# A Framework for Incorporating Business Risks in Physical Asset Replacement Decisions in Capital-Intensive Industries

by

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*Thesis presented in partial fulfilment of the requirements for the degree of Master of Science in Engineering Management in the Faculty of Industrial Engineering at Stellenbosch University*

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December 2016

# Declaration

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Date: December 2016

# Abstract

**A Framework for Incorporating Business Risks in Physical Asset Replacement Decisions in Capital-Intensive Industries**

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December 2016

The global financial crisis in 2008 and the subsequent recession brought the turmoil of unprecedented uncertainty and risk to capital-intensive organizations forcing them to re-evaluate capital investment strategies for physical assets. The business landscape now, in 2016, share similar economic and business risk related circumstances. Capital-intensive organizations are frequently faced with the challenging decision of when to replace physical assets. This decision needs to be made as a function of traditional asset replacement factors such as performance degradation, operating and maintenance costs, asset salvage value, and tax implications as well as organization-specific circumstances and the external business environment. Today, many organizations tend to focus on traditional asset replacement factors therefore not including the evolution and impact of business risks which may significantly influence strategic initiatives such as operating and capital expenditure decisions.

In this study, a quantitative framework is developed to incorporate the forecasted impacts and evolution of business risks over time into physical asset replacement decisions in capital-intensive industries. More specifically, a logical and structured framework incorporating both qualitative and quantitative business risks as well as traditional asset replacement factors using the Markov Decision Process (MDP) modeling technique is developed. The framework provides managers with a tool to assist them in generating an optimal physical asset replacement policy for a finite period of time into the future while adhering to a specified objective function.

An extensive literature review is conducted which covers Asset Management (AM), asset replacement theories, business risk management, and modeling techniques serving as the foundation of the proposed framework. Validation of the proposed framework was accomplished by means of a case study conducted at a diamond mining organization in Southern Africa facing a volatile business environment proving both the theoretical and practical value of the framework. The results indicate that the developed framework is a useful tool to incorporate business risks in physical asset replacement decisions in capital-intensive industries.

**Keywords:** Asset Management, Physical Asset Replacement, Business Risks, Capital Investment, Markov Decision Process

# Uittreksel

## ’n Raamwerk om Besigheidsrisiko’s te Integreer in Fisiese Batevervangingsbesluite in Kapitaalintensiewe Nywerhede

*(“A Framework for Incorporating Business Risks in Physical Asset Replacement Decisions in Capital-Intensive Industries”)*

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Die wêreldwye finansiële krisis in 2008 en die gevolglike resessie het ongekende onsekerheid en risiko teweeggebring in kapitaalintensiewe organisasies en hulle sodoende gedwing om bestaande kapitaal beleggingstrategieë vir fisiese bates te hersien. Die huidige besigheidslandskap, in 2016, toon soortgelyke ekonomiese en besigheidsrisiko verwante omstandighede. Kapitaalintensiewe organisasies word dikwels gekonfronteer met die uitdagende besluit wanneer om fisiese bates te vervang. Hierdie besluit moet gemaak word as ’n funksie van tradisionele batevervangingsfaktore soos die agteruitgang in bateverrigting, toenemende bedryfs- en instandhoudingskoste, bate herwinningswaarde en belastingimplikasies asook organisasie-spesifieke omstandighede en die eksterne bedryfsomgewing. Baie organisasies is geneig om op die tradisionele batevervangingsfaktore te fokus en neem dus nie die evolusie en impak van besigheidsrisiko’s, wat ’n aansienlike invloed kan hê op strategiese inisiatiewe soos bedryfskostes en kapitaalbesteding besluite, in ag nie.

In hierdie studie word ’n kwantitatiewe raamwerk ontwikkel om die voorspelde impak en evolusie van besigheidsrisiko’s met die verloop van tyd te integreer in fisiese batevervangingsbesluite in kapitaalintensiewe nywerhede. ’n Logiese en gestruktureerde raamwerk word ontwikkel waarin beide kwalitatiewe en kwantitatiewe besigheidsrisiko’s sowel as tradisionele batevervangingsfaktore ingesluit word met behulp van die Markov besluitnemingsproses modellering tegniek. Die raamwerk bied aan bestuurders ’n instrument om hulle te help in die ontwikkeling van ’n optimale fisiese batevervangingsbeleid vir ’n beperkte tydperk in die toekoms, terwyl dit aan ’n bepaalde doelfunksie voldoen.

’n Omvattende literatuurstudie is uitgevoer wat batebestuur, batevervangingsteorieë, besigheidsrisiko-bestuur, en modellering tegnieke insluit en dien as die basis van die ontwikkeling van die voorgestelde raamwerk. Die validering van die voorgestelde raamwerk is tot stand gebring deur middel van die uitvoering van ’n gevallestudie by ’n diamantmyn in Suider-Afrika wat ’n uitdagende sosio-ekonomiese en sakeomgewing in die gesig staar. Die gevallestudie beklemtoon beide die teoretiese en praktiese waarde van die raamwerk. Die resultate dui daarop dat die ontwikkelde raamwerk ’n waardevolle instrument is om besigheidsrisiko’s in fisiese batevervangingsbesluite te integreer in kapitaalintensiewe nywerhede.

**Sleutelwoorde:** Batebestuur, Fisiese Batevervanging, Besigheidsrisiko, Kapitaalbelegging, Markov besluitnemingsproses

# Acknowledgements

I would like to express my sincere gratitude to the following people and organizations that contributed to the work that culminates in this thesis:

- My research supervisor, Professor P.J. Vlok, for his invaluable guidance, wisdom and time invested in this thesis.
- Anglo American, for funding the research in this thesis.
- Doctor Mingzhou Jin and Doctor Anahita Khojandi from the University of Tennessee, for their inputs on this research.
- My family, for their continuous support and encouragement throughout my entire study period.
- My friends, for their continuous motivation and encouragement.

The Author
December, 2016

# Dedications

*This thesis is dedicated to my parents, **Frank** and **Sonnette van Wyk**, for your unwavering support, trust and unconditional love.*

# Contents

# List of Figures

# List of Tables

# Acronyms and Abbreviations

| | |
|---|---|
| AAC | Anglo American Corporation |
| ACRG | Asset Care Research Group |
| AI | Artificial Intelligence |
| AM | Asset Management |
| AMCU | Association of Mineworkers and Construction Union |
| AMS | Asset Management System |
| ANN | Artificial Neural Networks |
| ARIMA | Auto Regressive Integrated Moving Average |
| ARMA | Auto Regression and Moving Average |
| BCM | Business Centered Maintenance |
| BIM | Building Information Modeling |
| BS | British Standard |
| BSI | British Standards Institution |
| CM | Corrective Maintenance |
| CMMS | Computerized Maintenance Management Systems |
| DMS | Dense Media Separation |
| DOM | Design-Out Maintenance |
| EAM | Engineering Asset Management |
| EAC | Equivalent Annual Cost |

| | |
|---|---|
| ERP | Enterprise Resource Planning |
| FMEA | Failure Mode and Effects Analysis |
| GAAP | Generally Accepted Accounting Principles |
| GFMAM | Global Forum on Maintenance and Asset Management |
| GIS | Geographical Information Systems |
| GUI | Graphical User Interface |
| IAM | Institute of Asset Management |
| IRR | Internal Rate of Return |
| ISO | International Organization for Standardization |
| LCC | Life Cycle Costs |
| MDP | Markov Decision Process |
| MLP | Multi-Layered Perceptron |
| MPMT | Mean Preventive Maintenance Time |
| NPV | Net Present Value |
| OEE | Overall Equipment Efficiency |
| OERG | Operational Excellence Research Group |
| OM | Operating and Maintenance |
| PACED | Proportionate Aligned Comprehensive Embedded Dynamic |
| PAM | Physical Asset Management |
| PAS | Publicly Available Specification |
| PdM | Predictive Maintenance |
| PDCA | Plan-Do-Check-Act |
| PM | Preventive Maintenance |
| RCM | Reliability Centered Maintenance |

| | |
|---|---|
| ROA | Return On Assets |
| ROI | Return On Investment |
| SAMP | Strategic Asset Management Plan |
| SE | Systems Engineering |
| SEG | Strategy Execution Gap |
| SLTO | Social License to Operate |
| TEDR | Total Expected Discounted Revenue |
| TPM | Total Productive Maintenance |
| VAR | Vector Auto Regression |

# Nomenclature

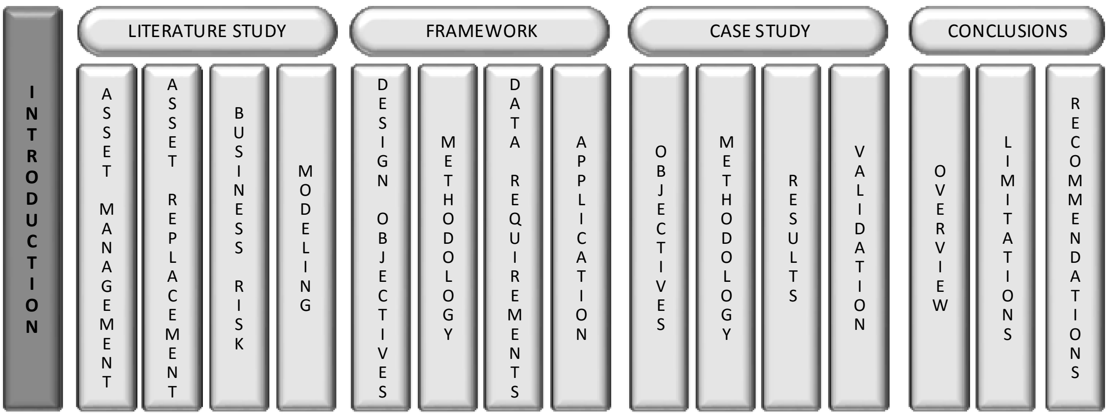
### Markov Decision Process

| | |
|---|---|
| $a_t$ | Replacement action available at time $t$ |
| $A_s$ | Set of replacement actions |
| $M_t(s'\|s_t, a)$ | Transition probability matrix describing the system dynamics for each action $a_t$ at a decision epoch $t$ |
| $N$ | Total number of decision epochs |
| $P_t(s'\|s_t, a)$ | System transition probability at time $t$ |
| $R_t(s_t, a)$ | Immediate economic reward associated with an action $a$ and system state $s$ at time $t$ |
| $s_t$ | State describing system conditions |
| $s'$ | System state at the next decision epoch $(t+1)$ |
| $t$ | Discrete time |
| $T$ | A set of points in time at which replacement actions are taken |
| $V_t$ | Total discounted expected value for objective function |
| $x$ | Total number of system states |
| $\gamma$ | Discount factor to account for inflation |
| $\pi$ | Decision policy containing a number of replacement decisions $d_t$ for a finite time period |

# Chapter 1

# Introduction

*"There are risks and costs to action. But they are far less than the long range risks of comfortable inaction."* - John F. Kennedy (1917 - 1963)




**Chapter Outcomes:**

- Introduction and contextualization of this research.
- Discussion and presentation of research domain, problem statement and delimitations of the study.
- Presentation of research objectives for this study.
- Presentation of research design and methodology implemented.
- Development of thesis structure and layout.

## 1.1 Introduction

Chapter 1 introduces the fundamental concepts investigated in this study. More specifically, theoretical background is provided for the study and it is contextualized within the existing body of knowledge. Moreover, the significance and value of the research conducted are discussed. This is followed with the problem statement that the study aims to explore throughout the thesis which is translated into a research proposition. Next, the limits and boundaries with regards to the scope of the research are introduced. Achievable research objectives are developed that adhere to the problem statement and scope of the study. The research design and methodology is then introduced to discuss the research outlook and methods used to evaluate the research proposition. Lastly, the chapter concludes with a discussion on the outline and structure of the thesis.

## 1.2 Theoretical Background

Today, many organizations in capital intensive-industries are still experiencing the effects of the 2008 global financial crisis. Renowned economists consider this to be the worst financial crisis since the Great Depression in 1929 to 1939 (Brunnermeier, 2008). The global financial crisis in 2008 brought the turmoil of unprecedented uncertainty and risk to capital-intensive organizations. Many organizations were forced to significantly downsize their operations or close down permanently in order to cut costs and perform damage control as a result of the global recession that ensued (Shah and Littlefield, 2009). Since the recession, several economic and political events such as the European financial crisis and growing political tensions have added to the enduring uncertainty of an economic recovery and an inclination towards prosperity.

The uncertain and precarious economic climate, created by the aforementioned events, have impacted the manner in which many organizations, especially capital-intensive organizations, conduct their business post 2008. Studies conducted by the Aberdeen group for the period 2009 through 2014 revealed that on average 65% of the 139 surveyed asset-intensive organizations decreased operating budgets and capital expenditure by as much as 20% or completely halted expenditure, on a year-over-year basis (Shah and Littlefield, 2009; Paquin, 2014). To remain competitive in the demanding economic climate, Jardine and Tsang

(2013) point out that companies in asset-intensive industries are identifying new and innovative ways to:

- Improve the utilization of asset systems.
- Increase risk and safety management performance.
- Improve decision-making processes of investment opportunities.

