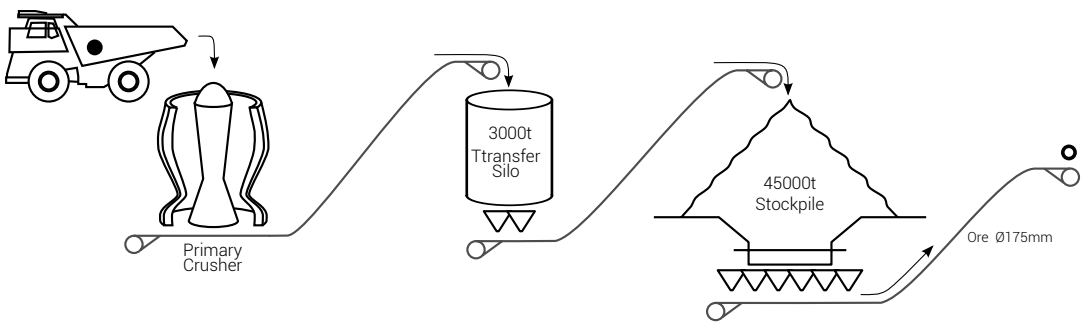

FIGURE 5.1: Process flow diagram of operations showing Primary Crusher and Stockpile.

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Secondary Crushing

The primary stockpile supplies the secondary crushing circuit with material. One of six variable speed apron feeders withdraws ore from beneath the stockpile to transfer it to a conveyor, which feeds a vibrating grizzly. Apron feeds are rotated to ensure adequate material turnover on the stockpile (they withdraw ore from different areas of the stockpile) and to prevent chute blockages.

A grizzly sorts material into oversize (Ø> 80mm) and undersize. Oversize material is transferred to the 600 ton Secondary Crusher feed bin by conveyor. Three pan feeders operate separately to withdraw material from the bin to the secondary crushers at the desired feed rate. Each of the three pan feeders supply material to one of the three Secondary Cone Crushers (SC). Secondary crusher product is conveyed by means of the secondary screen feed conveyor to the secondary screen feed bin. Undersize material from the grizzly is recombined with the secondary crusher product at this bin.

Two variable speed belt feeders transfer the secondary crushed ore to two vibrating double deck multi-slope screens. The upper deck has 80mm square aperture panels and the lower deck has 40mm x 52mm slotted panels.

Oversize material from both screens reports to a conveyor which recycles the ore back into the secondary crusher feed bin.

Undersize material from each of the secondary crusher screens reports to a dedicated conveyor which discharges the product into the HPGR silo conveyor, from where the ore is transferred to the 15000 ton HPGR feed silo.

Secondary crushing operations are displayed in Figure 5.2.

Tertiary Crushing

Tertiary crushing is performed by a High Pressure Grinding Roll (HPGR). The HPGR operates in closed-circuit with sizing screens to maintain a HPGR product size of 100% $\leq$ Ø8mm. Two variable speed silo belt feeders withdraw secondary screened ore from the feed silo and discharge onto the HPGR bin feed conveyor, to supply material to the 1250 ton HPGR feed bin.

Material is withdrawn from the HPGR feed bin by means of the two variable speed bin belt feeders. Each bin belt feeder has an overband magnet to remove any tramp

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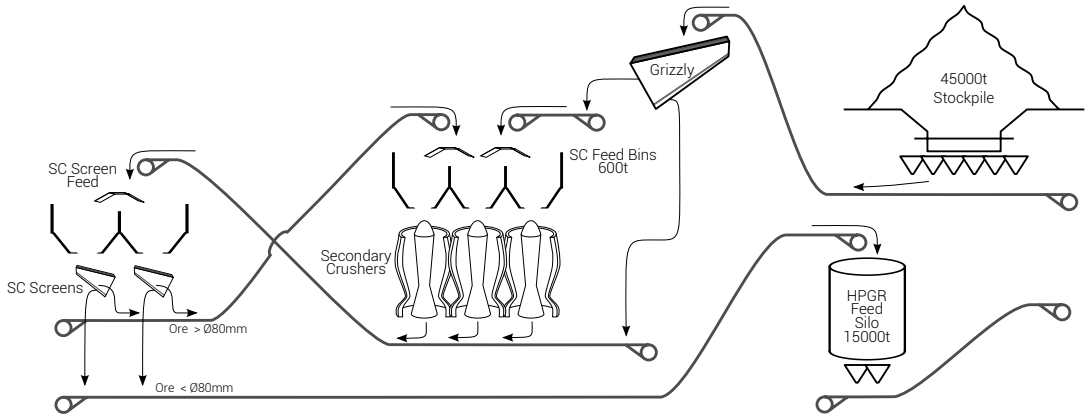

FIGURE 5.2: Secondary crushing operations showing Secondary Crushers.

metal present. The feeders discharge onto the HPGR feed conveyor, which feeds the HPGR. The HPGR product conveyor transfers the material to the HPGR screen feed bin.

The HPGR screen feed bin has a live capacity of 380 tons. HPGR product material is withdrawn from the bin by means of two variable speed belt feeders, each feeding a double deck multi-slope vibrating screen. Screen oversize material is fed back into the HPGR feed bin.

Undersize material from each screen is transferred by dedicated conveyors onto the main HPGR product conveyor, which discharges into the 15000 ton mill feed silo.

Two variable speed belt feeders withdraw HPGR product from the primary mill feed silo, and discharge material onto a feed conveyor, which in turn feeds the primary mill inlet feed conveyor via a diverter chute. The primary mill reduces the size of the ore product from 8 mm to the required floatation feed size of Ø75μm, after which it is passed to rougher floatation and secondary milling. The dry section of MNC is delimited by the primary mill and is the area of study for this case study.

Tertiary crushing operations are shown in Figure 5.3.

5.2.2 Maintenance Operations at MNC

MNC's maintenance strategy consisted of scheduled preventative maintenance with

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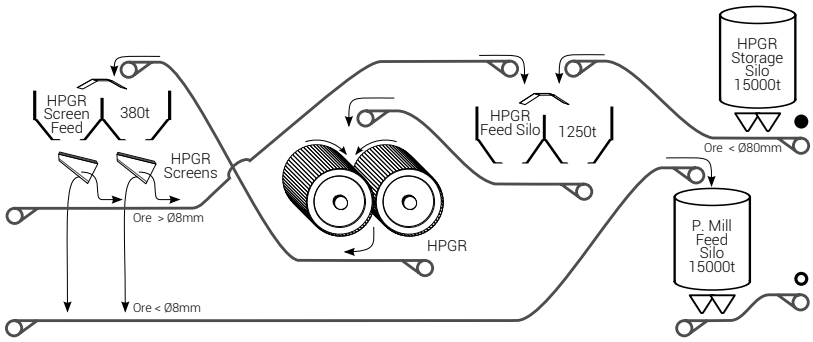

FIGURE 5.3: Tertiary crushing operations showing High-pressure Grinding Roller and Primary Mill.

inspections at regular intervals, and a two day maintenance period every other month during which production was halted and larger, intrusive interventions could be performed. To minimise the risk of failures, PM tasks are typically selected on the low side of average lifetime, and as a result equipment is generally over maintained. In the case of MNC, this is not necessarily a bad thing, as catastrophic failures generally take far longer to repair. The intrusive nature of maintenance is somewhat offset by the large buffers present in the system; these allow isolation of areas in the single-stream plant on which maintenance can then be performed while other parts run unaffected, provided that the outages are planned beforehand so that stockpiles can be replenished or emptied, and the maintenance task does not take too long to complete. This was however not the case, as management typically chose to lay the complete plant to rest while planned maintenance was performed.

5.2.3 Description of Underperforming Areas

Maintenance Planning

Mining can clearly be characterised as an asset centric or asset intensive industry, where plant profitability is directly linked to production uptime. At MNC there are a large amounts of physical assets that need to be kept running in order to generate a profit for the organisation. Fogel & Terblanche (2013) note that mining processing operations need a high level of reliability from equipment in order to generate constant volumes of product, as this continuous production is their stream of revenue. Thus a logical progression from this observation is that equipment maintenance at a mine is imperative

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for the company to be profitable.

MNC has struggled to achieve the design capacity of the plant since start of operations in 2008, and the consensus among plant management is that unexpected breakdowns of machinery are a large contributing factor. According to maintenance records, and through interviewing plant personnel, there was still a large degree of 'fire-fighting' occurring — where engineers would chase problems, fix them, only to discover that a problem had arisen elsewhere. Furthermore there was a feeling that there was a lack of synergy between machines — that the interactions between machines, and the links between failures were not properly understood, which caused a lack of overview on a systems level. Engineering management felt slightly helpless, and tended to pin the breakdowns on design faults in the system, which being a young and pioneering plant may well have been the case. Overall there was a lack of *line of sight* and a lack of focus, as the engineering department was chasing problems down as they arise, without prioritising their importance. It was thus desperately required to gain a hold on unplanned downtime at the plant, as these outages had a serious effect on the company's bottom-line.

Novelty of Operations and Shortage of Skills

As mentioned previously, MNC is a young plant, making use of use of new technology, and is manned by a young crew. This novelty poses may challenges to the plant, as it tries to reach a more predictable state through maturity in operations.

Failures are generally modelled as a function of processing time. The reliability time of many components over their respective lifetime can be described by a so-called "bathtub" curve, which was introduced in Section 4.3.2.5 which elegantly describes the components' failure characteristics throughout their life spans. For convenience the bathtub curve is again shown in Figure 5.4.

Phase 1: is the burn-in phase, the failure rate is initially high but it is reduced rapidly over a short time. Failures that occur in this phase can be attributed to manufacturing faults or flaws within the design of a component, or, for example, sub-optimal operation of a machine by inexperienced operators.

Phase 2: is the useful life of the components or system. The failure rate within this phase is characterised by a constant and low failure rate. Ideally any plant would want

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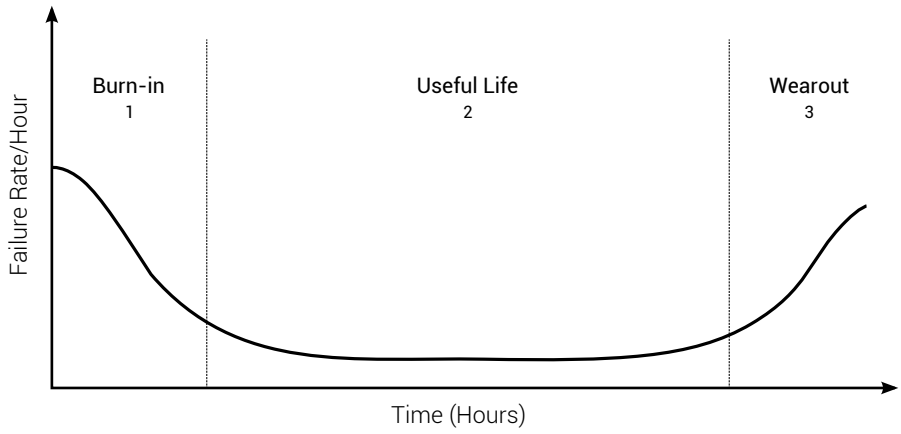

FIGURE 5.4: The "bathtub curve" failure rate graph.

achieve this phase and prolong it for as long as possible.

Phase 3: the failure rate rapidly increases. This wear out phase occurs due to aging, wear, corrosion etc. of the component or system.

A manufacturing plant can be viewed as a system of inter-dependent components, each subject to their own bathtub failure curves. Thus the system as a whole will exhibit some compounded function of failures according to its components' behaviour. The bathtub curve was mentioned here to illustrate how novelty in a manufacturing plant is necessarily complex, and that these teething problems are a natural and acceptable occurrence. During phase 1 it is very difficult to create meaningful maintenance plans due to a lack of data and the unpredictable nature of failures, and most of the focus of the engineering department will be fire-fighting.

MNC is slowly reaching phase 2 of the curve, after high initial failure rates and an inability to reach monthly production targets for almost four years. This stabilised environment allows maintenance engineers to re-examine failure data and to establish maintenance plans which are more suited to each of the respective components. The down-side of reaching this phase is the resulting apathy that is created at the plant — when the going is good, engineers tend to back off and let things run their course. However it is imperative that this phase is prolonged as much as possible, so that the high failure rates of phase 3 are delayed.

A fairly young team has been employed to run MNC — with an average age of about

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twenty-eight years, there may be a lack of experience among management personnel. Coupled with the novelty of the plant and the uncertainty that this brings, the personnel at the plant may be overburdened with the responsibility of running the plant and perhaps do not have the time to invest in other initiatives or take a ruminative view on operations.

As noted by Mitchell (2007), emphasis on cost reduction has several added liabilities. One is the loss of experience as skilled maintenance engineers and supervisors take advantage of more worthwhile opportunities. Many companies do not realise how safe, reliable operation and the absence of problems are directly connected to the efforts, contribution, commitment, skill, and experience of individuals responsible for the results. As champions depart, their experience is lost and their programs are dismantled. All that has been gained — the progress and momentum in developing effective maintenance programs is quickly lost unless training and resources are allocated in anticipation of future needs.

Poor Data Analysis and Data Integrity

A vital facet of asset management, according to ISO 55000 (2013), is that it is constructed on accurate data and information. An accurate description of the status-quo is required, so that informed decisions can be made about the prioritisation of improvement opportunities. Mitchell (2007) notes the importance of having clear, specific, quantitative objectives, and measuring and monitoring these objectives accurately.

Woodhouse (2007) notes that in juxtaposition to the ease of data access is the recognition of the criticality of data quality, and this is often difficult and expensive to maintain. Even if analysts know what information is worth collecting and how it would be used, it can be very difficult to persuade those who collect the raw material of the need to do so in a consistent and accurate manner. Completing work orders to indicate what item had failed, why, and what was done as a result, can be a major challenge in motivation if employees do not understand the value of the data they are gathering. Furthermore, if a strong blame culture exists at the plant there will be an inherent distortion in the data away from admissions of culpability.

At MNC, a wealth of data samples are constantly streamed from the plant, and these are not utilised to their full potential. The potential to use this data for condition-based maintenance, for example, should be tapped into by plant engineers, as this could

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present an opportunity for significant improvement of maintenance practices at the plant. Indeed, many PAM initiatives rely on solid operational knowledge and measurements, which stem from personnel understanding the value of data and what can be achieved by proper interpretation thereof. Data integrity is an issue which personnel don't seem to take seriously, though this is understandable considering the lack of perceived value of data. The question they should be asking is *"How do we use data to support goals and decision making?"*.

5.3 Implementing the Opportunity Identification Methodology

In the previous sections an overview of the operations of plant under study were given. This was to familiarise the reader with the structure of the plant. Problem areas were identified to create alignment with the objectives of the study, so that the reader can gain an appreciation for what the study is attempting and why it is deemed necessary at this plant.

The following sections describe how the methodology created in Chapter 4 was implemented at MNC. For the readers convenience, the methodology is repeated in Figure 5.5, and is referred to throughout the chapter. To be noted once again, is that only the *Modelling* section is dealt with in this thesis, and that the remaining sections are depicted to provide the context of the modelling phase within a greater Asset Management project.

5.3.1 Data Collection Process

As discussed in Section 4.3.2.4, it was required to collect data from MNC in order to create and validate the simulation model. The quality and quantity of the data used is directly related to the accuracy of the model, so information that is complete and accurate is highly beneficial. Data requirements are shown in Table 5.1.

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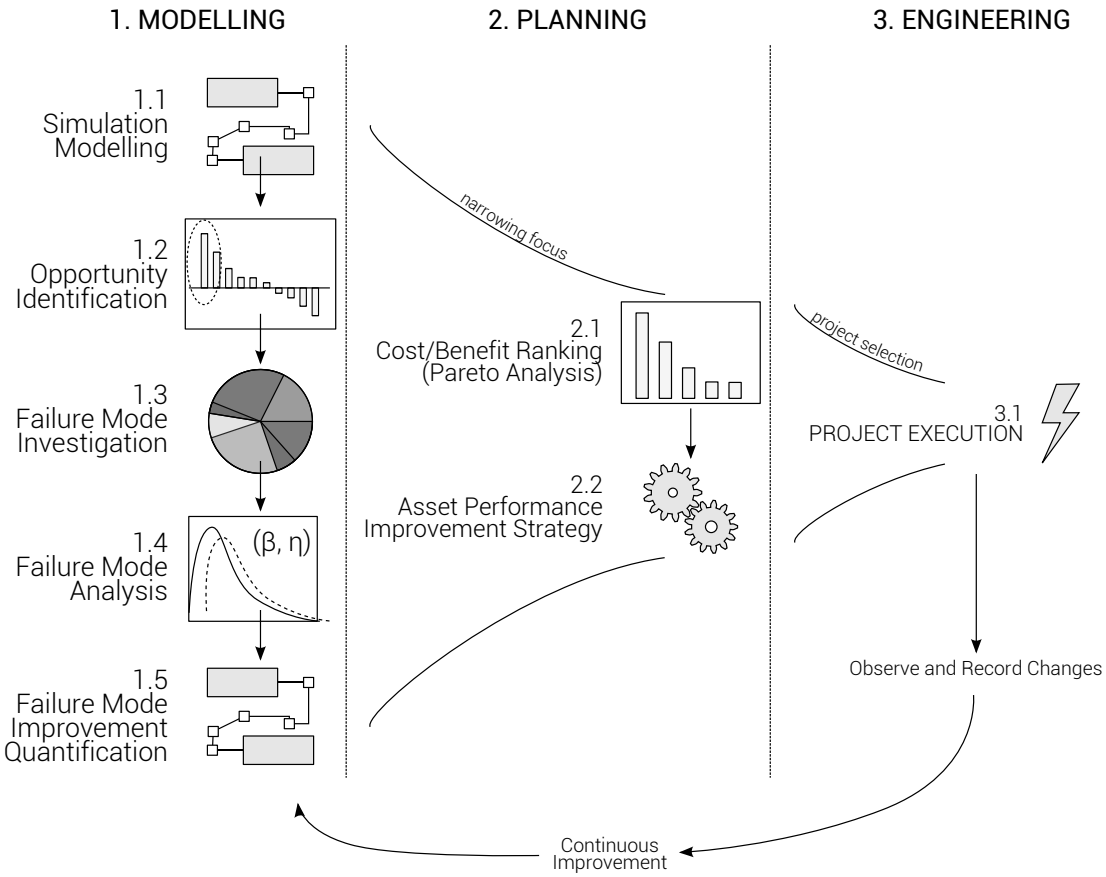

FIGURE 5.5: Project methodology overview showing the application of simulation to prioritise maintenance interventions in the wider context of asset management.

TABLE 5.1: Data Requirements for simulation.

Item	Data Required
Raw materials arriving from mining	Batch size, frequency
Throughput of each machine on dry-line	Observed throughput, stated capacity
Failure data of all machines	Frequency, downtime
Maintenance data for each machine	Date, unplanned/planned, time
Physical details of each machine	Size, throughput, buffers etc.

5.3.1.1 Sources of Data

MNC uses *PI* condition monitoring suite by software company OSIsoft[1], which collects data on machine operating parameters. The OSIsoft PI System with real-time data

[1]Founded in 1980, OSIsoft LLC is headquartered in San Leandro, CA, with operations worldwide. `http://www.osisoft.com/`

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acquisition offers a central repository for data through a facility or across multiple locations. Information can be automatically collected from many different sources, such as control systems, lab equipment, calculations, and manual entry. Users can then access this information using a common set of tools. In this case, a Microsoft Excel plugin was used, which exports sampled data to a spreadsheet and makes collection of large amounts of data a simple process.

Due to the wealth of data available, it was required to decide which parameters would be the most effective to monitor. What was required was an accurate indication of machine uptime, and on failure, a description of the failure mode. Fortunately the condition monitoring system provides such a facility for some of the major machinery in the plant, namely the Primary Crusher, Secondary Crushers, HPGR and the Primary Mill.

An attempt was made to obtain maintenance data from the plant's SAP system, however it was found that these data were unreliable as they require human intervention to record. Many breakdowns observed from PI data were missing or not reported accurately. Furthermore, an indication of machine downtime was required, which is not necessarily given by repair duration.

Plant personnel were available for interview and this provided useful information on the many nuances and control elements present in the system which are not obvious from merely obtaining data and process flow diagrams. Personnel were also consulted to ensure the validity of data collected. Some failure information, especially that of the conveyors, was difficult to obtain as the failures needed to be interpolated from other systems' breakdowns, and thus personnel provided valuable insight on the reliability of the conveyors by giving examples of how conveyors fail and how they are repaired, giving an estimation of times required for various failure modes.

The condition monitoring system PI makes use of data "tags" which correspond to a certain measurement. A summary of the tags used is given in Table 5.2.

Period of Study

A snapshot of the *current* operation of the plant was desired, and so the most recent data available was used. As explained in 4.3.2.4, methods were employed to ensure that the data collected was free from increasing/decreasing trends and an accurate description of

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Table 5.2: PI tags used for failure and throughput data collection.

Machine	Measurement	Purpose
Primary Crusher	Breakdown Reasons: Comments	Failure Frequency and Repair Duration
Weightometer WT-009B	102CV-001 Mass Flow (tph)	Primary Crusher Output
Secondary Crushers	Breakdown Reasons: Comments	Failure Frequency and Repair Duration
Weightometer WT-036B	405CV-001 Mass Flow (tph)	Secondary Crusher Output
HPGR	Breakdown Reasons: Comments	Failure Frequency and Repair Duration
Weightometer WT-402	406CV-003 Mass Flow (tph)	HPGR Output
Weightometer WT-107B	407CV-001 Mass Flow (tph)	Primary Mill Input
Primary Mill	Breakdown Reasons: Comments	Failure Frequency and Repair Duration

the *status quo*. The range of data collected was for a period of approximately 13 months, from August 2011 until the middle of September 2012, though as mentioned previously, some of this data was discarded if trends showed that it was not representative of the current operation of the plant.

5.3.1.2 Sampling Details and Simplifications

The system failure rate is modelled as an aggregation of several failure rates depending on the failure mechanisms of the sub-components of the production system. A more detailed analysis could be performed which isolates certain failure modes and can provide recommendations on which maintenance interventions should be performed.

Condition monitoring system PI variables are sampled as often as once every second. It was found to be unnecessary to process this large volume of data, and thus an arbitrary sampling frequency of ten minutes was selected in order to reduce the volume of data collected. Fortunately PI provides the facility to interpolate sampled data which is numerical, so that the ten minute samples contain the average observation for that period and no information was lost.

An implication of this ten minute sampling period is that machine stoppages which lasted less than 10 minutes were not recorded. Furthermore, machine breakdown data now necessarily has a "resolution" of 10 minutes — that is a breakdown which is recorded as $t = 30$ minutes may actually be between 20 and 40 minutes. It can be shown that this does not affect the results, as the failure durations are uniformly distributed over any given period $T = [t - 10; t + 10]$ and thus the sampled mean will approach actual mean as the number of observations $n \to \infty$.

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For the purpose of the simulation model the MNC dry plant under study was simplified into its core components in order to reduce the complexity of the model. Failure data was available for major machinery, as explained in Section 5.3.1.1, and downtime information for any machine was not limited to failures on that respective machine, but rather any failure mode which caused that machine to cease operating. Thus some failure modes were either absorbed or omitted from each system. As an example, as conveyors in the model have their own failure characteristics, machine stoppages caused by conveyor downtime needed to be filtered from the data. Table 5.3 shows which failure modes where incorporated into the reliability calculations for each node, as well as showing which failure modes needed to be filtered from the collected data for each node.