Paquin (2014) states that the difficult economic and business climate is compounded by ongoing challenges coming from imminent industry-specific business risks such as a retiring workforce, volatile labour relations, aging infrastructure, safety and environmental performance, and compliance to regulatory requirements among other. Given these complexities, organizations are tasked to find innovative ways to maximize asset operational performance in order to create competitive advantage. In the period following the recession, a limited number organizations have regained stability in organizational performance but are now, in 2016, confronted with similar economic and business risk related circumstances. Organizations in capital-intensive industries such as the mining, manufacturing, and process industries depend on the performance of business-critical physical assets in order to generate revenue and achieve organizational objectives. Campbell *et al.* (2010) state that physical assets have the inherent ability to generate revenue. It is therefore important that organizations manage business-critical assets over its entire life cycle emphasizing both short term and long term performance *taking a greater range of variables into consideration to inform decision making* than in past practices.

### 1.2.1 Asset Management (AM)

The discipline of AM has been around for many decades dating back to as early as the 1950's. Waeyenbergh and Pintelon (2002) state that the term *Asset Management* only gained recognition during the knowledge-based era of AM starting in the 21st century. According to El-Akruti *et al.* (2013), managing and maintaining assets have evolved from a perception of it being a "necessary evil" to a "must have" in the current business landscape. The current business landscape, described in Section 1.2, has put further emphasis on AM and it is presently the subject of intense research, discussion and exploration for both industry, in particular asset-intensive organizations, and academia (Amadi-Echendu, 2015).

AM is a fast growing and evolving concept used by organizations in different industries including the mining, manufacturing, information technology, and aerospace industries among other (IAM, 2014). These organizations use AM activities or programs to create sustainable value from their assets to create competitive advantage and improve financial performance. These assets include information technology assets, human assets, financial assets and physical assets. AM aims to optimize the interaction between these asset categories by implementing a holistic approach to achieve the operational and financial objectives of an organization. Contemporary AM perspectives transcend traditional organizational boundaries by emphasizing cross-functional relationship between business units and highlights organizational synergy (Amadi-Echendu *et al.*, 2010).

Ismail and Paquin (2013) identify a number of benefits for implementing AM in asset-intensive organizations by stating that the performance metrics an organization achieves is dependent on the maturity and the implantation quality of an AM program. A summary of the benefits of implementing AM is provided in Table 1.1. It is evident that the top performing organizations create competitive advantage resulting in: (1) an increase in Overall Equipment Efficiency (OEE), (2) increase in Return On Assets (ROA) versus the corporate plan, (3) unrivaled unscheduled asset downtime, and (4) a decrease in maintenance costs.

**Table 1.1:** Benefits of Asset Management (AM)

| **Performance Metric** | **Best-in-Class** | **Industry Average** | **Bottom-of-Class** |
|---|---|---|---|
| Overall Equipment Efficiency | 89% | 83% | 69% |
| Unscheduled asset downtime | 3.5% | 8.3% | 16.9% |
| Return On Assets | +24% | +4% | -7% |
| Maintenance costs | -13% | -4% | +1% |

The implementation of AM within organizations have significantly increased since the release of the first AM standard called Publicly Available Specification (PAS) 55 in 2004 developed by the British Standards Institution (BSI). Since being released in 2004, PAS 55 proved to be a ground breaking AM standard in bridging the organizational gap between business units as well as the gap between theoretical development and practical implementation of AM activities. The enormous success of PAS 55 lead to the development of several standards since its release. A second version of PAS 55 was published in 2008 which was the foundation for the International Organization for Standardization (ISO) 55000 series of AM standards published in 2014. Succeeding the ISO 55000 series was *The Asset Management Landscape* published in 2014 by the Global Forum on Maintenance and Asset Management (GFMAM). The latest AM standard, *Asset Management – an anatomy*, was developed by the Institute of Asset Management (IAM) and published in December 2015. This standard is regarded as the most complete and current authority on AM standards. Van den Honert *et al.* (2013) state that AM standards create a coherent way to implement an Asset Management System (AMS) within an organization.

Section 2.2 is dedicated to exploring the history, rise and current landscape of AM. An in-depth discussion of the most significant AM standards, scope, and benefits of implementing AM is provided in Sections 2.2.1 to 2.2.4. In addition, a high-level discussion on how to implement AM in an organization is provided, demonstrating the holistic and cross-functional nature of an AMS.

### 1.2.2 Asset Replacement

At the center of a Strategic Asset Management Plan (SAMP) for capital-intensive organizations is the asset replacement process. Campbell *et al.* (2010) state that asset replacement is a critical component of the capital investment strategy of a physical asset-intensive organization. Physical assets are one of the greatest investments in capital-intensive enterprises that require large amounts of expensive equipment to generate revenue. Fellows (2015) states that capital expenditure in 2015, in the mining industry alone, was estimated at more than US$ 150 billion. Moreover, Paquin (2014) recognizes in a study conducted by the Aberdeen Group in 2014 that 40% of the 149 executives surveyed, regarded the failure of business-critical assets as the most important risk faced by the company.

According to Rose *et al.* (2010), a physical asset should be replaced when it has reached the end of its useful life cycle in an organization's overall reliability strategy taking into consideration a wide range of factors. Taking many factors into consideration improves the accuracy and consistency of the replacement process. This is especially true in the current business landscape where the impetus is placed on reducing costs and increasing overall reliability in a sustainable manner. Jardine and Tsang (2013) define the optimal replacement age of an asset as the point in time where the total Life Cycle Costs (LCC) is at its minimum value. An Equivalent Annual Cost (EAC) analysis is often performed to determine this point in time. However, Al-Chalabi *et al.* (2015) state that not only economic factors should be considered. Emphasis should be placed on the operating condition of the asset as well its operating environment. Physical assets often operate in harsh working environments which result in performance degradation over time, increased Operating and Maintenance (OM) costs and possible safety risks due to defective equipment and frequent breakdowns. As a result, labour costs rise and pressure is placed on production schedules. These factors form part of what is known as the *traditional asset replacement* analysis.

Hartman (2001) defines a traditional asset replacement analysis as the provision of asset purchase and sale decisions for a defined time period based on selected factors such as initial capital expenditure, OM costs, and salvage value. Furthermore, Hartman and Tan (2014) state that a traditional asset replacement solution aims to provide a replacement policy adhering to a specified objective function while certain economic considerations remain constant across the analysis time period. Moreover, the traditional model assumes asset performance deterioration with age or operating life. In addition to the aforementioned aspects, Rogers and Hartman (2005) state that technological advances in the market must also be considered. Hartman and Tan (2014) note that *one of the most prominent obstacles in asset replacement problems is the incorporation and quantification of uncertainty, implicit or explicit, and risk* as explored in the next section.

Section 2.3 is dedicated to exploring the concept of asset replacement in more detail. More specifically, Sections 2.3.1 to 2.3.4 investigate traditional asset replacement approaches by focusing on the factors that influence the decision-making process. In addition, the theme of risk and uncertainty in asset replacement is explored to emphasize the possible effects of business risks.

### 1.2.3 Business Risk

The is some degree of risk involved with any managerial decision. Managing risks in an organization has evolved from a single person investigating insurance options to an entire risk department monitoring, evaluating and controlling various types of risk including strategic, operational, and external risks. Doff (2008) and

Sadgrove (2015) define business risk as the possibility of generating lower than anticipated profits as a result of numerous factors. Hopwood *et al.* (2012) identify a number of these factors including the overall economic climate, government regulations, competition, and supply chain problems. Furthermore, van Wyk *et al.* (2016) recognize that business risks evolve over time therefore influencing organizational decision-making on a medium and long term basis. Incorporating the evolution and impact of business risks in asset replacement decisions can therefore greatly improve an organization's capital-investment strategy and economic prosperity.

Two industry examples of business risks (labour relations and overall productivity) having a significant influence on an asset-intensive organization are introduced to demonstrate the impacts certain events can have on organizational performance and decision-making on a medium to long term: The 2014 labour strike in the platinum mining sector in South Africa resulted in the shutdown of 40% of the world's platinum production (Bohlmann *et al.*, 2015). The dispute regarding workers' wages and working conditions between Association of Mineworkers and Construction Union (AMCU) and the mining organizations lasted five months and resulted in 70 000 workers downing their tools. The end result was a US$ 2.25 billion loss in revenue for the companies involved which are still reeling from the events. Mitchell *et al.* (2014) state that the overall productivity including labour, capital, and operating productivity in the mining industry decreased by 30% between 2004 and 2012. The dramatic decline in productivity is attributed to numerous factors including: (1) inexperienced labour teams and an aging workforce, (2) lack of innovation, (3) declining ore grades and (4) economies of scale caused by the super cycle in the mining industry.

Discussions on business risks in this thesis emphasize the concepts required to develop the framework for this study and is by no means an in-depth analysis, review or discussion of the business risk management field. Section 2.4 is dedicated to exploring the concept of business risks. More specifically Sections 2.4.1 to 2.4.3 explore various definitions, risk management, and the impact of business risks in the AM domain and especially asset replacement.

Equipped with an overview of the main concepts in this research as presented in the preceding sections, Figure 1.1 illustrates the research domain for this thesis. A framework incorporating business risks in physical asset replacement decisions in capital-intensive industries may ultimately be beneficial to an organization's capital investment strategy. In addition, such a framework would add value to the management of an asset portfolio which includes business-critical assets where capital investment, sustainability planning, and optimal life cycle management of assets are performed within an AMS. To develop such a framework, the two main fields of study are AM and risk management. Within AM and risk management, the concepts of business risks and asset replacement are connected by using a suitable modeling technique as explored in Chapter 2.

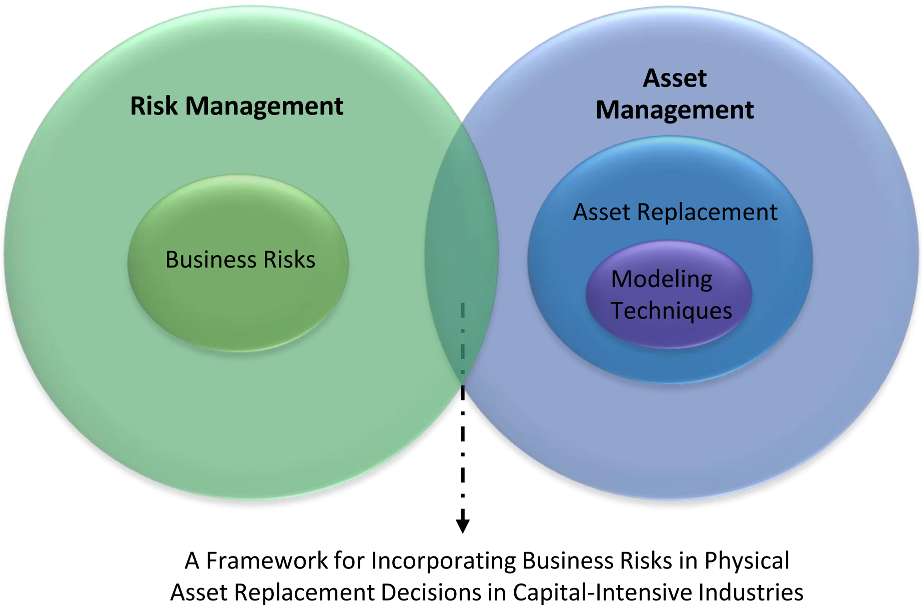



**Figure 1.1:** Research domain of this study

## 1.3 Problem Statement

The development of internationally recognized AM and risk management standards, such as the ISO 55000 series and the British Standard (BS) 31100, have provided impetus and creditability to these respective fields complimenting each other. Within industry and academia, the incorporation of risk management in AM tends to be modular, qualitative-based, and not integrative into physical asset-related decision-making processes. Organizations in capital-intensive industries tend to focus on *traditional asset replacement factors* and do not consider the effects of evolving business risks which may significantly influence strategic initiatives such as operating and capital expenditure decisions [1].

Considering the introductory sections on asset replacement and the potential impacts of business risks, there is great opportunity inherent in developing a framework that incorporates business risks and their evolution over time into physical asset replacement decisions in capital-intensive industries. Making the correct capital investment decisions is critical to the success of any organization within capital-intensive industries. Deciding on whether to keep or replace an existing physical asset with an accepted level of certainty of success while considering business risks is a challenging task. Furthermore, business risks, both internal and external, are constantly evolving thus adding to the complexity of physical asset-related decisions (keep or replace). These important decisions, involving millions of dollars, are often made without any inclusion or quantification of business risks such as labour relations, safety and health performance, stakeholder relationships, commodity price and exchange rate fluctuations to name but a few. These overall business risks (operational, strategic, and external) play a major role in the decision making process and therefore needs to be included in the calculations and forecasting of certain asset-related decisions.

In addition, the motivation for this research stems from a number of additional considerations. Hartman and Tan (2014) conducted an extensive literature review on the field of asset replacement and found that there is no coherent framework, model or strategy available for incorporating the effects of business risks in asset replacement decisions within an organization by taking various factors such as business risks and asset-related information into account. There is also a growing call from academia and industry leaders in capital-intensive industries to take a broader view of AM and risk management and include a wider range of variables into decision-making due to mounting levels of volatility and change (Bain and Company, 2014; GFMAM, 2014; Hodgkinson, 2014; Hartman and Tan, 2014; Hopwood and Chopra, 2015).