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Table 5.3: Downtime reasons considered for each system.

System	Excluded downtime	Included downtime
Primary Crusher	Conveyors	Grease system
	Stockpile Full	Lube system
		Main Shaft
		Maintenance
		No Trucks
		Other
		PLC / comms failure
		Power failure
		Rockbridge
Secondary Crushers	Conveyors	Repairs to other secondary crushers
	Bin / Silo Levels	Feedback Fault
		Grizzly
		Lube system
		Maintenance
		Other
		Power failure
		Screens
		Standby
HPGR	Bin / Silo Levels	Bearing
	Conveyors	Gearbox
		Hopper
		Lube system
		Maintenance
		Other
		Power failure
		Screens
		Skewing
Primary Mill	Conveyors	Bolts and Liners
	ML-002 Offline	Brake system
	Silo Levels	Cyclones
		Lube system
		Maintenance
		Other
		Power
		Pumps

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Validation of collected failure data

Due to the fact that PI continuously collects physical data from plant machinery, the historical data obtained from the system was assumed to be accurate and the instruments properly calibrated. In addition, all the PI failure data could be cross-referenced to SAP maintenance records (where these existed), as well as to scheduled maintenance.

In some cases, PI requires an operator's input in the case of a failure where the failure cause is not automatically registered by PI. In this case, the failure mode is recorded as "Other" by PI, with additional information about the failure entered by the operator in a separate field. This field accounted for roughly a third of the failures recorded per machine, and therefore additional care was taken to filter this "Other" column for unrelated failure modes (as explained previously in this section and in Table 5.3.

5.3.1.3 Physical Characteristics of Plant Machinery

The physical characteristics of plant machinery were obtained from:

- Plant control narratives
- Plant process flow diagrams
- Plant design schematics
- Calculated from the recorded PI data

Collected values were validated through interview with plant personnel, though in some cases where imperfect information was available, e.g. in the case of silo capacity being slightly less than design capacity for operational reasons, the design capacity was preferred. Conveyor velocities were calculated from PI weightometer data, while lengths and capacities were obtained from design schematics. Machine throughput rates were calculated using data from PI weightometer feeds and throughput rates were found to be approximately normally distributed for all machines; details are given in Table 5.4, as well as Figure 5.6 which shows the layout of the plant with each weightometer's respective mean throughput, and the throughput when averaged over an extended period of time.

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TABLE 5.4: Throughput rate distributions calculated.

Area	Code	Description	Mean (tph)	Variance (tph)
102	WT009	PC Output	2010	190
	WT217	Transfer Silo Output	1962	154
405	WT704	Stockpile to grizzly	1422	80
	WT023	SC bypass from grizzly	816	210
	WT036	SC output	2580	650
	WT411	SC return from screens	610	250
	WT705	SC to HPGR	1246	222
406	WT010	HPGR feed	1596	68
	WT402	HPGR output	2332	141
	WT416	HPGR return from screens	962	185
	WT433	HPGR to PM	1371	185
407	WT107	PM Feed	944	10

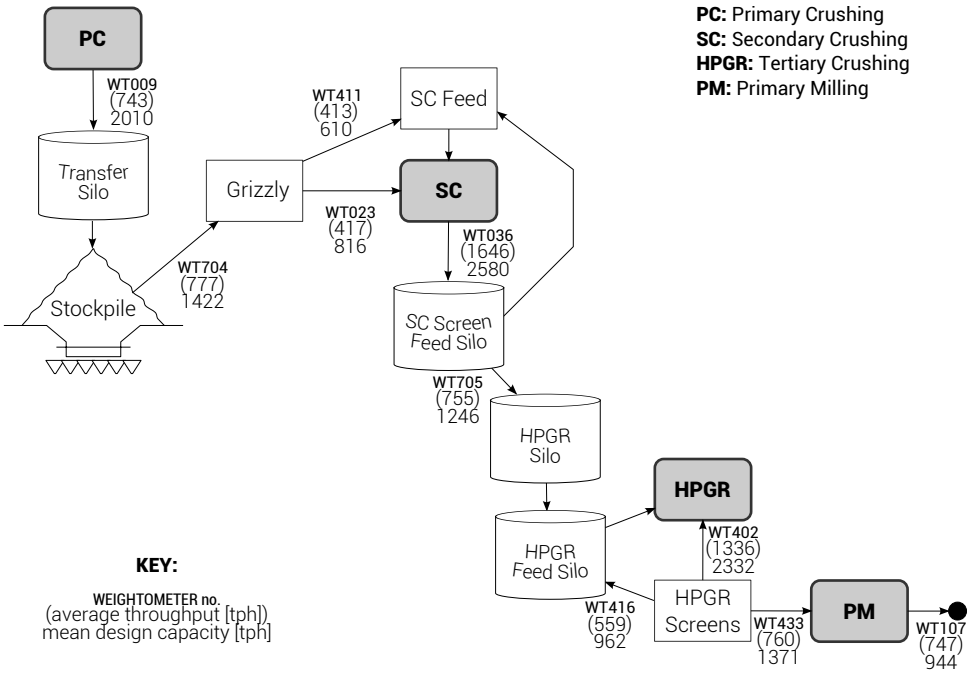

FIGURE 5.6: Basic layout of the dry section showing material flows

5.3.2 Data Analysis

5.3.2.1 Determining Failure Distributions

The *Weibull* distribution was used to model failure rates as well as failure durations. As described previously in Section 4.3.2.5, the Weibull distribution is used often in

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descriptive statistics due to its flexibility and is given by:

$$f_x(x) = \frac{\beta}{\eta}(\frac{x}{\eta})^{\beta-1} \cdot exp(-(x/\eta)^{\beta})$$

where β is the shape and η is the scale parameter of the distribution. $f_x(x)$ provides the probability of system failure at instant x, exactly. The method used to determine is detailed in Section 4.3.2.5, with Microsoft Excel's solver being used for optimisation. Two-Sample Kolmogorov-Smirnoff tests were performed with a significance level $p = 0.01$ in order to accept or reject the proposed distributions. A visual goodness-of-fit test is shown in Figure 5.7 for Secondary Crusher 1[1]. The tests indicate that the Weibull distribution and its calculated parameters are indeed satisfactory to model the plants' failure occurrences and repair times.

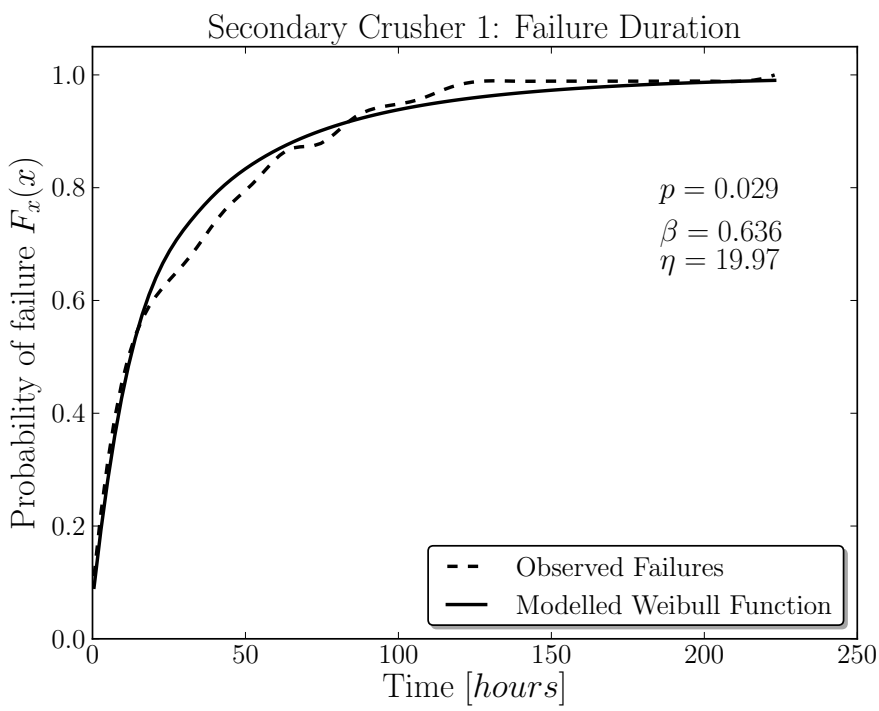

FIGURE 5.7: Visual goodness of fit test

Conveyor failures were modelled after the failure data available for the 102-CV001 conveyor which transports ore from the Primary Crusher to the proceeding transfer

[1]Modelled functions for all components are displayed in Appendix A

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Table 5.5: Calculated Weibull distribution parameters for failure frequency.

	Frequency			
	β	η	MTBF (hrs)	σ (hrs)
Primary Crusher	**0.910**	**45.73**	47.83	52.61
SC001	**0.974**	**15.39**	15.57	15.99
SC002	**0.941**	**30.71**	31.57	33.55
SC003	**0.890**	**17.29**	18.31	20.61
HPGR	**0.965**	**28.99**	29.45	30.54
Primary Mill	**0.727**	**110.06**	134.57	188.54
Conveyors	**0.801**	**364.60**	412.7993	519.76

Table 5.6: Calculated Weibull distribution parameters for failure duration.

	Duration			
	β	η	MTTR (hrs)	σ (hrs)
Primary Crusher	**0.546**	**15.52**	26.72	53.01
SC001	**0.636**	**19.972**	27.97	45.89
SC002	**0.576**	**16.04**	25.51	47.23
SC003	**0.675**	**21.40**	28.08	42.82
HPGR	**0.621**	**5.77**	8.31	13.99
Primary Mill	**0.641**	**13.40**	18.61	30.21
Conveyors	**0.647**	**12.06**	16.56	26.55

transfer silo. It was found that the data available for this conveyor was the most reliable, as breakdown data could be directly isolated from the PI tag *Primary Crusher Downtime: Reasons* — this was not possible in other areas of the plant. Other sources of failure data (i.e. SAP PM02 transactions) were found to be unreliable and were not used. Through interviewing plant personnel it was determined that operating conditions for the conveyors are similar, and thus all conveyors modelled after 102-CV001 and have identical failure frequencies and repair times.

As described in Section 4.3.2.4, it was required to obtain data that was current and to be mindful of increasing and decreasing trends in the data. A combination of the Laplace Trend Test, as described by Vlok (2012), and a visual test was performed to this end.

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5.3.3 Translation of Concept to Computer Model

5.3.3.1 Selection of Simulation Software

The considerable amount of calculations required to simulate a problem makes using simulation software inevitable, observe Azadeh *et al.* (2010). Simulation has become a popular methodology and selecting an appropriate simulation software package is one of the decisions that must be considered when executing a simulation project. Numerous types of simulation software packages have been developed for modelling simulation problems, and the increasing variety of simulation software packages in the software market makes the selection of an appropriate simulation software package a critical decision.

The simulation software used was Simio, a discrete event simulation package by Simio LLC[1]. Simio was first presented by Pegden (2007), with the intention of simplifying model by moving away from process design and promoting the use of objects. Simio employs an object-oriented approach to simulation and is thus highly flexible and customisable, maintaining support for multiple paradigms including object-oriented, process oriented, discrete-event, continuous, and agent-based modelling. Simio provides 3-Dimensional model viewing and animation, which is beneficial for recreating real-world systems and for model debugging and validation.

The model created in Simio is shown in 3D in Figure 5.8 and Figure 5.9.

The model was demonstrated to plant personnel on two occasions to confirm the validity of the process logic, layout, and operation of the plant. Personnel were satisfied that the model was a reasonable representation of the actual process.

5.4 Simulation Results

As explained in previous sections, the goal of the simulation is to discover the opportunities in improving asset reliability which, when altered, have the greatest impact

[1]Simio LLC is a private company headquartered in Pittsburgh Pennsylvania dedicated to delivering leading edge solutions for the design, emulation, and scheduling of complex systems. See `http://www.simio.com/`

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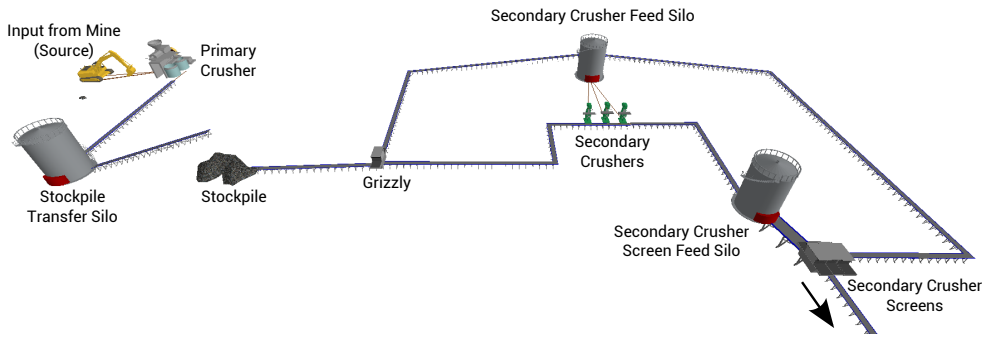

FIGURE 5.8: A view of the simulation model showing the Primary Crusher, Secondary Crusher and Stockpile.

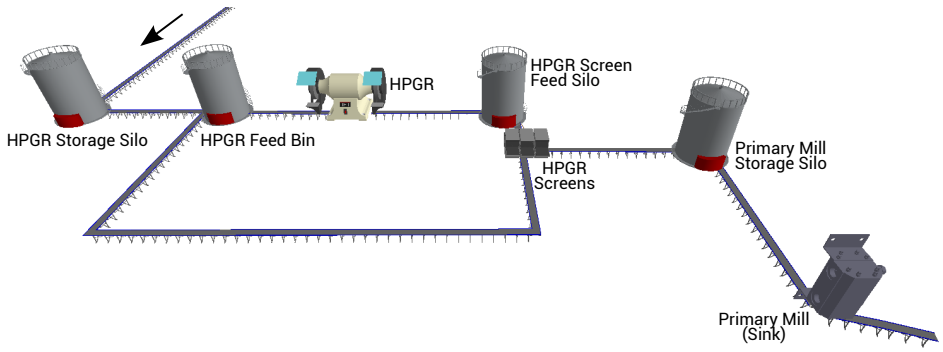

FIGURE 5.9: A view of the simulation model showing the HPGR and the Primary mill.

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TABLE 5.7: Linear regression slope values calculated.

Component	**a1** *(tons per % MTBF improvement)*
Secondary Crushers	1284.3
Primary Crusher	243.9
Primary Mill	195.8
HPGR	97.9

on the throughput of the overall system. The method of sensitivity analysis used to uncover these factors is explained in detail in Section 4.4. This section presents the results of the simulation study performed at MNC.

The components chosen to investigate were: Primary Crusher, Secondary Crushers [1], HPGR, and the Primary Mill. The MTBF intervals to test were selected at regular intervals of 20%, namely at 0%, 20%, 40% and 60%. The least-squares method of linear regression between calculated means was presented in Section 4.4. A total of 120 runs of 6 months each, with a warm-up period of 2 weeks, per scenario were performed, in order to reduce the confidence interval [2] half-width to approximately 2000 units per month for each scenario.

The result of the sensitivity analysis is the gradient or slope of the linear regression, given in the form $y = a_0 + a_1 x$. For example, a gradient of $a_1 = 1000$ on the Primary Crusher is interpreted as a 1000 tons per month increase in overall production throughput that a one percent improvement in MTBF on the Primary Crusher will induce.

The included Figures 5.10(a) – 5.10(d) present the results from each simulation scenario, and show the deducted linear regression, while Figure 5.11 shows a comparison of all the results. The results are tabulated in Table 5.7

5.4.1 Interpretation of Simulation Results

The results of the simulation showed that the greatest opportunity for increasing plant throughput can be found by improving the reliability of the Secondary Crushers. The sensitivity analysis performed on the simulation scenarios showed that improvements to the reliability of the secondary crusher system caused the greatest increase in plant

[1] SC001-SC003 were combined into one system.
[2] Confidence intervals of means of simulation runs were discussed previously in Section 4.3.2.2

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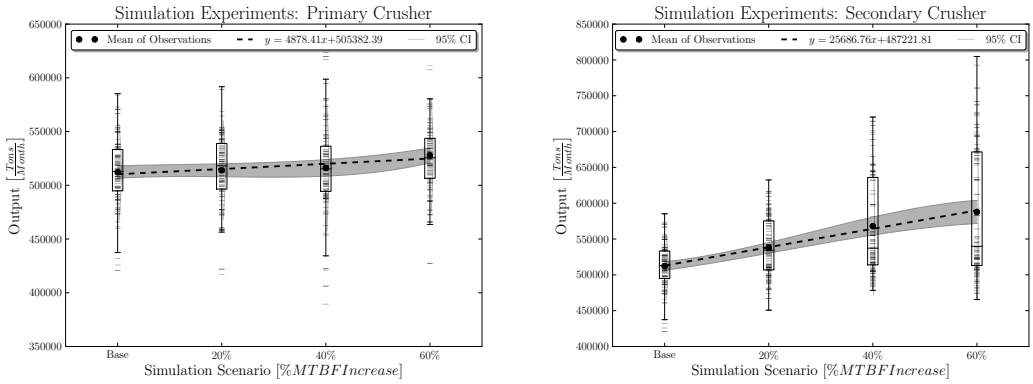
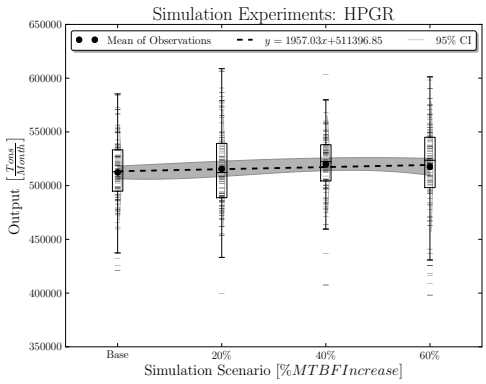
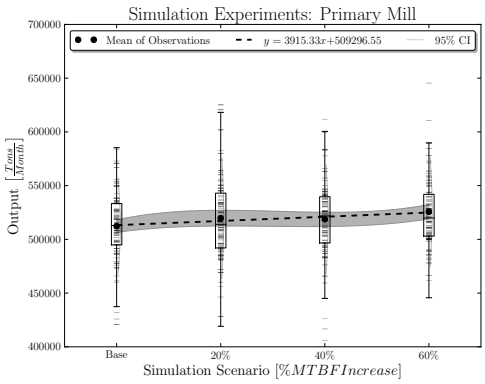


(a) Primary Crusher

(b) Secondary Crusher



(c) HPGR



(d) Primary Mill

FIGURE 5.10: Simulation results

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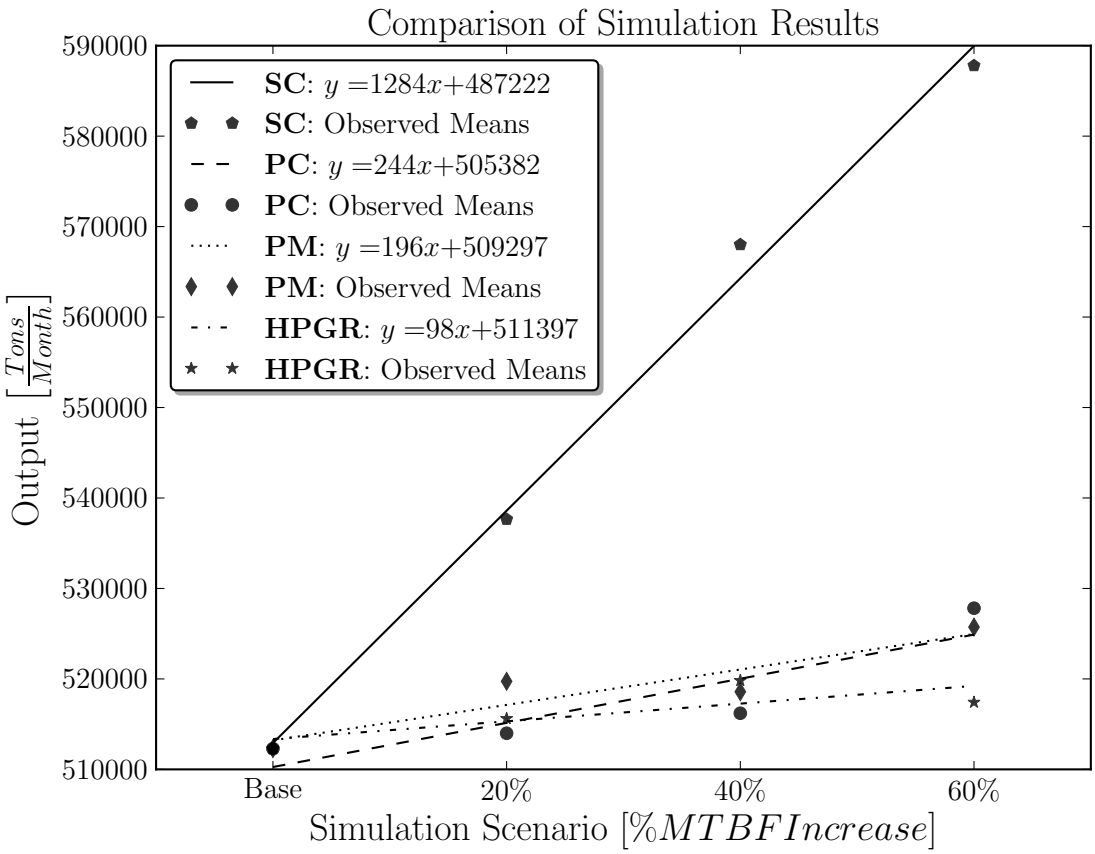

FIGURE 5.11: Comparison of linear regression results from simulation.

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throughput, when compared to the other components modelled in the simulation. For every 1% improvement in the secondary crushers' MTBF, a gain of 1284.3 $^{\text{Tons}}/_{\text{Month}}$ may be realised. The Primary Crusher (PC), High Pressure Grinding Roller (HPGR) and PM showed smaller gains of 243.9 $^{\text{Tons}}/_{\text{Month}}$, 195.8 $^{\text{Tons}}/_{\text{Month}}$ and 97.9 $^{\text{Tons}}/_{\text{Month}}$ respectively.

This result should be interpreted as an indication that there is excess capacity downstream of the secondary crushers which they are unable to fulfill currently. To be noted is that all other parameters, i.e. failure data, were unchanged for these experiments. By design the secondary crushers should not be a bottleneck in the system, as they have much greater throughput than downstream systems (HPGR and Primary Mill). Thus a possible interpretation is that the secondary crushers have become a bottleneck in the system purely due to reliability related causes, which can be alleviated by improving asset management at the plant.

A further observation of the study is that improving any or all of the other components (PC, HPGR or PM) will have far smaller returns on the output of the plant, as the bottleneck clearly resides in in the secondary crushers.

From these results it becomes clear that the reliability and throughput of the secondary crushers must be aggressively monitored and improved in order to increase the monthly throughput of MNC.

5.5 Investigation of Failure Modes and Project Selection

The previous section unveiled that the greatest improvements in throughput can be brought about by improving the reliability of the secondary crushers. This section examines reliability data from the secondary crushers in an attempt to uncover which failure modes are historically the greatest source of downtime, and which can be remedied for the most effective increase in ore throughput.