Managers in industry are thus faced with the need for a framework with the following characteristics: (1) quantify business risks using a holistic approach,

[1] See for example Mitchell *et al.* (2007), BSI (2008), Jardine and Tsang (2013), ISO (2014), Henderson *et al.* (2014), Hartman and Tan (2014), IAM (2015)

(2) provide a level of certainty associated with an asset replacement decision, (3) create consistency and repeatability, and (4) make defensible decisions by considering various types of business risks. Such a framework, incorporating all of the aforementioned aspects, would focus on and contribute to the scope of AM as illustrated in Figure 1.2.

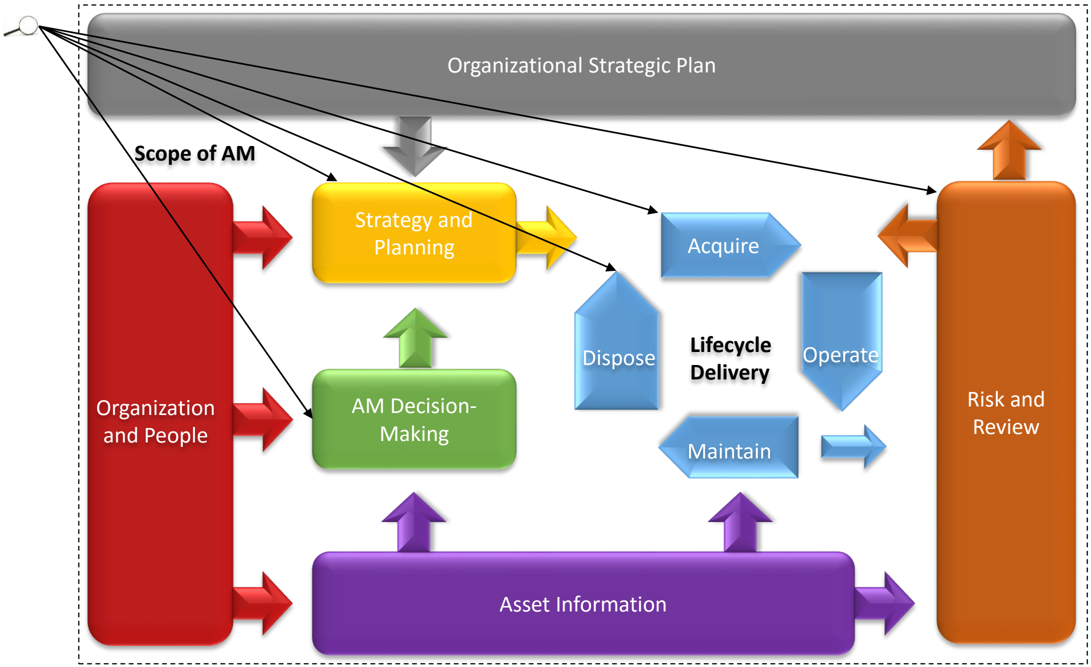



**Figure 1.2:** Contribution to the scope of AM
*Adapted from (IAM, 2014)*

Firstly, the framework would assist an organization in its AM decision-making processes for asset replacement. This is captured in the asset strategy and plans of an organization. The asset strategy and plans determine the life cycle management of business-critical assets. The framework for this study focuses on the acquisition and disposal decisions of a single asset but also uses information from its operating and maintenance life cycle stages. The risk and review phase is the main focus and contribution of this framework. It would incorporate strategic, operational, and external risks in the decision-making process to adhere to some organizational objective function over a finite period of time. In summary, the framework would be used in the management of an asset portfolio in an organization where capital investment, sustainability planning, and optimization is performed. Moreover, the primary objective of this framework is not to compete with failure statistics or other traditional methods used to determine the optimal replacement time of assets, but rather to add new insights to the decision-making process by taking a wider range of variables into consideration when making important decisions using traditional methods as a foundation. Leading from the discussion in this section and the previous introductory sections, the central research question for this thesis is formulated as:

> *Can a quantitative decision-making framework be developed to incorporate business risks in physical asset replacement decisions in capital-intensive industries?*

From the central research question, this thesis will aim to reject the research proposition defined in Table 1.2.

**Table 1.2:** Research proposition of thesis

| |
|---|
| A quantitative decision-making framework can not be developed to incorporate business risks in physical asset replacement decisions in capital-intensive industries. |

## 1.4 Delimitation

It is important to establish boundaries in which the research is conducted to ensure that scope creep is prevented. It is therefore important to properly define, document, and control the scope of the study (Bryman and Bell, 2014). This process of establishing the study boundaries is termed *delimitation* and also assist the reader to keep focus on the intended purpose of the research.

- The thesis is bound to the Physical Asset Management (PAM) domain and more specifically, asset replacement and life cycle management of a business-critical asset. Therefore other asset categories such as intangible assets and human assets are not discussed in detail in the development of the framework. In addition, other AM considerations such as determining the optimal maintenance tactic or scheduling of shutdown maintenance work, and lead times of a spare asset are not considered.

- Discussions on risk management and business risks in this thesis only emphasize the concepts required to develop the framework for this study and is by no means an in-depth analysis, review or discussion of the broad and complex field of risk management.

- The framework incorporating business risks into physical asset replacements will focus on a single business-critical asset for a finite period of time. The replacement of multiple assets or a fleet of assets is not therefore not the focus of this research.

- The said business-critical asset is considered in its entirety. Therefore the reliability of sub-systems or individual components of the asset are not considered independently.

- Both qualitative and quantitative variables that affect the asset replacement process are considered. Therefore traditional asset replacement factors and business risks are incorporated in the framework.

- The replacement actions are limited to: (1) keeping and repairing the asset to a satisfactory operating condition and (2) replacing the asset under consideration with a new asset that is immediately available. The expansion of an asset system is therefore not considered.

- The framework is bound to organizations in capital-intensive industries operating in a volatile business and economic environment.

With the problem statement explored and the scope of the study established, the next section introduces the research objectives of the study.

## 1.5 Research Objectives

The overall objective of this research is to answer the central research question put forth in Section 1.3 and subsequently evaluate the research proposition. Considering the problem statement and the delimitation of the study in the preceding sections, a number of research objectives are developed to comprehensively answer the central research question and evaluate the research proposition. A summary of the research objectives is provided in Table 1.3.

**Table 1.3:** Summary of research objectives

| # | Research Objective | Chapter |
|---|---|---|
| 1. | Establish the fundamentals of the main concepts in this research. | 2 |
| 2. | Emphasize the importance of including business risks into asset replacement decisions. | |
| 3. | Identify a suitable modeling technique for the framework. | |
| 4. | Comprehension of general framework design principles. | 3 |
| 5. | Describe framework scope, objectives, and development methodology to incorporate business risks into asset replacement decisions. | |
| 6. | Develop framework to incorporate business risks into physcial asset replacement decisions in capital-intensive industries. | |
| 7. | Conduct case study at a capital-intensive organization by applying the proposed framework developed in Chapter 3. | 4 |
| 8. | Validate the framework and case study results and perform a sensitivity analysis. Moreover, discuss and interpret the results obtained. | |
| 9. | Draw conclusions from results analysis and evaluate research proposition. | 5 |

Research objectives one to three are aimed at establishing the fundamentals of the main concepts required to develop to framework incorporating business risks into physical asset replacement decisions in capital-intensive industries. Chapter 2 achieves this through a comprehensive literature analysis of AM, asset replacement, business risks, and modeling techniques. The next three research objectives are pursued in Chapter 3 which contribute to developing the proposed solution, or framework. The main objective of the framework is to provide the user with a systematic and structured process for integrating the impacts and evolution of business risks into physical asset replacement decisions in capital-intensive industries. Overall features and objectives of the framework include: (1) practicality, (2) a holistic approach, (3) logical and structured, (4) interactive, and (5) generic in nature to be applied to any business-critical asset.

Chapter 4 aims to achieve two research objectives. The first research objective is to apply the proposed solution, developed in Chapter 3, to a business-critical asset at a diamond mining organization in Southern Africa. The second objective in Chapter 4 is to validate the framework and the case study results.

In addition, a sensitivity analysis is performed and the results obtained are discussed. Chapter 5 is tasked with the final research objective which is to draw conclusions from the case study in Chapter 4 and the research conducted in this thesis in its entirety. The central research question is answered and the research proposition is evaluated. With the research objectives and delimitations formalized, the following section describes the research design and methodology employed in this thesis.

## 1.6 Research Design and Methodology

The research design can be considered as the logic or blueprint implemented that illustrates how a research study is conducted (Thomas, 2010). The research design indicates all major parts of a research study that functions together to address research questions and objectives. Creswell (2015) states that the research design for a study is the intersection of three main concepts including the research approach, research methods, and the philosophical worldview as illustrated in Figure 1.3. An overview of these main concepts are provided together with a discussion on the specific concepts used in this research.

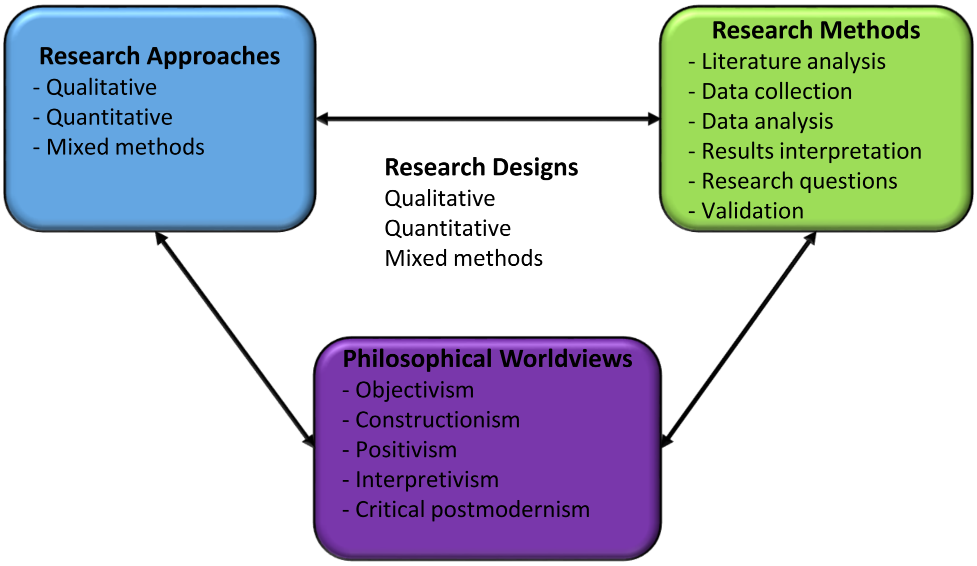



**Figure 1.3:** Research design paradigm
*Adapted from Thomas (2010) and Creswell (2015)*

According to Bryman and Bell (2014), research design comprises of three classification methods including qualitative, quantitative, and mixed methods. Moreover, Creswell (2013) recognizes that studies are not limited to using only qualitative or quantitative research designs and often implement a hybrid combination of the aforementioned methods known as *mixed methods*. The first main factor in determining the research design classification of a study is the research approach. Bryman and Bell (2014) state that a qualitative research approach emphasizes words rather quantification when collecting and analyzing data. In contrast, a quantitative approach emphasizes quantification when collecting data and views social reality as an external and objective reality. Mixed methods are therefore vested in the middle of the aforementioned research approaches integrating certain aspects of both approaches. The second main factor influencing research design classification is the research methods used in a study. Creswell (2015) state that research methods refer to the mechanisms used to move from underlying assumptions to research design, data collection and analysis and ultimately validation of the results obtained.

The final factor influencing the research design of a study, illustrated in Figure 1.3, is the philosophical worldview employed to conduct the research which significantly influences the perceived relative importance of reality, although no paradigm is considered to be superior. Bryman and Bell (2014) state that there are mainly two competing paradigms influencing philosophical worldviews including epistemology and ontology. Epistemology emphasizes what can be regarded as acceptable knowledge in a discipline while ontology is concerned with the nature of social phenomena. The aforementioned paradigms can be demarcated into several philosophical worldview positions. Focusing on the research design and methodology implemented in this research, the following is noted as summarized in Table 1.4. This thesis combines qualitative and quantitative research approaches to implement a mixed methods approach. Both approaches are therefore used throughout the research process. Combining qualitative and quantitative methods forms an integrated solution by triangulating different data sources and establishing results and findings on the convergence of both types of data. The philosophical worldview that characterizes the research conducted in this thesis is positivistic. Positivism is unbiased and emphasizes the importance of using natural scientific methods in the research process.

**Table 1.4:** Summary of thesis research design and methodology

| | |
|---|---|
| Research design | Qualitative and quantitative approach |
| Philosophical worldview | Positivism knowledge claims |
| Research methods | Literature analysis, framework development, data collection and analysis, results, validation, and discussion. |
| Research approach | Qualitative and quantitative approach |

## 1.7 Thesis Structure

This section provides an overview of the thesis structure and layout of the document. The document follows a logical and structured process that is in alignment with the order in which the research was conducted. This facilitates a methodical flow in the reading process of the document and the progressive achievement of the research objectives discussed in Section 1.5. Moreover, a figure acting as a road map is presented at the beginning of each chapter to indicate the location of the reader in the research process. The thesis is structured as follows:

**Chapter 1: Introduction**
Chapter 1 serves as the introductory section which discusses the fundamental concepts of the study including Asset Management (AM), asset replacement, and business risks. These fundamental concepts are investigated to formulate a problem statement and research proposition. The problem statement is translated into research delimitations, research objectives and a research design and methodology implemented to direct the research towards evaluating the research proposition. The chapter is concluded by providing an outline and structure of the document.