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Table 5.8: Secondary Crusher: Failure Modes Investigated

System	Excluded downtime	Included downtime
Secondary Crushers	Conveyors	Repair other secondary crushers
	Bin / Silo Levels	Feedback Fault
		Grizzly
		Lube system
		Maintenance
		Other
		Power failure
		Screens
		Standby

5.5.1 Analysis of Secondary Crusher Failure Modes

The PI condition monitoring and control system installed at MNC (as described in Section 5.3.1.1) records failure descriptions in the event of downtime. The control system contains set triggers which cause production to stop when set off. For example, if the silo level monitor of a preceding buffer reaches a low-threshold (i.e. the feed silo is empty) this trigger will cause the secondary crusher to stop until it is manually restarted again, with the reason for downtime recorded as *Bin/Silo Levels* in the *Downtime Reasons* field in PI. If the downtime is not the result of one of these pre-defined triggers, the reason for downtime is recorded as *Other*, and the machine operator is tasked to manually input a description of the event, which is then recorded in the *Downtime Comments* field.

An investigation of these recorded downtimes was performed. A portion of Table 5.3 is repeated in Table 5.8 and shows which of these triggers was investigated.

5.5.2 Failure Modes Analysis – Results

In addition to the 12 pre-defined downtime states in Table 5.8, a total of 208 downtime reasons were recorded on the Secondary Crushers by personnel during the study period. These reasons were collated for similarity and summed, and the top 10 downtime reasons, representing approximately 92% of recorded downtime, were thus calculated. These are separated into downtime resulting from a failure on any of the crushers, and downtime resulting from external factors.

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Table 5.9: Secondary Crusher Failure Modes Analysis results

	Failure Mode	Recorded Downtime [hrs]
On Crusher	Lube System	4055.7
	Maintenance	2975.7
	Feedback Fault	849.8
	Remove Steel Debris	691
	Crusher	617.8
	Communications Fault	117.2
	Blocked Chute	96
	Power Failure	89.3
Other Downtime	Bins/Silo Levels	3293.8
	Conveyor	2163.2

Due to the operational similarity and situation of the three crushers they are considered as one unit for this analysis. A study period of 9840 hours resulted in $9840 \times 3 = 29520$ hours of data for the three crushers. The total downtime recorded by PI for the secondary crushers was 16146 hours.

The major stand-out was the crushers' lubrication system, accounting for $\frac{4055.6}{16146.3} = 25.12\%$ of recorded downtime on average for the crushers. Two further major sources of downtime were the removal of metal from the crushers' chutes and conveyors, and feedback faults, mainly caused by overloads and jams. The *Crusher* field contains sundry maintenance performed, while the *Maintenance* field consists of planned maintenance ont the crushers as well as plant shutdowns. The failure modes are presented in Figure 5.12, as well as Table 5.9.

5.5.3 Quantifying the Improvement

In the previous section, a diagnosis of problems on the secondary crushers showed that the crushers' lubrication system is a major source of frustration, and accounts for approximately 25% of the crushers' downtime. The simulation results of Section 5.4 indicated that for every 1% increase in the secondary crushers' MTBF, an overall plant throughput increase of approximately 1284 tons per month can be expected, meaning that eliminating this failure mode represents an opportunity to increase the plant's monthly throughput by $25 * 1284 = 32100\,{}^{\text{tons}}/_{\text{month}}$. This is demonstrated in Figure 5.13.

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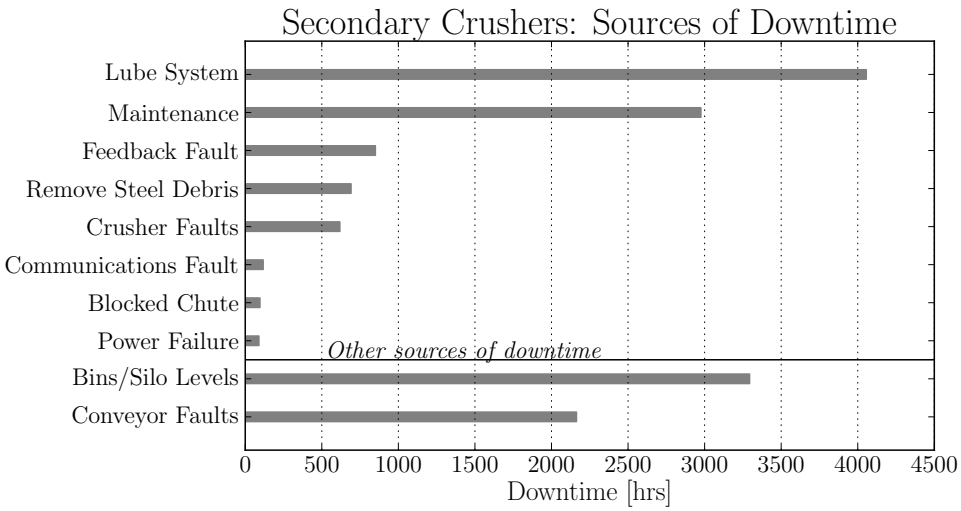

FIGURE 5.12: Sources of Downtime on the Secondary Crushers

5.6 Summary – Case Study MNC

This chapter presented a case study which demonstrated the method described in Chapter 4, developed to address the challenges put forth by the problem statement in Chapter 1.

A case study was performed at Mogalakwena North Concentrator, a South African platinum ore processing plant owned by Anglo American Platinum Limited. The operation of the plant was described in detail in order to give the reader context. Current problems and challenges faced by the management of the plant were investigated, in order to provide rationale for the case study as described by the problem statement. The main discoveries of this diagnosis were that the plant faces challenges related to its age, a lack of *line of sight* in maintenance planning, inconsistency in production, and a lack of a systems overview in identifying which factors were critical in achieving its production targets. It was discovered that the plant had been under-performing in previous months, though it had shown that it was capable of achieving its nameplate throughput on some occasions.

Approximately 13 months worth of data was collected from the plant's condition monitoring system, which was analysed in order to model the failure distributions of the most important components in the system, namely the Primary Crusher, Secondary Crushers, HPGR and the Primary Mill. Data on physical characteristics of machinery

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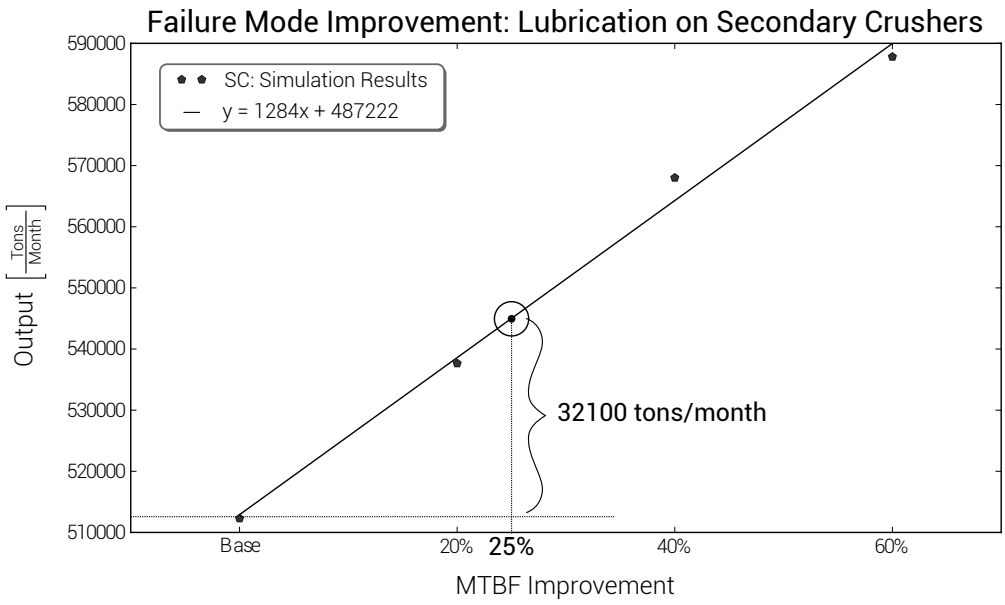

FIGURE 5.13: Quantifying the value of eliminating downtime due to the faulty lubrication system.

was collected from various sources. A comprehensive simulation model was built which incorporated this data, and simulated according to the methodology presented in Chapter 4.

Results showed that the Secondary Crushers are currently the major bottleneck in the system, and remain so due to reliability related causes, as it was found that their throughput potential is perfectly adequate to supply downstream components. This finding was the result of a sensitivity analysis which showed that, compared to all modelled components, system throughput is most sensitive to improvements in reliability in the Secondary Crusher system. An investigation of the failure modes causing downtime on the secondary crushers revealed that the lubrication system was the major source of downtime, accounting for approximately 25% of recorded failures. Using the linear regression calculated in Section 5.4, it was shown that eliminating this source of downtime could increase the plant's throughput by 32100 tons, which is a 6% increase on monthly production.

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5.6.1 Qualitative Benefits of Simulation Modelling

A vital part of this project was the validation of the simulation model, as well as being able to convince the management of Mogalakwena that the results of the model were worth investigating. During the multiple feedback sessions that were held at the plant, where the simulation model and the results of the simulation were demonstrated to personnel, it was found that the animation of the model was absolutely vital in gaining attention, and that this formed the main focal point of discussion moving forward. Combined with the results, it seemed that some personnel were, for the first time, forming an appreciation of what actually happens in the plant from a systems perspective, and were coming to notice the interplay between the various components in the system.

In the authors opinion, the discussions fostered, and the arguments created between the managers of the various systems, was at least as valuable as the actual modelling results. When given concrete evidence of what is happening and needs to happen in the plant, and then collectively accepting that evidence, the various minds start pulling together to form an understanding of the way forward, and move away from the finger pointing, accusatory remarks, and deferment of responsibility, which are the symptoms of a meeting where the problems identified are based on only speculation, as during these times every manager seems to have a different opinion. It is only when the diagnosis is accepted that the proper operation can be undertaken.

5.6.2 Comments

The feedback loops present in the HPGR and secondary crusher circuits present interesting challenges to plant operation, as they necessarily need to operate at approximately twice the throughput of other machines, due to their inefficiency at crushing ore — due to the design of these crushers, their efficiency at reducing ore to the required size is nominally no more than 50% to 55%.

From TOC principles (as mentioned in Section 3.4), an alleviation of the constraints on the secondary crushers would shift the system's bottleneck to a different part of the system. Goldratt *et al.* (1992) mentions that the system's bottleneck should ideally be located at a point which has a steady rhythm and behaves predictably. In the case of

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the dry section of MNC, this should be the Primary Mill, as points further upstream are susceptible to fluctuations of ore supplied from the mine. If one looks at the maximum throughputs for the various nodes in the dry section, this is should be the case. However, due to reliability problems on the secondary crushers, the bottleneck has shifted to them. This presents a problem, firstly because the crushers struggle to operate in parallel, and secondly because due to their design, the hardness of ore can effect the gap adjustment in the crushers, reducing their efficiency and thus increasing the re-crushing rate and lowering their output.

A consideration when analysing downtime on the crushers is that due to the design of the plant it is difficult to run the remaining crushers while maintenance is being performed on any one of them. Thus the parallel setup, which one thinks would create some operational redundancy and thus improve reliability, actually has little effect.

There are many actions which alter the operating and reliability characteristics of the machinery — for example something may have failed once, and was down for a long time, but then when it was fixed it was fixed in such a way that it won't break again. In this instance the failure data is inadequate to describe the current operating characteristics of the plant. Thus simulation and data analysis often can't unveil the "story behind the story", and communication with the operators of the plant is vital to validate whether the results obtained are, in fact, realistic. This is a limitation of simulation, and of modelling in general — Simulation alone can't uncover the root causes of problems arising in the system; an interpretation of the results is always required by an operator with some background knowledge of the plant. Furthermore, the simulation does not show or relate to *maintenance* or *failure* related downtime, but rather takes an analysis of *all* the reasons which caused downtime on each respective component, which may or not be attributable as a *root cause* to the failure, though this should become apparent during the failure modes investigation portion of the project.