**Chapter 2: Literature Review and Contextualization of Study**
The primary focus of Chapter 2 is to review and contextualize the main concepts in this study including AM, asset replacement, and the effects and importance of business risks. The interdependence between these main concepts are investigated, emphasizing the effects of business risks and its evolution over time on organizational decision-making. Lastly, suitable modeling techniques are reviewed and compared in order to identify the best modeling technique to incorporate business risks in the physical asset replacement process in capital-intensive in-

dustries.

**Chapter 3: Design and Development of Framework**

Chapter 3 presents an overview of the design and development of the framework as the proposed solution to incorporate business risks into physical asset replacement decisions in capital-intensive industries. The development of the framework implements general framework design principles and the objectives, methods and outcomes of each step is communicated. Moreover, a detailed process of developing the mathematical MDP model as part of the framework is provided. The framework is developed to adhere to the specified framework features as part of the objectives of this research. The framework developed in this chapter is used as a template in the case study presented in Chapter 4.

**Chapter 4: Case Study and Results**

Chapter 4 applies the proposed solution developed in Chapter 3 to a case study in the mining industry in Southern Africa. More specifically, the case study focuses on a Caterpillar 793C haul truck at a diamond mine. The implementation of the framework incorporating business risks into asset replacement decisions and the results obtained are presented and reviewed to validate the research.

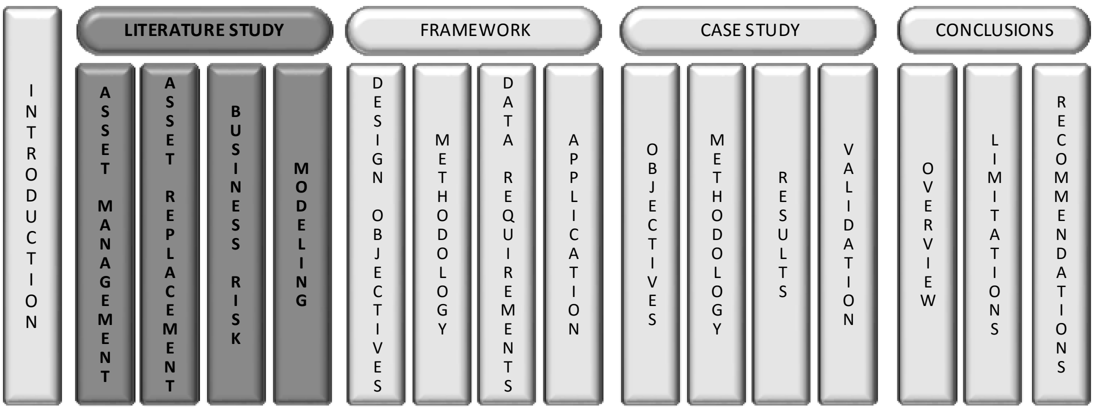
**Chapter 5: Conclusions**

Chapter 5 reflects on the research conducted and brings closure to the study. A brief summary of the research is provided and final conclusions are drawn with regards to the problem statement, research objectives, and the research proposition. Lastly, a discussion on the limitations of this study and recommendations for future research follows.

# Chapter 2

# Literature Review and Contextualization of Study

*"Study the past if you would define the future"* - Confucius, Chinese philosopher and reformer (551 BC - 479 BC)




**Chapter Outcomes:**

- Comprehension of AM as a holistic management approach with the emphasis on the PAM domain and new developments within the AM field.
- Contextualization of asset replacement strategies in AM. Recognition of the various factors influencing asset replacement decisions.
- Recognition of the effects that business risks have on asset replacement decisions.
- An understanding of various types of business risks.
- Knowledge of qualitative and quantitative modeling techniques and its importance in asset replacement decisions.

## 2.1 Introduction

Mouton (2001) states that it is essential for any new research study to include a comprehensive literature review. In addition, Webster and Watson (2002) identify that the main purpose of a literature review is to explore what research has already been conducted in a related field and to use this body of knowledge as the basis for new developments. Furthermore, Mouton (2001) recognizes that other reasons to conduct a literature review include, ensuring that a previous study is not duplicated and to investigate instrumentation that has proven to be valid and reliable thus using this instrumentation to guide the research. In addition, Cronin *et al.* (2008) state that a good literature review has the following characteristics:

- Critical and objective review of the relevant topical literature.
- Comprehensive in its analysis of the core aspects of the research study.
- Accurate terminology is used and jargon is avoided.
- A variety of sources are used and authors are acknowledged for their work.
- A transparent research process is followed and documented.

Considering the aforementioned information, this chapter presents a comprehensive literature review focusing on the main aspects of the study and aims to contextualize these aspects within the research. These main aspects include: (1) Asset Management (AM), (2) asset replacement theory, (3) business risks, and (4) modeling techniques that aid decision-making processes. AM is defined in the first section and the evolution of AM is investigated. The latest trends in AM are identified and its relation to the research study is clearly stated with the emphasis on Physical Asset Management (PAM) and, more specifically, asset replacement theory which is an integral part of PAM. Different asset replacement theories are introduced and contextualized in the research. Next, a variety of business risks are investigated to showcase their effects on the decision-making process for different industries and applications. Lastly, various modeling techniques applicable to decision-making theory and their applications are reviewed. Both quantitative and qualitative modeling techniques are reviewed to identify the most applicable method or combination of methods for the generic decision-making framework to be developed in this study.

## 2.2 Asset Management

This section aims to provide a comprehensive definition and overview of AM and its related concepts with the main focus on the PAM domain. The term *asset* refers to any entity that adds value or possesses potential value to an organization. These assets include physical, financial, human, intangible, and information assets. The value that these different asset categories add to organizations may be tangible or intangible (ISO, 2014). *Physical assets* include entities such as equipment, machinery or property depending on the organization and is at the heart of all AM strategies since it contributes towards achieving organizational objectives. *Management* can be defined as the process or methodology that coordinates the efforts of people using the available resources to achieve some organizational objective (Stevenson, 2010). However, AM is not just the management of assets in an organization as the term *Asset Management* suggests. Woodhouse (2003) and Hastings (2010) provide noticeable different definitions for *Asset Management* in different industries and applications. These definitions refer to AM in the context of: (1) the management of financial portfolios, (2) the acquisition or disposal of companies as used by financial directors, (3) software vendors seeking greater product credibility, and (4) equipment maintainers or owners to describe a core role in the life cycle activities of a physical asset. The latter definition of AM, also used by Frolov *et al.* (2010), which focuses on engineering applications, are discussed in more detail and emphasized in this thesis.

Amadi-Echendu *et al.* (2010) state that the definition of AM tends to be very broad in scope, vague and confusing due to the use of inconsistent terminology as found in literature. These definitions that are broad in scope include information on various aspects such as production, operations, infrastructure and general management techniques (El-Akruti *et al.*, 2013). Furthermore, many authors refer to AM as Engineering Asset Management (EAM) contributing to the broad scope, various definitions and inconsistent terminology (Amadi-Echendu *et al.*, 2010). Several well-known and accepted definitions of AM are presented here to develop a comprehensive, yet concise definition of AM as used in this research study. The British Standards Institution (BSI) defines AM in their document Publicly Available Specification (PAS) 55-2 as:

*"systematic and coordinated activities and practices through which an organization optimally and sustainably manages its assets and as-*

> *set systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organizational strategic plan." - (BSI, 2008)*

The definition provided by the BSI was one of the first formally acknowledged definitions of AM. Many formal and accurate definitions have originated since, the most recent version developed by the Institute of Asset Management (IAM) describing AM as:

> *"It converts the fundamental aims of the organization into the practical implications for choosing, acquiring (or creating), utilizing (operating) and looking after (maintaining) appropriate assets to deliver those aims. And it does so while seeking the best total value approach (the optimal combination of costs, risks, performance and sustainability)." - (IAM, 2014)*

Considering the broad scope and vagueness of definitions found for AM and the confusion regarding EAM and other synonymical uses, a comprehensive yet concise definition of AM is developed here to be used throughout this research. Therefore Asset Management can be defined as:

> *"A holistic process of creating sustainable value in an organization by balancing certain drivers such as risk, performance, reliability, and cost over the entire life cycle of a project or process. Furthermore, AM focuses on the interaction between physical assets and other existing assets within an organization such as financial, human, intangible, and information assets to enable an organization to achieve its objectives."*

### 2.2.1 The Rise of Asset Management

The term *Asset Management* only gained recognition during the knowledge-based era of AM. Asset Management was effectively known as *Maintenance* before the knowledge era which started in the 21st century. Maintenance not only referred to the physical actions of maintaining equipment but also to the managerial aspects associated with it. The evolution and history of AM is shown in Figure 2.1. Moubray (1997) describes the evolution of maintenance in *Reliability-Centered Maintenance* and states that the conventional strategy for maintaining physical assets in the period up to the 1950's was to operate equipment or machines until failure occurred. Assets in this period were over-designed and was considered to be easy to fix. Maintaining assets were considered as a "necessary evil" in this time period.

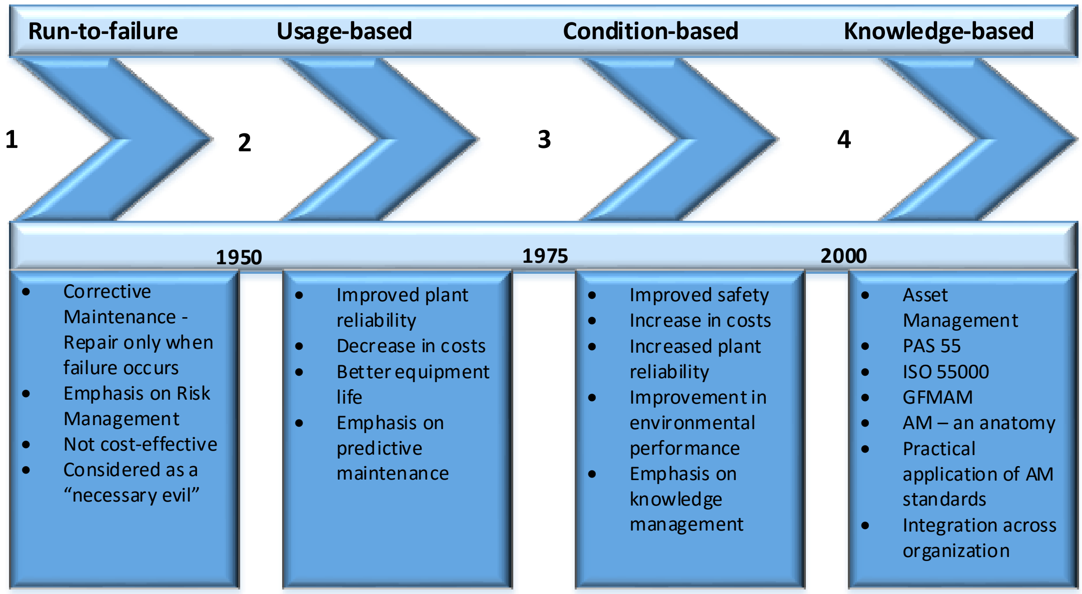



**Figure 2.1:** Evolution of Asset Management
*Adapted from Moubray (1997) and Waeyenbergh and Pintelon (2002)*

However, it was recognized that unplanned equipment failure was not only a serious safety threat but also very expensive as it led to plant unavailability and thus a decrease in production. Therefore great emphasis was placed on risk management which led to the second generation of maintenance effectively known as the usage-based era. This period (1950 - 1975) led to greater plant availability, increased equipment life and lower operating costs. Emphasis in this era was placed on condition based (predictive) maintenance. This era led to excessively high maintenance costs and encouraged the development of control and planning systems for maintenance activities. The third generation (1975-2000) of maintenance were known as the condition-based era and focused on decision-making systems based on information obtained from knowledge management systems. However, the condition-based era also contributed to excessive costs and thus paved the way for the current generation of AM known as the knowledge-based era.

The knowledge-based era led to numerous improvements on the condition-based era and included: (1) increased plant reliability, (2) improved safety measures, and (3) superior environmental performance. According to Amadi-Echendu *et al.* (2010), an interdisciplinary approach was introduced as early as the 1990's to address and resolve the most obvious AM problems. The IAM (2014) recognizes that modern AM concepts in the knowledge-based era are derived from three primary origins including financial services, oil and gas industry and the public service sector. The knowledge-based era led to the recognition of the collective term *Asset Management* and saw the development of the first AM standard known as Publicly Available Specification (PAS) 55-1 in 2004. Great emphasis is placed on the integration across all units and disciplines within an organization to support AM activities in this era. Many AM standards and documents have been developed since PAS 55-1, the most significant including: (1) PAS 55-2 in 2008, (2) International Organization for Standardization (ISO) 55000 series in 2014, and (3) AM–an anatomy in 2014. These AM standards are investigated in Section 2.2.2 in more detail. AM standards and documents have led to the practical implementation of various AM strategies across many industries. Furthermore, El-Akruti *et al.* (2013) state that AM is now an integral part of organizational strategy and a necessity for growth in many engineering sectors. Modern AM is the focus of this research study and will be discussed in more detail in the following sections.