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6 | Conclusion

Introduction

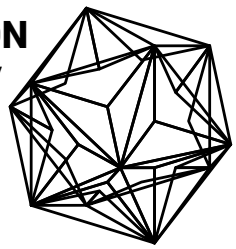
PAM Landscape

PAM Prioritisation Techniques

Prioritisation Methodology

Case Study

CONCLUSION
Summary of Study
Null Hypothesis
Findings
Limitations
Outlook



CHAPTER 6 merges the research findings of the study into final conclusions on which the success of the study is judged. A summary of the study is provided and the key points highlighted. It is shown that the study satisfies the central research question and that the null hypothesis is duly rejected. In addition, the chapter points out limitations of the study and provides recommendations for further study.

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6.1 Project Summary and Research Findings

6.1.1 Summary – Maintenance Prioritisation

The purpose of PAM is to ensure the optimised mix of cost, risk and performance over an assets entire life-cycle, to ensure that the organisation derives the maximum value possible from its physical assets. In asset-centric organisations, that is, organisations that have a performance dependency on the management of their physical assets in terms of revenue generation, the management of physical assets is seen as a core competency in deriving value for the organisation.

Maintenance is defined as *the act of causing to continue*, and is a dynamic service activity which seeks to maximise the availability of machinery. Through this definition, in the context of PAM, it becomes clear that maintenance should be viewed as an integrated function in any production environment. Non-performance of machinery is becoming less and less acceptable, due to the increasing demands on availability in supply chains and the increasing pressure to drive performance in order to maximise profitability. Maintenance has undergone an evolution in recent decades from a *reactive* mindset, where interventions are only called when a component has failed, to a *proactive* mindset, where advanced modelling and condition monitoring tools attempt to calculate the optimum maintenance interval or threshold. This mindset shift has precipitated a shift to viewing maintenance as an integrated function to production and engineering, rather than some satellite department that only receives attention when things go wrong.

Maintenance has suffered in the past as being a "necessary evil", in that most maintenance actions are inherently disruptive to production, and have foremen, ever driven to achieve production targets, having to balance the hidden risks of failure of a machine with the more obvious downtime caused by maintenance delays. Indeed, maintenance is a *hidden benefit*, as its value is derived from *preventing* events from happening — a question that often arises is *"'How does one determine the cost of something may or may not have happened?"* This is noted directly in ISO 55000 (2013), which states that the measurement of asset and asset management performance is crucial, and that having risk-based, data driven planning and decision-making processes is the only way to realise the organisation's strategic intent.

A typical production environment will experience a limitation in resources, such as

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time, money and personnel, therefore a necessary step in an effective PAM maintenance optimisation plan is to prioritise the available interventions and focus on the factors which will bring about the greatest benefit to the organisation.

From these considerations it was clear that a method is needed to isolate the effects of reliability related constraints, so that its effects can be determined and the results used to direct efforts in the most effective manner.

After performing an exhaustive literature review on current and historical world-views in PAM, with a focus on maintenance, and the state of the art in maintenance prioritisation modelling, a number of tools were examined which are currently widely available and aim to achieve related goals. It was determined that plant simulation was the most worthy venture to pursue as its versatility enabled it to conform to all the intended requirements.

A methodology was developed which would enable simulation to be used as a tool to prioritise maintenance interventions at a production facility. This method involved extensive modelling of failure characteristics, and used the simulation model to provide a sensitivity analysis, which not only provides the analyst with a prioritised list of areas which require attention, but also quantifies the opportunity which exists in remedying the downtime on that component.

A case study was performed at a South African platinum ore processing plant in order to test the designed methodology, and it was shown that the methodology is effective at helping analysts determine where the critical components in the system reside.

6.1.2 Null Hypothesis

In Chapter 1, the Null Hypothesis was stated as follows:

H_0 :	A modelling approach which isolates the effects of reliability related downtime can not be used to prioritise and quantify maintenance improvement opportunities in a production process.

Thus a method to prioritise and quantify maintenance objectives was sought. This was expanded in the problem statement in Section 1.4, and summarised in Section 3.1,

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where it was additionally shown that the selected methodology conforms to all the desired requirements. Many of the challenges which analysts typically face when building quantitative models of production systems were overcome, such as those described by Achermann (2008) in Section 1.4. These included:

Cumbersome modelling: Transformation of the model required specialised engineering knowledge, such as knowledge of statistics, failure analysis, data analysis and programming, and being comfortable width simulation software. Besides these factors, the technique was employed rapidly and the case study could be repeated at another plant.

Inefficient modelling techniques: Model building using object-oriented simulation software was efficient, and it was shown that the model could easily be tweaked in order to explore different maintenance scenarios. There was hardly any trade-off between functionality of the model and modelling efficiency.

Limited extendability: Models built with object-oriented simulation software are easily modified and can be used to explore different scenarios. The qualitative benefits of animating the operation of a plant and demonstrating this to personnel were also clear.

Inadequate modelling of preventative maintenance impact on availability: The model was able to demonstrate the effects of poor maintenance (implied by poor availability) on production throughput for selected nodes in the production system.

The case study performed in Chapter 5 further confirmed that the research objectives have been fulfilled:

1. Relevant literature was studied and a comprehensive understanding of PAM, maintenance and modelling was obtained;
2. Various alternative options were examined and evaluated for appropriateness to fulfill the requirements of the study;
3. A method was chosen and thoroughly examined;
4. A methodology was designed around that solution;

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5. A case study was performed, which proved through experimentation that the chosen method fulfills all the requirements of the study.

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

> *"A modelling approach which isolates the effects of reliability related downtime on a complex production system is a useful diagnostic tool to identify constraints and bottlenecks caused by poor asset management, and can be utilised as a management tool to quantify and prioritise the available improvement opportunities."*

6.2 Limitations

An essential part of any research study is the acknowledgement of limitations, as well as potential weaknesses that are encountered during the study. The prioritisation methodology developed for this project was found to be limited in the following ways:

- The model is inherently very dependent on the quality and quantity of the available data. In the absence of failure data, assumptions need to be made, which may detract from the usefulness and the level of acceptance of the results.
- Failure data is inherently historic and may not offer an accurate snapshot of the *current* operation of the plant. Resistance to results may come from personnel who determine that recent changes in the plant positively alter operating characteristics.
- The methodology focusses on the opportunities present in improving maintenance. In the MNC case study there were relatively large gains which could be found by improving reliability, however this may not be the case in other systems. In systems which are more reliable, the gains which are realised could be smaller than the simulation's confidence intervals, which would render the results inconclusive. However, in such cases one may be able to conclude that opportunities for improvement lie outside the realm of reliability, and further studies may be performed by simulating scheduling, throughput, design changes etc.

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- The failures observed are typically heavily stochastic in nature, meaning that there will be extremely large variance in breakdowns and repair times, and long periods of no activity in the simulation. This necessitates long simulation run lengths and a large number of replications in order to reduce the variance in output, which is costly computation-wise.

- Simulation is always a simplification of the real world operation of a system. In many cases it may present an oversimplified view, especially relating to the interplay between components in the system. For example, it may be the case that increasing the throughput through a component by improving an upstream bottleneck changes the operating characteristics of the component, which in turn has a snowball effect on other components downstream.

- The study is limited to quantifying results only on throughput improvement, when there may be many other important corollaries to improved reliability which are qualitative in nature or harder to quantify, such as improved supplier relations. In general, the benefits of good asset management are far-reaching and well-documented. For example Fogel & Terblanche (2013) state that there is clear evidence that asset management improves factors such as safety, shareholder value and energy use.

- The model doesn't take human intervention into account and the ability for plant control to not be completely stochastic, but actually controlled to some degree by human operators. For example, operators may push a machine to reach production targets each month by deferring maintenance at the end of the month.

- Simulation can't offer instant results. Running replications may take many hours to days to complete, depending on the required accuracy.

Many of the items listed above are inherited directly from the limitations of simulation. This is in line with the maxims presented by Chung (2003:p5): 1) Simulation cannot give accurate results when input data is inaccurate, 2) Simulation cannot provide simple answers to complex problems, 3) Simulation alone cannot solve problems.

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6.3 Applicability of Method to Other Industries

The case study presented in this thesis was undertaken at a platinum ore processing plant in South Africa. A subsequent study, which is not documented in this thesis, was performed at Jwaneng Diamond Mine in Botswana under similar conditions. While the subsequent study only serves to further validate the hypothesis presented here, it is felt that a report on the applicability of the method to *other* industry sectors outside of ore processing is required in order to ratify the generality of the null hypothesis. While a further case-study is not available due to time constraints, the experience of performing the prior studies has allowed for some qualified comments to be made about how the method would fare in different situations.

Reliability is defined as the quality of being reliable or dependable. Investigating and modelling a system for opportunities to improve reliability would necessitate that the system consists of components which have a reliability attribute which affects the operation of the system and is objectively and quantitatively measurable. The components should interact with one another in a predictable manner, and the system under study should also be sufficiently complex that simulation is warranted over simpler analysis.

Simulation inherently has a confidence interval which is naturally bounded by number of replications of the model that can be run. That is, in general, the greater the number of replications (with diminishing returns), the tighter the confidence bands surrounding the observed mean. However, a further tolerance must be introduced for the quality of the input data and the simplifying assumptions made by the model—the less confidence there is in the data and the simpler the model, the wider the adjustment to the confidence bands needs to be.

A basic pillar of the analysis is that critical nodes are identified by improving their reliability and then comparing them by throughput improvement to other nodes. If the gains in throughput improvement are small, and thus fall within the natural confidence interval of the simulation, it would be impossible to identify critical nodes and reliability improvement opportunities from the results. The observation may be made in this case, however, that the constraints on the system may be unrelated to reliability. However, the author would like to argue that in this case, it is unlikely that the method would have been called upon in the first place.

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Some requirements for implementation are, thus, that it has been postulated by management that the plant is experiencing reliability problems from the outset, and that there are sufficient data available to accurately model the physical plant and describe failures in order to create confidence in the results.

Other than the afore-mentioned points, the method may be reasonably applied in any plant from which a valid simulation model can be created.

6.4 Outlook

During the investigations some considerations emerged which may be worth further investigation:

- Perhaps the biggest potential to further the study lies in improving the complexity of the simulation model to include, for example, advanced maintenance scheduling which attempts synergistic relations between production and maintenance. The increased complexity of the model may uncover important details which manifest on smaller scales, and can be used to play out more intricate scenarios.
- Using the simulation model for optimisation is an approach that was not explored. Great potential exists in using a plant simulation similar to the one developed in the case study, to determine, for example, optimum maintenance intervals and allocation of resources. For example, a question which could be asked is: "What is the cheapest combination of improvements which can be made in order to provide a sustainable improvement in monthly output of x%?"
- The efficiency of the simulation model can be improved to drastically reduce the computation time. The long run lengths and large variances requiring many replications make model validation difficult and prolong time to results. Other software options can be explored, and tools can be created to reduce the time it takes to program the model. This is bound to happen over time, as the usability of simulation software is constantly improving, as is the computational power of computers.
- One of the findings of this project was the value of the simulation model, particularly the results and the animation, in fostering useful discussion among key

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players in management, production and engineering. It was felt by attendees of feedback sessions that the results were invaluable as a catalyst for cross-functional conversation with reduced finger-pointing. Thus the value of using quantitative asset contribution models to drive organisational alignment to asset management by actively isolating the function of reliability is a topic which should be researched.

All of the above-mentioned recommendations for further study are suggestions to improve the research study conducted, and represent opportunities which can be pursued further.