### 2.2.2 Asset Management Standards

Standards are developed with the goal of enabling communication such as detailed specifications, processes, and frameworks to a broad audience of stakeholders (Krechmer, 2006). In addition, Greenstein and Stango (2006) state that industry standards are critical documents required for market performance and economic growth. This section provides an overview of the most influential AM standards in the order of their release. The internationally recognized AM standards that are presented here include: (1) PAS 55, (2) ISO 5500X series, (3) The Asset Management Landscape, and (4) AM–an anatomy. A comparison is then made between these standards to relate and emphasize their different roles in the AM industry and to showcase their strengths and weaknesses.

**Publicly Available Specification (PAS) 55**

PAS 55-1 was the first internationally accepted standard for AM. The standard was first published in 2004, as indicated in Figure 2.2, in a collaborative effort between the British Standards Institution (BSI) and the Institute of Asset Manage-

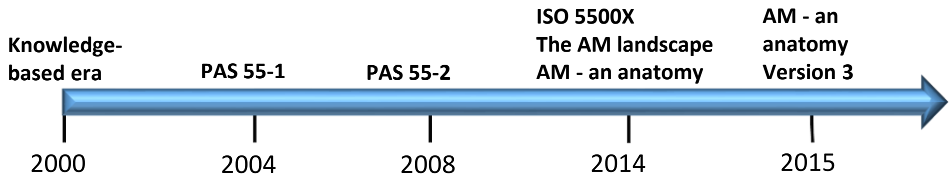



**Figure 2.2:** Timeline of AM Standards

ment (IAM). These institutions identified that there was a major requirement for a standardized document that would provide organizations with guidelines on how to manage their business-critical assets. The main objective of this guideline was to provide industry with standardized definitions, terminology and strategies that would enable organizations to reduce risk and increase reliability of the most important physical assets within an organization. A revised version, PAS 55-2: 2008: Asset Management standard, was published in 2008 to provide guidelines for the application of PAS 55-1 with the emphasis on the optimal management of physical assets (BSI, 2008). Since being released in 2004, PAS 55 proved to be a very successful and ground breaking AM document, although lacking certain aspects such as a detailed AM strategy implementation approach (van Grunsven, 2012). PAS 55-2 provides guidelines to establish, implement, maintain and improve an Asset Management System (AMS) rather than detailed approaches, implementation strategies or tools to implement PAS 55-1 (BSI, 2008). An overview of PAS 55, developed by Van den Honert *et al.* (2013), state that the basis of PAS 55 is the Deming cycle, primarily used for quality control (Moen and Norman, 2006).

The Deming cycle, Plan-Do-Check-Act (PDCA), as used in PAS 55 divides the processes and strategies that an organization needs to follow to implement a whole life cycle management approach (acquire, utilize, maintain, dispose) to an AMS. Moreover, Van den Honert *et al.* (2013) indicate two key aspects of an AM implementation strategy for each quadrant of the Deming cycle that provides a concise summary of PAS 55. Organizational leadership and AM planning is categorized in the *Plan* phase. Then, AM enablers and implementation plans are categorized in the *Do* phase. Next, AM performance evaluation and assessment are shown in the *Check* phase. Lastly, improvement strategies and management review are classified in the *Act* phase completing the Deming cycle. In conclusion, PAS 55 encourages organizations to: (1) aim for best AM practices, (2) integrate AM practices across disciplines within an organization, (3) build an AMS based on knowledge systems, and (4) implement a holistic view of AM within an organization to involve everyone from artisan to management and thus create a bottom-up approach. It is widely recognized that PAS 55 is famous for providing a structured approach of *what* needs to be implemented, without including instructions or tools on *how* to implement certain AM aspects.

**ISO 5500X Series**

The International Organization for Standardization (ISO) published the ISO 5500X series for AM in January 2014. The development of this series of documents was based on the highly successful PAS 55 AM documents ISO (2014). The series consists of three documents including: (1) ISO 55000, (2) ISO 55001, and (3) ISO 55002. According to Ma *et al.* (2014), the ISO 5500X series is a significant improvement on PAS 55 as a result of the broad scope of applications, not only applying to the management of physical assets but any type of asset. A brief discussion of the scope of each document in the ISO 5500X series is presented here and their primary objectives are listed:

- **ISO 55000:** This document provides an overview and key terminology of AM and an AMS to be used in the other two documents in the ISO 5500X series. ISO 55000 also contextualizes both the ISO 55001 and ISO 55002 documents. This document also provides general principles and fundamentals of the AM industry and provides an exhaustive list of potential benefits to an organization for the adoption of AM principles.

- **ISO 55001:** The primary objective of this document is to provide requirements for the implementation of Asset Management Systems to the management of an organization. These requirements are based on a whole life cycle approach and can be implemented in any organization regardless of size, structure or industry. In addition, a high-level approach for the measurement of an organization's ability to comply with industry-specific regulatory, statutory, and legal requirements is also presented.

- **ISO 55002:** This document aims to provide practical guidelines for the implementation of ISO 55001, i.e., how to implement an AMS in an organization. Detailed instructions and strategies on *what* to do are provided on areas such as AM leadership, operational capabilities, support systems, system performance evaluation, and improvement strategies.

The generic aspect of the ISO 5500X series can be considered as a strength in that it caters for organizations of different size, structure and industry. However, it can also be perceived as a weakness since many organizations do not have the knowledge on *how* to implement AM related aspects. ISO (2014) encourages users of this series of AM documents to use it in a collaborative effort with the relevant sector-specific documents such as safety or technical manuals to achieve the best AMS results. It is noted that the ISO 5500X series and PAS 55 document share many similar characteristics. The most obvious characteristic being the fact that both documents are based on the same Deming cycle. Therefore the same basic structure for the life cycle implementation of an AMS apply, only with the ISO 5500X series being more detailed and user-focused. The ISO 5500X series of standards, however, do not include all aspects of AM. An important aspect that is not emphasized in this series of standards is *how* to implement AM. Furthermore, the development of AM capabilities beyond the conformance to ISO 55001 is not discussed or recognized. In addition, Amadi-Echendu (2015) states that the release of the ISO 5500X series has led to great emphasis being placed on *AM certification*. Professional associations and individuals that are certified to ISO 5500X standards, may therefore conduct an audit of another organization's AMS adding credibility to an individual, organization or an industry as a whole.

**The Asset Management Landscape**

The *Asset Management Landscape* was first published in November 2011 with the second, and most renowned, edition being published in March 2014 by the Global Forum on Maintenance and Asset Management (GFMAM). The main objective of the first edition was to combine all available knowledge at the time in the field of AM to encourage international collaboration in an effort to expand this subject. The second edition's primary objective was to incorporate the knowledge gained from the ISO 5500X series with the first *Asset Management Landscape* edition and to focus on international organizations with assets in different countries and therefore different operating conditions. At the time of publishing the second edition, GFMAM consisted of members from 10 countries combining the expertise of each member to develop this edition from a variety of disciplines (GFMAM, 2014). This document also refers to the ISO 5500X series to correlate and compare content and can be used in conjunction to deliver the best results. Another prominent feature of this document is to provide information regarding AM certification programs and procedures. Other objectives of the second edition include:

- Providing up-to-date key terminologies and definitions in the subject of AM and correlate content to the ISO 55000X series.
- Comparing best practices from GFMAM members to provide a comprehensive overview of the AM landscape.
- Provide a platform for exchanging and aligning maintenance and AM knowledge and practices.
- Providing ISO 55000 certification assessors with a structure and criteria to conduct an AM audit.
- Providing a basis to compare different AM certification programs, competence frameworks, and organizational AM maturity.

*The Asset Management Landscape* second edition also aims to emphasize the broad scope of AM by suggesting 39 subjects that fully encompasses the field of AM and cross-references these subject areas to the ISO 5500X series (GFMAM, 2014). These 39 subject areas are defined in detail and can be classified into six major high-level groups. The six major subject groups are introduced here and briefly discussed.

1. **Strategy and planning:** Align organization objectives with AM activities and asset outputs. Organizational alignment enables all employees to add sustainable value by constantly referring to AM plans and activities to achieve organizational objectives.
2. AM **decision making:** Emphasis is placed on creating value from assets over their entire life cycle. This subject group is concerned with the different challenges faced and approaches to decision-making. Moreover, the effects of a decision on the life cycle performance of assets are included in this subject group.
3. **Life cycle activities:** Emphasis is placed on reducing ensuing costs by integrating AM activities across the organization. This subject group targets cost reductions in capital intensive organizations by sufficient planning for asset life cycle delivery.

4. **Knowledge enablers:** This subject group focus on capturing useful data and using it to make informed AM decisions. Capital intensive organizations rely on asset data and information as enablers across all AM activities. Typical mechanisms used in the knowledge management process include Enterprise Resource Planning (ERP) and Building Information Modeling (BIM) software.

5. **Organization and people:** The implementation of an AM strategy can bring significant changes to an organization. Investing time and knowledge into employees responsible for the implementation of AM strategies and objectives is critical in the process of achieving AM and organizational objectives.

6. **Risk and review:** This subject group focuses on the risk management process which include the identification, interpretation, and management of risks. An important aspect of this subject group is the review process. The review process is a critical feedback mechanism that is used to measure progress and initiate continual improvement of the AM strategy and activities.

These six subject groups are the main focal points of the AM standards succeeding *The Asset Management Landscape* and is introduced in more detail in Section 2.2.3 to facilitate the discussion on AM scope, benefits, and implementation strategies. GFMAM (2014) states that these six subject groups should always be considered as part of a holistic process and be treated as interdependent parts of an overall process.

**Asset Management – an anatomy**

The Institute of Asset Management (IAM) published the first edition of this document in 2011 and the second edition in July 2014 superseding the ISO 5500X series and *The Asset Management Landscape*. The second version of *Asset Management – an anatomy* is in alignment with other preceding AM standards including the ISO 5500X series of standards and *The Asset Management Landscape* published by the GFMAM. The main objective of this document is to act as a comprehensive reference guide to professionals seeking to understand the field of AM in more detail by providing a high-level overview of AM. Moreover, *Asset Management – an anatomy* builds on all previous AM knowledge, particularly the 39 subjects found in *The Asset Management Landscape* and points out the strengths and limitations of the most recognized AM standards previously published. In addition, this standard emphasizes that the 39 subject areas describing the scope of AM should be considered as non-discrete and interdependent topics that perform together towards a common objective.

The scope of the second version goes into more detail than the AM requirements found in the ISO 5500X series and PAS 55. The second version of *Asset Management – an anatomy* is also the first AM standard to clearly state what is *not* AM. Certain aspects that are not considered to be AM includes Quality Management, Lean principles and Six Sigma, although these engineering and management tools can be used as part of an AM strategy (IAM, 2014). This standard is a great leap forward compared to previous AM document due to the fact that it provides certain tools, albeit a limited number, strategies and practical examples on *how* to implement AM activities within an organization while still adhering to the generic aspect of AM.

The IAM published the third version of this document in December 2015 (IAM, 2015). The latest version is aligned with previous AM standards and use consistent terminology so that it can be used in conjunction with previous AM standards. Moreover, the third version of *Asset Management – an anatomy* builds on the knowledge of all previous AM standards discussed in this section. The greatest improvement on the second version is the detailed discussions on the six subject groups. These six main groups are decomposed into the 39 subjects that fully describe AM. Moreover, a significant improvement in the third version is the tools and strategies provided on *how* to implement AM in various organizations of different size and industry. In addition, the 39 subjects are correlated to the AM clauses introduced in the ISO 55001 document. *Asset Management – an anatomy* is used as the basis for describing the scope, benefits and implementation strategies for AM in Section 2.2.3.

### 2.2.3 Asset Management: Scope, Benefits and Implementation

Using the definitions, terminology, history and knowledge provided in the previous sections, AM is now looked at in greater detail to provide the basis for PAM and ultimately asset replacement. Figure 2.3 provides a comprehensive holistic view on the field of AM and will be used as the foundation in the discussion of what AM looks like in organizations, why it is implemented and also how it is implemented. Analyzing Figure 2.3, it is evident that the complete scope of AM is included in the six major subject groups which can be decomposed into the 39 subjects that the AM standard developed by the IAM, *AM – an anatomy*, emphasizes (IAM, 2014). These six subject groups are focused on in this section. Before discussing the full scope of AM, it should be noted that these six classes must be considered as concurrent processes and an integrative approach should be followed when applying these aspects within an organization.