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A | Appendix A – Modelled Weibull Functions

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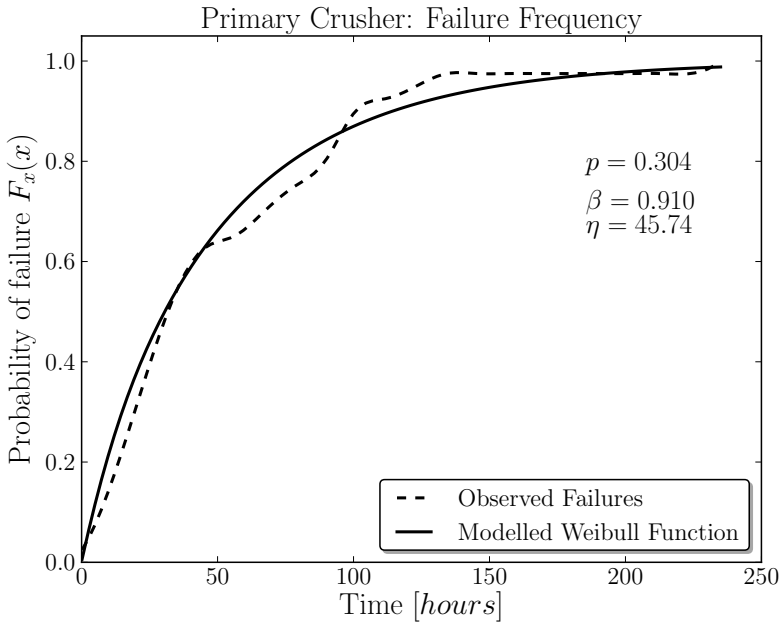

FIGURE A.1: Weibull Model of Primary Crusher Failure Frequency

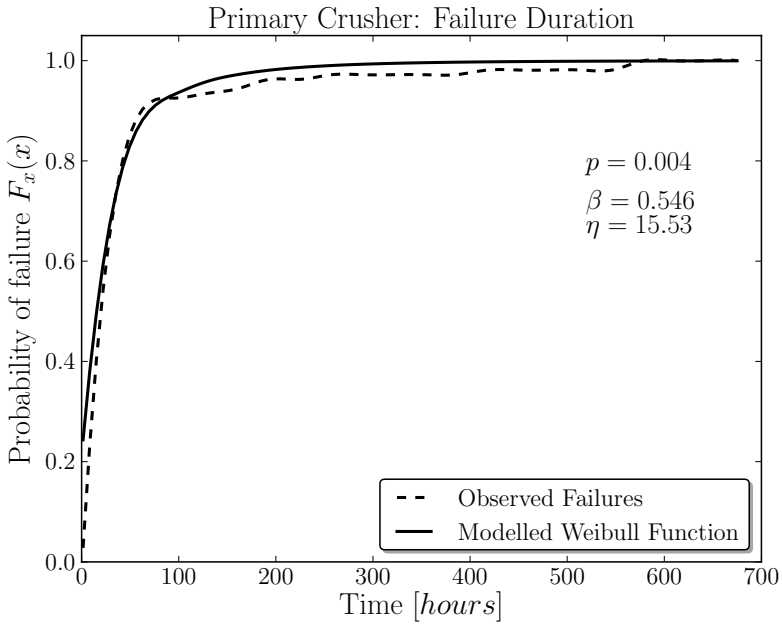

FIGURE A.2: Weibull Model of Primary Crusher Failure Duration

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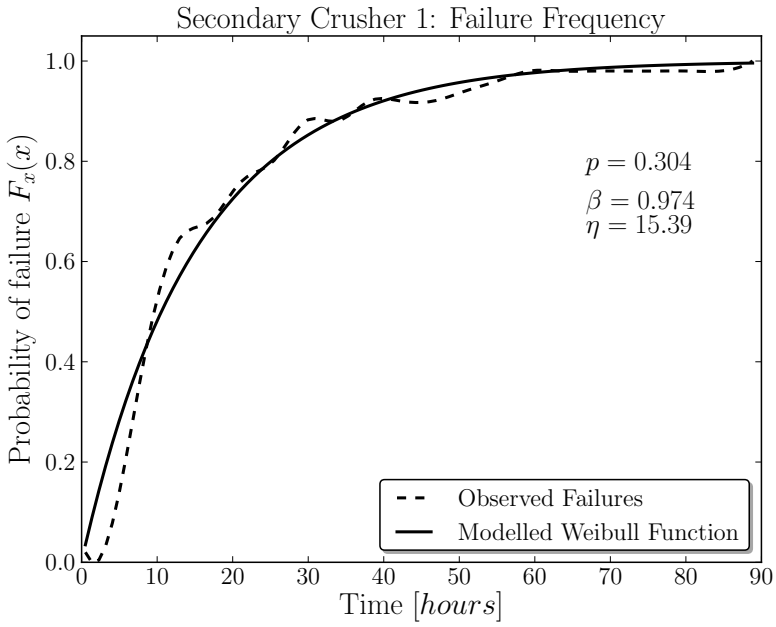