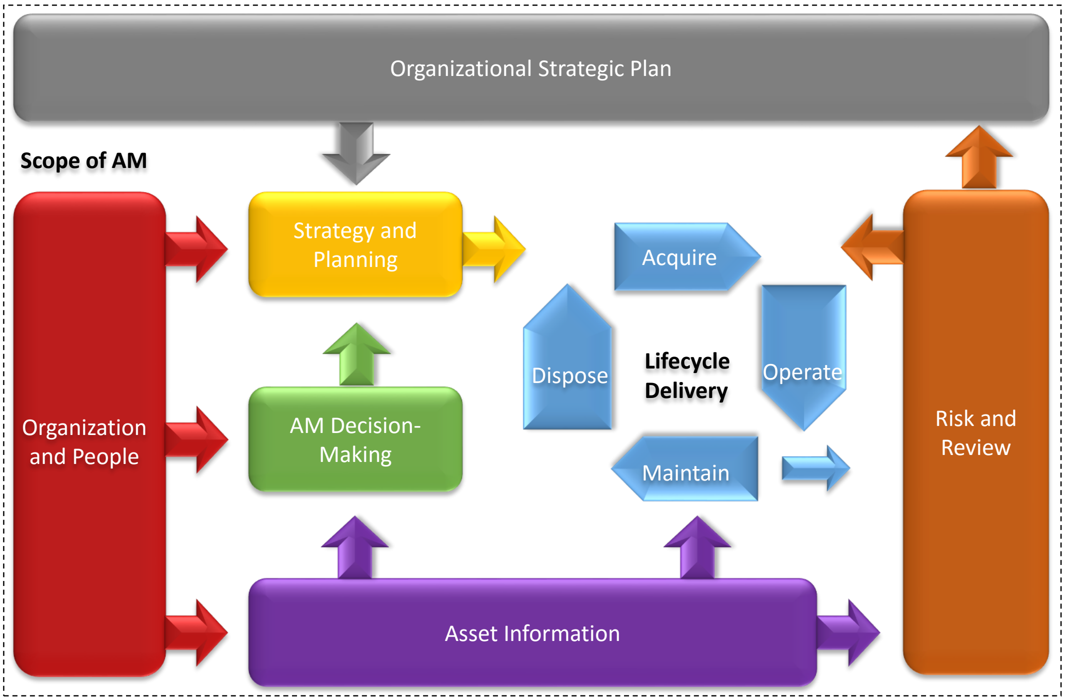



**Figure 2.3:** Holistic view of Asset Management
*Adapted from IAM (2014)*

The first subject group to be investigated is the *strategy and planning* group. This group requires transparent organizational strategic objectives being translated into a Strategic Asset Management Plan (SAMP). Many organizations find themselves in a strategy crisis, not because the wrong strategy is selected, but because the execution or implementation is not sufficient (Sull, 2007). This inability of organizations to execute a chosen strategy is often referred to as the Strategy Execution Gap (SEG). The AM policy of an organization is the basis for all AM planning and implementation activities and is a high-level plan of AM objectives. According to PAS 55-2, an AM policy for any organization should have the following characteristics (BSI, 2008):

- Consistent with all organizational objectives and management decisions.
- Appropriate for the size, structure and industry of the organization.
- Compliant with all organizational documents regarding safety and risk management.
- Clearly defined framework for the development of an AMS that supports achieving AM objectives.
- Support from the executives and effective communication to the rest of the organization.

With a comprehensive AM policy in place, the organization must translate its strategic objectives into measurable AM plans. These AM plans must clearly state who is responsible for the respective tasks, where financial aid can be acquired, what resources will be required, and when the benefits of the AM plan can be expected to realize. With the necessary AM policy and planning, the next subject group can be investigated, which is the AM *decision-making* phase.

A prerequisite for making competent and consistent AM decisions is a sufficient AM policy and planning framework (ISO, 2014). The key to making good AM decisions is the acquisition of the applicable critical-asset knowledge and applying this information to the AM planning framework. AM decision-making aspects include capital expenditure, operation and maintenance strategies, and the resource strategy (IAM, 2014). This list is by no means exhaustive and only emphasizes the most generic decision-making factors. Decisions made at any stage in the life cycle of an asset, affects all subsequent stages and other group subjects. For example, the decision to acquire a certain asset impacts the organizational performance, maintenance strategy, and risk requirements. Furthermore, certain tools can be used as part of this decision-making process to ensure that the optimal decisions are made. Engineering modeling tools such as the Markov Decision Process (MDP), Bayesian models, Monte Carlo simulations, and Auto Regressive Integrated Moving Average (ARIMA) models can be used to forecast outcomes of capital expenditure decisions including certain risk parameters with a specified confidence interval. Engineering tools and techniques such as Lean thinking, Six Sigma, and Reliability Centered Maintenance (RCM) can be used to support the decision-making process (Moore, 2011). In addition, other qualitative methods such as a Failure Mode and Effects Analysis (FMEA) and the

Delphi method can be used in certain AM decision-making processes.

The IAM (2015) recognizes that the best business decision is not always the optimum balance between risk and cost. As discussed in the definition of AM in Section 2.2, it is the point where an organization achieves its objectives in a sustainable manner while balancing cost, risk, and performance. These three drivers are of particular importance for any organization to achieve its objectives and should be an integral part of the decision-making process. The economic optimum point in AM decisions is therefore the decision that has the optimal total business economic impact considering all business drivers. To achieve optimal performance, many constraints have to be considered including financial, resources and regulatory constraints (IAM, 2014). Moreover, the optimal business decision is found when the aforementioned business drivers are considered over the entire life cycle of an AMS to achieve optimal performance.

The *life cycle management* subject group is where the majority of expenditure in an organization is incurred. Although there are many variations and nuances for the description of life cycle stages, Figure 2.4 represents a standards version of typical stages in the life cycle of an asset. Life cycle management activities should not be considered as independent activities. Life cycle management becomes more complex when:

- An asset system consisting of many discrete assets are considered.
- Assets in an AMS have different operating lifetimes and maintenance strategies.
- Component replacement takes place and operating conditions change.
- Assets have multiple owners and is subject to different operating levels and maintenance strategies.

Life cycle management of single discrete assets is easy to understand and to apply (IAM, 2015). However, assets usually contribute value in the context of multiple assets functioning together to form an AMS. In the context of asset systems, Systems Engineering (SE) aspects are frequently applied to ensure optimal financial performance in subsequent life cycle stages following a decision. SE in an AM context takes into consideration the interdependency between critical assets and is therefore an important component of an AM strategy. The *life*

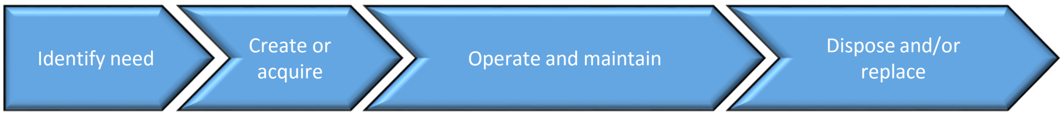



**Figure 2.4:** Typical asset life cycle stages
*Adapted from IAM (2015)*

*cycle management* of an AMS should be considered at different levels ranging from individual, discrete assets to an asset portfolio as is indicated in Figure 2.5. Moreover, Figure 2.5 indicates value contributions to an organization made by assets in different contexts. Firstly, reviewing the definition of *asset life cycle* it is found that the generic aspects of life cycle management include acquisition, utilization, maintenance, and disposal or replacement (ISO, 2014). Asset life cycle management has small variations depending on what level of an AMS is focused on. The main objective of life cycle management is to add value to an organization. Different values and priorities are often found in an AMS due to different stakeholders with a variety of agendas. With reference to Figure 2.5, these values and priorities from the various stakeholders' point-of-view are discussed here. Starting at the bottom level that includes discrete assets, the main priority is to manage assets efficiently and effectively over their entire life cycle to enable system performance in the next level. Physical Asset Management (PAM), and in particular maintenance management, is the focus of the individual assets level and is discussed in more detail in Section 2.2.4.

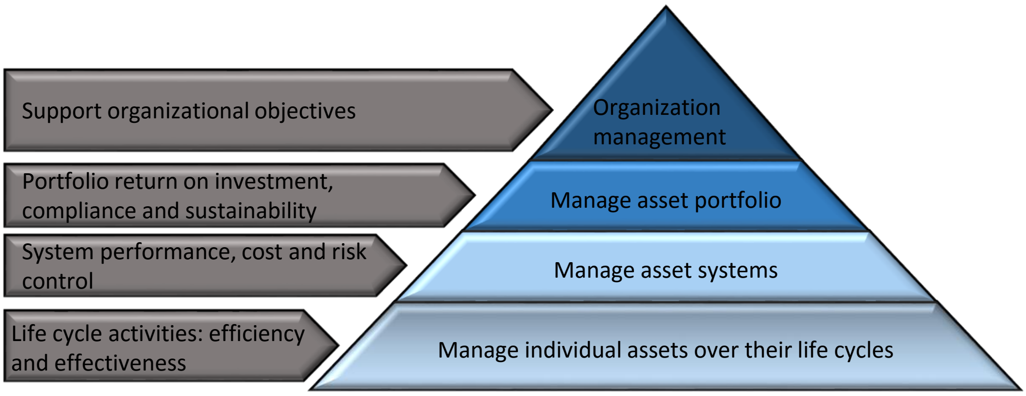



**Figure 2.5:** Hierarchy of assets within an organization
*Adapted from IAM (2015)*

The system level combines the discrete assets to form a continuous line of assets functioning together to optimize value, performance and risk (IAM, 2014).

An industry example of an asset system is the process of crushing coal. Coal is fed into a crusher (discrete asset) where it is crushed and transported on a conveyor belt (discrete asset) to a high pressure grinding roller silo (discrete asset). Furthermore, each of these discrete assets consist of many subsystems but function together to form an asset system and therefore create value from a process within an organization. The bottom two levels in Figure 2.5 emphasize performance management and optimization and can thus be accredited to the operation and maintenance business units (stakeholders) in an organization. The top two levels in Figure 2.5 focus on creating financial value in a sustainable manner and include the management of asset portfolios, closely linked to organizational strategies and objectives. These organizational strategies and objectives include aspects such as Return On Investment (ROI) and customer satisfaction therefore focusing on high-level management decisions.

The *organization and people* subject group is considered by many AM practitioners to be one the most important subject groups to achieve AM excellence and organizational objectives. This subject group focuses on the human aspect when implementing AM strategies and activities in an organization. This group include subjects such as: (1) organizational leadership, (2) organizational structure, (3) clarity of leadership and (4) organizational culture (IAM, 2014). These aspects are often the difference between a leading AM organization and an average performing organization. The IAM reiterates the importance of employees in the AM implementation process by stating the following:

> *"It is vital to remember that people do asset management and therefore people, and their knowledge, competence, motivation, and teamwork have a huge influence on asset management outcomes." - (IAM, 2015)*

Subjects in this group are interconnected and dependent on each other due to the human nature component. Organizational leadership is considered to be the most influential subject in this class. Strong AM leadership is required when an organization is faced with complex decisions and conflicting objectives such as the priorities for the operations and maintenance departments in an organization. Operations are seeking to maximize production while maintenance needs to preserve asset condition. In such cases senior management needs to consult the AM policy and planning phase to find the optimal business solution. Organizational structure and culture are two highly interdependent subjects (GFMAM, 2014). Human assets need to be inspired and motivated to achieve organizational objectives and the AM strategy should complement this process. Senior management (leadership) is important in facilitating this process and effective communication is seen as the most important tool (IAM, 2014) in this regard.

*Risk* is present in any managerial decision. An organization therefore needs to recognize that risk may be present or affect many aspects of daily operations including: (1) employee safety, (2) environment, (3) finances, (4) reputation, and (5) operational performance so that the most critical risks can be identified and incorporated in the AM decision-making process. Moreover, the risk and review process is important in engaging stakeholders and receiving feedback that assist decision-making. *Risk assessment, management and review* is the last major class presented in this section that comprehensively describes the scope of AM as found in Figure 2.3. The remaining subject group, *Knowledge enablers*, is included in the discussion in in Section 2.2.4 where PAM is focused on. Risk and review in the AM process is greatly interdependent with AM decision-making and forms the base for various aspects including asset performance monitoring, sustainable development and change management.

Risk management processes are fundamental to enable organizations to prepare for unplanned events that could have catastrophic consequences if not dealt with properly. Risk management ensures the development of contingency plans and other mechanisms to assure organization continuity (IAM, 2014). A main feature of risk management is to identify business-critical assets and to aid the development of programs to mitigate the risks associated with these assets. In modern times, risk management has become a significant part of all organizations in the PAM domain, with many entities having a risk department solely focus on risk management. Furthermore, IAM (2015) states that the risk and review process plays a critical role in preparing organizations for events such as safety accidents, climate change, and financial volatility. A detailed methodology to develop mitigation or contingency plans is found in the Business Continuity Management - Code of Practice developed by the BSI and is considered to be outside the scope of this discussion (BSI, 2006). If implemented successfully, the aforementioned subject groups should lead to many benefits in an organization. In an unyielding complex economic environment, organizations need to look to innovative management strategies such as AM to gain a sustainable competitive advantage (Henderson *et al.*, 2014). The proactive approach embedded in AM leads to an increase in profitability and sustainability for organizations implementing AM.

**Benefits of AM**

Organizations are constantly searching for ways to improve business performance, therefore increasing production while decreasing expenditure. Organizations need to benefit from implementing AM strategies, such as creating sustainable value while reducing overall business risk. These potential benefits are widely recognized in the AM industry and include the following [1]:

1. Increase in performance of risk and safety management practices as well as stakeholder confidence.

2. Improvement in financial performance with reference to ROI, service levels, and projected cash flow. This is especially true for capital intensive organizations .

3. Improvement in decision-making of investment opportunities, therefore controlling capital expenditure and operational expenditure.

4. Improvement in environmental impact performance and personal and process safety.

5. Increase in equipment life and Overall Equipment Efficiency (OEE) through improved data and analytics practices.

6. Reduction in maintenance costs and unscheduled downtime as a result of the standardization and simplification of plant equipment.

7. Improvement in organizational communication across business units and divisions.

8. Improvement in organizational sustainability and social responsibility.

9. Improvement in regulatory, statutory and legal compliance.

[1] See Mitchell *et al.* (2007), BSI (2008), Jardine and Tsang (2013), ISO (2014), GFMAM (2014), Paquin (2014), Henderson *et al.* (2014), IAM (2014), IAM (2015)

10. Increase in organizational credibility, reputation, and stakeholder satisfaction.

However, Paquin (2014) states that implementing AM activities in an organization is not a guarantee for success. Furthermore, Paquin (2014) notes that while more than 70% of organizations benefit from the implementation of AM, performance gains are dependent on the extent to which AM is implemented. In addition, Moore (2011) states that senior management in organizations are often overwhelmed with the number of improvement strategies and tools available. This may lead to the selected AM tools and strategies not being implemented correctly or the wrong combinations being used. In addition, Hodkiewicz and Pascual (2006) state that a lack of technical and managerial skill often restrict the realization of the possible benefits of AM. Equipped with a holistic view of general AM principles, PAM is focused on in the next section which is the foundation of asset replacement.

### 2.2.4 Physical Asset Management Domain

Using the broad AM landscape provided in the previous sections, Physical Asset Management (PAM) is now focused on to contextualize the asset replacement process. In the current economic environment, organizations are recognizing the factors that are driving the need for AM with increasing intensity (Koronios *et al.*, 2007). Certain aspects such as managing asset risks and complying to various regulations are being focused on in organizational objectives more often. Senior management are emphasizing expenditure reductions, increasing ROI, and increasing asset value. To incorporate the aforementioned objectives, PAM is implemented. PAM is at the heart of any AM program in a capital or asset intensive organization where physical assets are the primary mechanisms used for revenue generation. The BSI (2008) states that PAM is optimizing the interaction of physical assets with other asset categories including human, financial, intangible and information assets over the entire life cycle of an asset or asset system. This definition, documented in PAS 55, and scope of PAM is graphically represented in Figure 2.6. Wheelhouse (2009) states than an efficient PAM program increases an organization's ability to achieve strategic objectives by allowing optimal asset planning, replacement, and rehabilitation. Asset information and risk management are therefore integral parts of PAM. Organizations that are asset-intensive place great emphasis on the management of asset information and risks associated with business-critical assets. These business-critical assets refer to the equipment, parts or machinery that are critical for the operation of an organization to achieve its objectives and generate revenue.

The scope of this study is focused on two primary classes of physical assets including plant and production equipment and mobile assets. Plant and production equipment are fixed assets that organizations use to produce goods and services and generate revenue. Mobile assets refer to physical assets that are used for moving, storing, protecting and controlling inventory within an organization or along the supply chain or assists the organization in delivering its core services. Table 2.1 presents examples found in industry for these two primary classes of physical assets.

**Table 2.1:** Scope of physical assets

| **Category** | **Industry examples** |
|---|---|
| Plant and production equipment | Manufacturing, food processing, oil and gas<br>mining, chemicals, power generation<br>pharmaceuticals |
| Mobile assets | Military vehicles, mining vehicles<br>shipping equipment, railway trucks, airlines |

The interaction between physical assets and other asset categories present in an organization is shown in Figure 2.6. The interdependent nature of these asset categories is vital in the holistic delivery of AM and organizational objectives. Table 2.1 illustrates the typical interfaces between physical assets and other asset categories (BSI, 2008).

A selected number of examples are discussed to illustrate the interaction between physical assets and other asset categories. Information assets such acceptable quality data and asset knowledge are required in the process of developing, optimizing and implementing AM plans. Focusing on the interaction between physical assets and human assets, the competency and motivation of the workforce and communication between management and shop floor have significant impacts on the performance of physical assets. Furthermore, financial assets are

**Table 2.2:** Interfaces between physical assets and other asset categories

| Asset category | Important interfaces |
|---|---|
| Human assets | Motivation, communication, leadership, teamwork, competency |
| Intangible assets | Organizational image, social impact, morale, reputation |
| Information assets | Performance, operating condition, costs and opportunities |
| Financial assets | Life cycle costs, capital investment, operating costs, overall value of assets |

required throughout the life cycle of physical assets and directly influences the total organization performance.

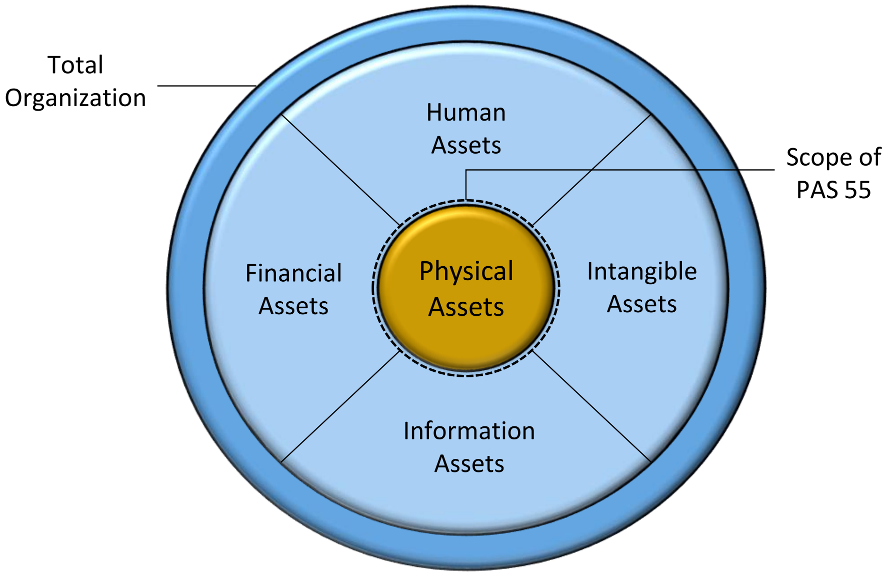



**Figure 2.6:** Holistic view of Physical Asset Management
*Adapted from BSI (2008)*

*Asset information* refers to the data associated with certain assets that should be captured in an asset register and an ERP software system depending on the level of AM implementation and maturity in an organization. Asset information itself is of no value to an organization if not used efficiently and effectively (Hemp, 2009). It is widely acknowledged in industry that many organizations are in possession of large quantities of data but do not use it effectively to add value to the PAM process. Asset *knowledge*, the last of the six subject groups that fully describes the scope of AM, is therefore needed. Asset knowledge refers to the combination of raw data and experience to aid the decision-making process regarding business-critical assets (IAM, 2014). The AM *strategy* that an organization implements is therefore of utmost importance when dealing with asset knowledge. The IAM (2014) states that typical information with respect to business-critical assets that must be included in an AM information strategy include but are not limited to:

1. Documentation of acquisitions, sales or lease agreements, also known as an asset register.

2. Asset specifications including manufacturer, age, serial number, and operating conditions and performance.

3. Physical location of asset or asset system, specifically in large organizations with Geographical Information Systems (GIS).

4. Documentation related to operational capabilities such as safety and technical manuals.

5. Asset condition information including reliability and maintenance history obtained from data records or experience.

6. Data attributes related to an asset or asset system.

7. Unstructured data such as drawings, failure modes and user manuals.

*Asset knowledge* is critical to the asset replacement process where many factors are considered to determine the optimal replacement time. The ISO 8000 series of standards provide detailed information and guidelines regarding asset information management for various industries (ISO, 2009). As part of the overall AM strategy an organization needs to develop before implementing AM principles, the IAM (2014) suggests that an Asset Information Strategy is also developed in collaboration with other standards such as the ISO 8000 series. Furthermore, the IAM (2014) states that as part of the Asset Information Strategy concepts such as BIM, ERP, Computerized Maintenance Management Systems (CMMS), and the capture of historical qualitative experience should be implemented to prevent the loss of asset knowledge when control is passed on to another employee or when an employee leaves the organization.

**Maintenance**

The subject group of *risk assessment, management and review* as discussed by IAM (2014) in *AM - an anatomy*, provides an introduction to the aspects of asset performance and health monitoring, change management and stakeholder engagement. These aspects can be classified under a field known as maintenance management which forms an integral part of PAM. Furthermore, Jardine and Tsang (2013) and Hartman and Tan (2014) state that maintenance is a determining factor in the asset replacement process as a result of the OM costs involved and assets' operating condition being altered. Moreover, maintenance management is critical in the process of deciding whether to repair or replace an asset. Vlok (2012) states that maintenance can be considered as the execution of PAM. Organizations implement maintenance activities with the primary goal of raising their profitability by increasing the reliability and availability of physical assets (Swart and Vlok, 2015). The IAM (2014), in *AM - an anatomy*, uses a medical analogy to accentuate the need for maintenance by stating that machines and equipment require maintenance just like the human body needs medical attention and that specialists in the respective fields are required. Furthermore, Sharma *et al.* (2011) state that maintenance tactics are becoming increasingly important due to the competitive nature of the manufacturing, mining, aviation, and process industries. In addition, organizations are aiming to extend asset life and optimize performance using various maintenance tactics (Shafiee and Chukova, 2013).

According to Márquez (2007), a good maintenance program is a prerequisite for maintaining product quality, reliability and availability at an acceptable level. Different maintenance strategies exist for different organizations. Moreover, it is important to include the overall maintenance strategy in the organization's AM strategy before maintenance tactics and tools are investigated. This prevents senior management being overwhelmed by the sheer number of maintenance tactics and tools. Many maintenance strategies exist such as RCM, Business Centered Maintenance (BCM), and Total Productive Maintenance (TPM) to name but a few. These maintenance strategies greatly affect the asset replacement process, because it changes the operating condition of assets and therefore costs and revenue associated with an asset.

Figure 2.7 shows an example of a simplified generic maintenance management strategy. First, an asset register must be developed which is then used to


**Figure 2.7:** Maintenance management strategy

perform a criticality analysis. The criticality analysis determines which assets should be considered as business-critical assets and is therefore the main focus of a PAM program. A FMEA is then conducted to identify failure modes, root causes and the effects of a failure on the business-critical assets. Based on the information obtained from the FMEA, a maintenance tactic is selected and a comprehensive maintenance program is developed and implemented. Furthermore, Murthy *et al.* (2002) state that the term *maintenance* is often perceived as only the physical aspect of PAM. Therefore many authors in literature refers to the field of maintenance related subjects as *maintenance management* (Márquez, 2007). Murthy *et al.* (2002) identify several features of an effective maintenance strategy in an overall organizational context include:

- Multidisciplinary approach between all business units in an organization.
- Information from all relevant sources are acquired and used.
- Quantitative models are used in collaboration with qualitative data.
- Maintenance management is viewed as a continuous improving concept.

The type of maintenance strategy employed for an asset greatly affects the asset replacement process. Operating and Maintenance (OM) costs contribute significantly to the total life cycle costs of an asset, which in turn is the main criteria considered when deciding on whether to replace or repair an asset. A brief overview of the main maintenance approaches found in industry is presented and its impact on the asset replacement decision-making process is illustrated. Maintenance tactics can generally be classified under three main approaches as indicated in Figure 2.8. These approaches include: (1) Design-Out Maintenance (DOM), (2) Preventive Maintenance (PM), and (3) Corrective Maintenance (CM) (Vlok, 2012).