FIGURE A.3: Weibull Model of Secondary Crusher 1 Failure Frequency

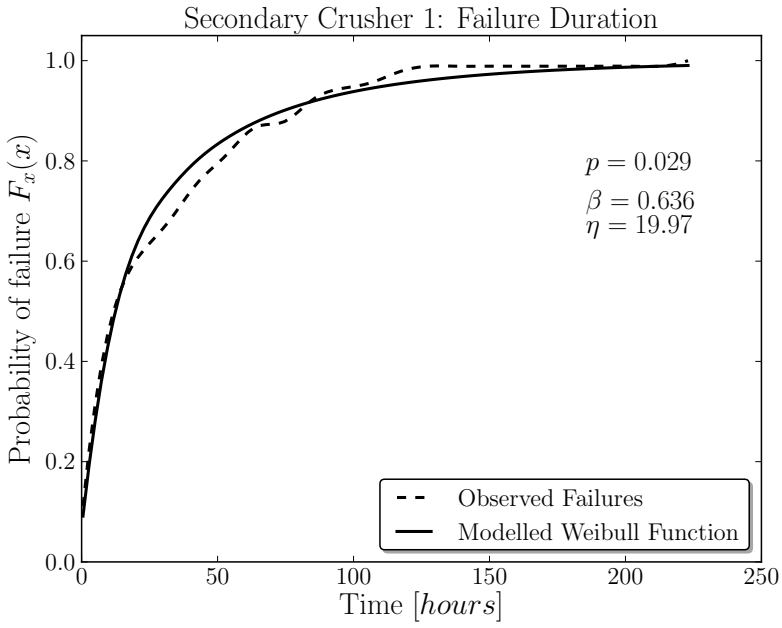

FIGURE A.4: Weibull Model of Secondary Crusher 1 Failure Duration

Stellenbosch University http://scholar.sun.ac.za

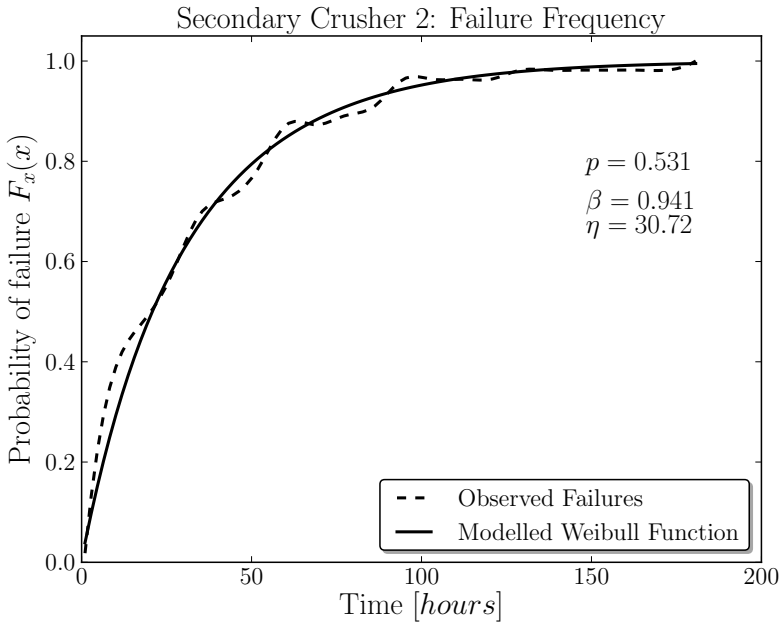

FIGURE A.5: Weibull Model of Secondary Crusher 2 Failure Frequency

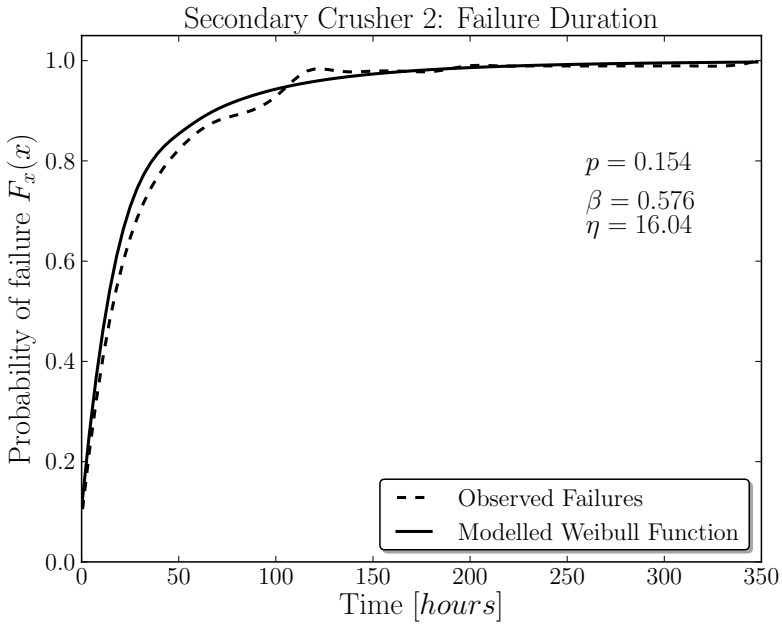

FIGURE A.6: Weibull Model of Secondary Crusher 2 Failure Duration

Stellenbosch University http://scholar.sun.ac.za

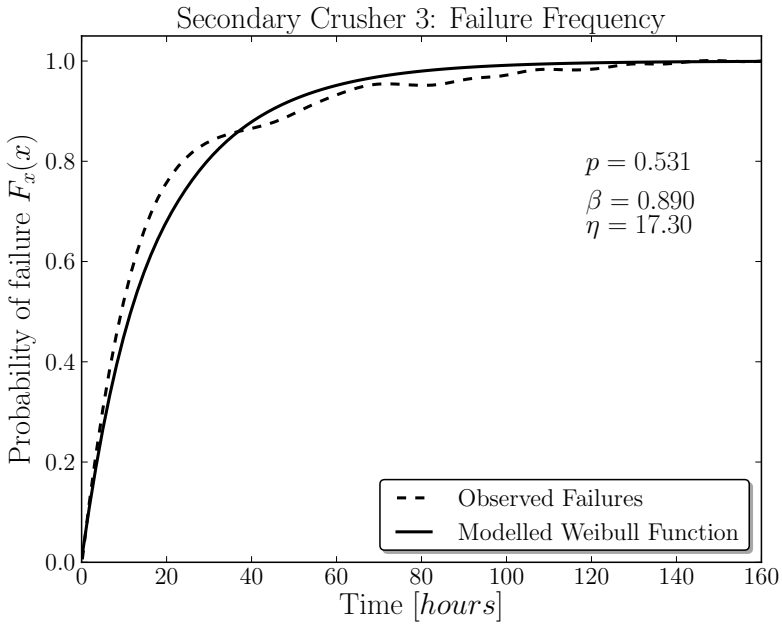

FIGURE A.7: Weibull Model of Secondary Crusher 3 Failure Frequency

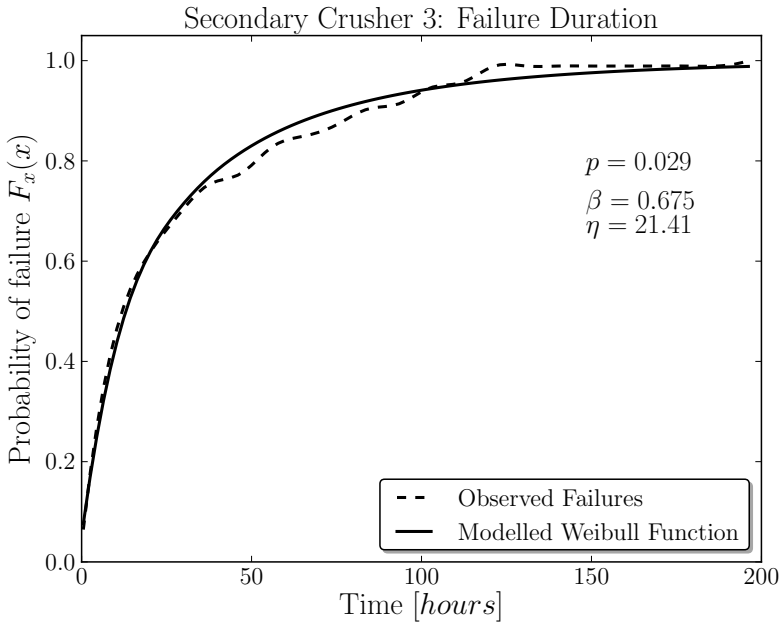

FIGURE A.8: Weibull Model of Secondary Crusher 3 Failure Duration

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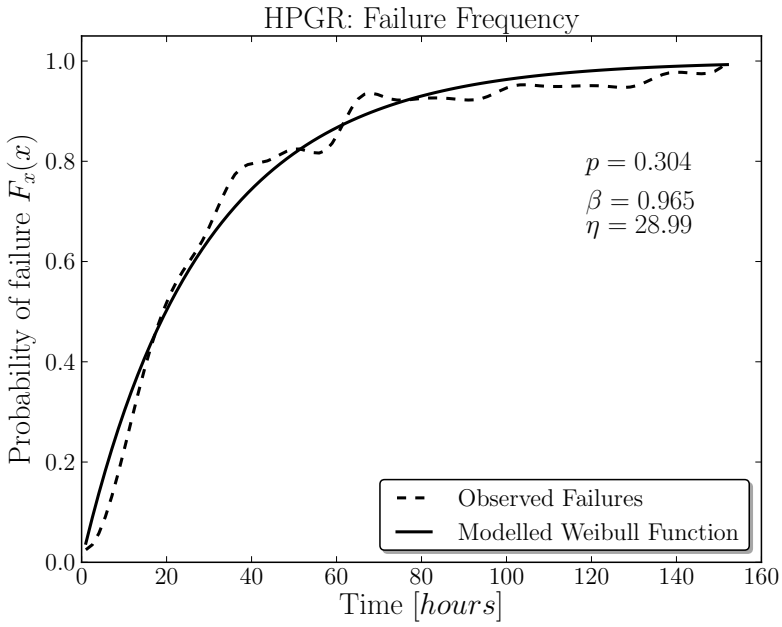

FIGURE A.9: Weibull Model of HPGR Failure Frequency

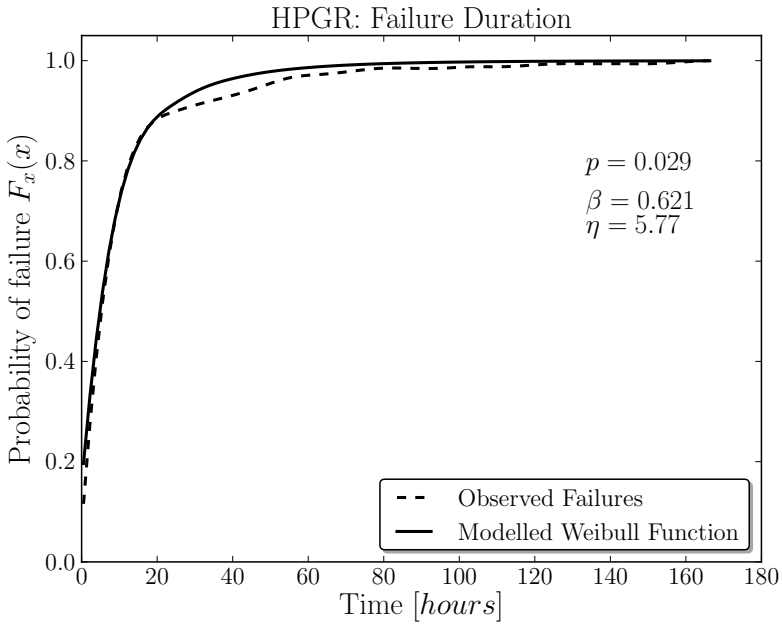

FIGURE A.10: Weibull Model of HPGR Failure Duration

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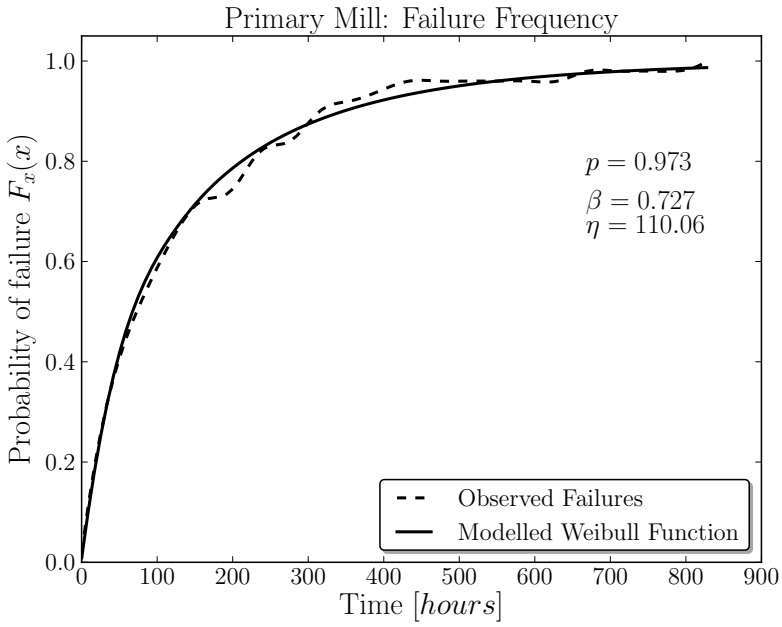

FIGURE A.11: Weibull Model of Primary Mill Failure Frequency

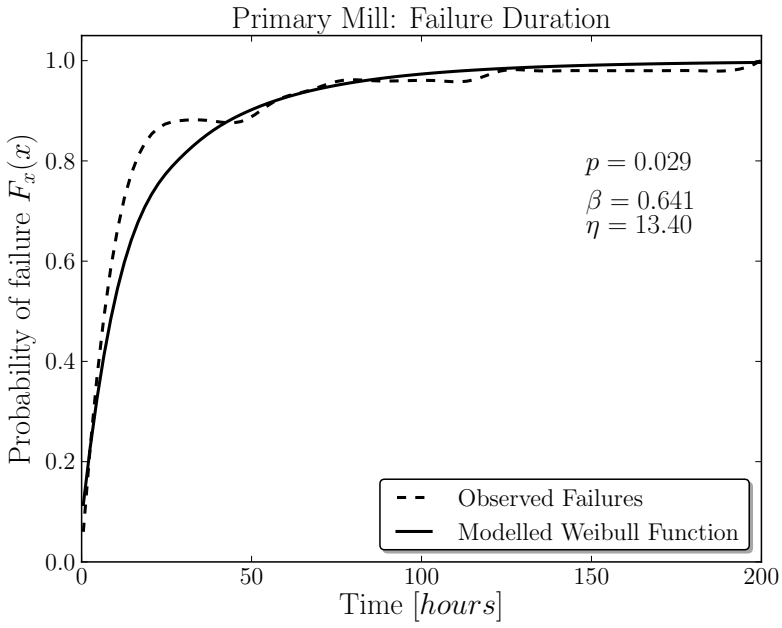

FIGURE A.12: Weibull Model of Primary Mill Failure Duration

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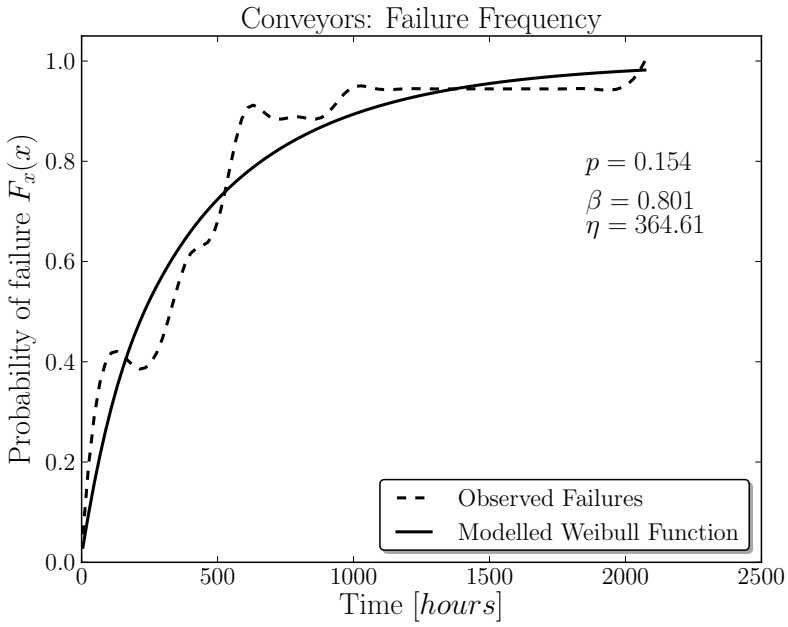

FIGURE A.13: Weibull Model of Conveyors' Failure Frequency

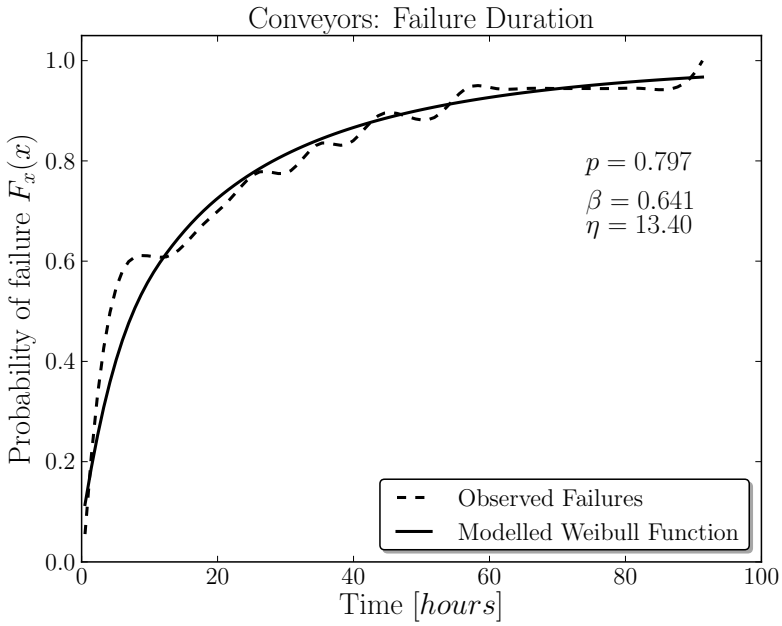

FIGURE A.14: Weibull Model of Conveyors' Failure Duration