Design-Out Maintenance (DOM) approaches focus on improving an asset's design in order to minimize or completely eliminate maintenance activities. Scarf

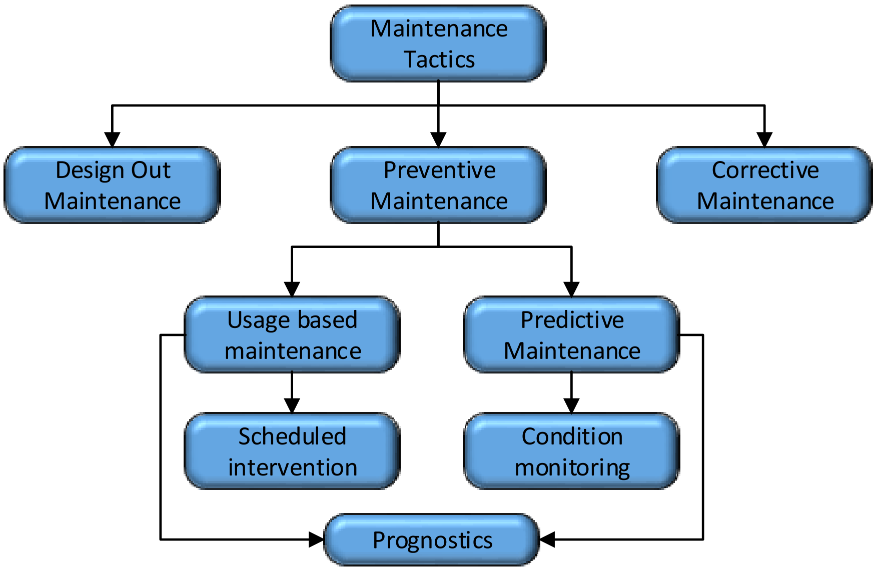



**Figure 2.8:** Holistic view of maintenance tactics
Adapted from Vlok (2012)

(2007) states that physical assets which are subject to high frequency failures or lengthy downtimes should be classified under DOM tactics within a maintenance strategy. Waeyenbergh and Pintelon (2002) agree by stating that the chemical process industry makes use of DOM tactics to increase reliability and minimize downtime due to the excessive economic impact of asset failures. Furthermore, Markeset and Kumar (2003) state that when considering a DOM approach, an organization has to consider many factors to ensure that it selects the most efficient and effective maintenance approach. Life cycle costs are the primary indicator when considering a DOM approach and tools such as a Fault Tree Analysis, FMEA, and an Event Tree Analysis should be used to evaluate all alternatives based on the total life cycle costs (Markeset and Kumar, 2003). The process of evaluating a DOM approach is illustrated in Figure 2.9.

Waeyenbergh and Pintelon (2002) state that the main disadvantages of the DOM approach are the time requirements to implement and the fact that it may lead to organizational change in structure. The opposite to DOM, according to Markeset and Kumar (2003), is "design for maintenance" which is designing an asset to be accessible, serviceable, and modular. This category of maintenance tactics include preventive and corrective maintenance and is preferred to DOM, which is often considered as the last resort in maintenance tactics (Waeyenbergh and Pintelon, 2002). DOM is therefore not as influential on the asset replacement

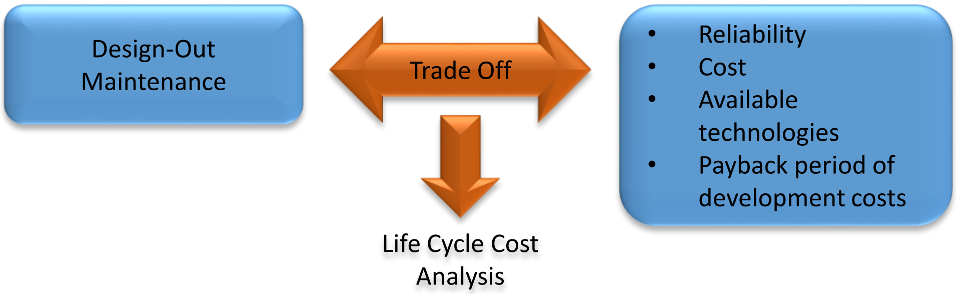



**Figure 2.9:** Design-Out Maintenance approach
Adapted from Markeset and Kumar (2003)

process as Preventive Maintenance (PM) and Corrective Maintenance (CM).

Preventive Maintenance (PM) aims to prevent asset failure by replacing or repairing assets before failure occurs. This maintenance approach is essential in the asset replacement process and assets that make use of PM are therefore the main focus of this research. The results of a good PM program, as stated by Dhillon (2002) and Tinga (2010), include greater plant availability, reduced equipment failure costs, increased planning ability, and increased health and safety performance. PM is popular in environments where reliability is of the utmost importance such as the aviation, mining, military, and power generation industries. Other indications that an organization is in need of PM practices are recommended by Dhillon (2002) and Tinga (2010) and include:

- High equipment unavailability due to frequent failures.
- Excessively high repair costs throughout organization.
- High frequency of unexpected failures causing excessive operator idle times.
- Unacceptable health and safety performance from assets.

In addition, Dhillon (2002) suggests an indicator on whether an organization should use PM activities using the following equation to determine whether it is economically viable:

$$(NBR) \times (ACPB) \times (\epsilon) > (TPM) \tag{2.2.1}$$

where,

$$
\begin{aligned}
\text{NBR} &= \text{Total number of breakdowns,} \\
\text{ACPB} &= \text{Average cost per breakdown,} \\
\epsilon &= \text{Proposed factor with value of 0.7} \\
\text{TPM} &= \text{Cost of PM in organization.}
\end{aligned}
$$

If the total cost of a PM program in an organization is indeed less than 70% of the total breakdown costs as indicated by Equation 2.2.1 and the organization satisfies the aforementioned criteria, then it is highly recommended that a PM program is implemented. An integral aspect of any PM program is the calculation of maintenance intervals to be applied. If the intervention time is too long, failure will occur and if intervention takes place too frequently, labour costs will be excessive. Therefore PM can be decomposed into two major classes, usage based maintenance and predictive maintenance. Usage based maintenance refers to the intervention, inspection, repair or replacement, irrespective of the condition or performance of the asset under inspection. Many different measures of intervention time exist, with the most commonly used measure being the Mean Preventive Maintenance Time (MPMT) shown in Equation 2.2.2 proposed by AMCP (1975):

$$MPMT = \frac{\sum_{k=1}^{m} f_k MPMT_k}{\sum_{k=1}^{m} f_k} \tag{2.2.2}$$

where,

$$
\begin{aligned}
MPMT_k &= \text{Mean Preventive Maintenance Time required to perform} \\
&\phantom{=} \ k\text{th maintenance action,} \\
\text{m} &= \text{Total number of data points,} \\
f_k &= \text{Frequency of } k \text{ th PM activity per operating hour.}
\end{aligned}
$$

Many other PM related equations and models exist such as the Poisson distribution, Weibull distribution, regression analysis, Markov model and the Inspection Optimization Model series. However, most of these models use similar or closely related processes and parameters depending on the trends found in the data. The other major PM class is Predictive Maintenance (PdM), also known as condition based maintenance. PdM aims to provide an understanding of the condition of assets and to use this knowledge to predict and schedule intervention measures. Moore (2011) states that PdM cannot predict *when* an asset will fail, it can only provide diagnostic information on the condition of assets. Popular condition monitoring technologies include: (1) vibration analysis, (2) infrared thermography, (3) lubricant analysis, (4) acoustic analysis and (5) electrical current analysis. The main generic phases of each PdM program include acquiring data, usually through a CMMS, processing the data and making a decision based on the results of the processed data. Heng *et al.* (2009) and Moore (2011) agree that the following advantages are associated with the implementation of a PdM program on the appropriate assets:

- Reduction in maintenance costs.
- Prevention of asset failure thus decreasing unplanned downtime.
- Improvement safety performance.
- Increase in OEE and thus production.
- Provides reliable information on degrading asset performance.

However, according to Moore (2011), there are also disadvantages associated with PdM programs. PdM is very expensive and can only be implemented on business-critical assets. Furthermore, Moore (2011) and Dhillon (2002) state that organizations implementing PdM often make common mistakes such as: (1) not providing adequate training to employees, (2) only relying on the data and forgetting about the human aspect such as inspection, and (3) do not have a satisfactory planning and scheduling process. In addition, Moore (2011) notes that it is generally recommended that small plants contract PdM related services to a vendor while it is more economically feasible for large plants to develop in-house PdM programs.

Another maintenance tactic exists in what is known as the *Prognostic approach*. This method can be considered as a hybrid maintenance tactic using principles from both usage based maintenance and PdM to forecast the residual life of an asset or asset system and use this knowledge to schedule optimal maintenance intervention. Tinga (2010) states that this method has attracted substantial attention from the research community in the last ten years, mostly supported by the development of systems known as Prognostics and Health Management systems aimed at military uses. According to Roemer *et al.* (2006), the prognostic approach can be represented as three basic levels including: (1) experience-based, (2) evolutionary methods, and (3) model-based. Furthermore, Tinga (2010) states that these levels are, in the aforementioned order, increasingly accurate but also at a higher cost and computational requirements. The basic hierarchy of prognostic approaches are shown in Figure 2.10. The experience-based approach uses historical failure data to predict residual life. Statistical methods such as regression analysis, exponential and Weibull distributions are popular methods to implement using this approach. The main obstacle associated with this approach is the availability and accuracy of the applicable failure data, although this can be overcome to an extend using modeling techniques such as the MDP, Artificial Neural Networks (ANN) and Fuzzy logic.

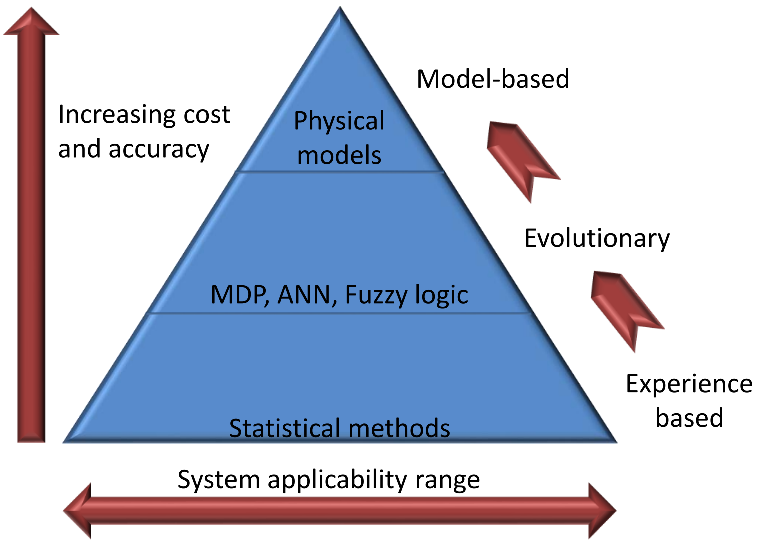



**Figure 2.10:** Prognostic maintenance approaches
Adapted from Roemer *et al.* (2006)

Evolutionary methods, also known as trending methods, are applied to assets where data are produced continuously using condition monitoring techniques regarding its current condition and knowledge are gained with respect to failure patterns (Roemer *et al.*, 2006). These failure patterns are extrapolated to determine the residual life of the asset under investigation. As is evident from Figure 2.10, evolutionary methods are more accurate than experienced-based methods but a trade off is made with regards to cost. The most accurate, complex and expensive prognostic approach is known as the model-based approach. Tinga (2010) states that this approach uses physical models and its failure mechanisms to simulate degradation. Types of physical models that are in current use include fatigue, creep, and corrosion models. Service life obtained using this approach is very accurate and historical data is not required. This approach is used extensively in the aviation and military industries.

The final maintenance tactic discussed here is known as Corrective Maintenance (CM). It is an important maintenance tactic that most organizations employ to some extent. Engineering systems fail occasionally irrespective of whether it was expected or unexpected. CM entails repairing or replacing parts after failure occurred (Dhillon, 2006). CM is therefore always a maintenance tactic that organizations must consider, even just for a fraction of their assets. The obvious advantages in this maintenance and operation strategy (run-to-failure) are that no asset's service life is not fully utilized and no unnecessary maintenance costs are incurred. However, the biggest liability of this strategy therefore is the fact that failure can occur unexpectedly which compromises the reliability of an asset system. In addition, Dhillon (2002) says that organizations implementing corrective maintenance tactics are not aware of deteriorating asset conditions which may have an effect on asset life span and more important, production output and product quality. Nakagawa (2006) and Tinga (2010) provide examples of where corrective maintenance tactics are applicable such as:

- Parts that are readily available and not time consuming to replace.
- Assets that are not business-critical or have a long life span.
- Assets where failure is not considered to be expensive or pose a health risk.
- Assets or asset systems which have built-in redundancy, thus isolating failure effects.

Analogous to preventive maintenance, many tools and mathematical models are available to calculate certain indicators regarding the maintenance tactic. In conclusion, it is noted that CM should be part of the majority of maintenance strategies since unscheduled breakdowns cannot be totally eliminated in any organization. CM is therefore not the main focus when considering maintenance strategies for assets in this thesis, due to the fact that it is implemented on non-critical assets. However, it must be emphasized that for a maintenance management strategy, the maintenance tactic that makes the most economic sense for a specific organization must be selected and implemented.

As discussed in the previous sections, PAM is a broad domain that includes various strategies, tools, and methodologies to optimize asset performance in an organizational context. Various factors contribute to implementing a successful PAM program including capital investment decision, asset life cycle costs, maintenance approach, and the interaction between asset categories as shown in the aforementioned sections. At the heart of PAM programs is physical asset replacement decisions. The key to making optimal asset replacement decisions is to identify the correct influential factors, consider the effects of these factors on organizational performance and to get the timing right (IAM, 2015). Section 2.3 investigates the state of the art of physical asset replacement with the primary goal of identifying the correct factors to include in the asset replacement process and analyzing its impact on the financial performance of an organization.

## 2.3 Asset Replacement

Organizations within the PAM domain are frequently faced with the decision to keep and repair assets, or to replace it. This decision is made as a function of various factors to replace assets at the optimal time. As assets are in operation, their physical operating condition deteriorate, Operating and Maintenance (OM) costs increase, and the salvage value decreases therefore forcing management to repair or replace assets. Furthermore, Campbell *et al.* (2010) state that asset replacement is a critical component of the capital investment strategy of a physical asset-intensive organization. Moreover, a sufficient capital investment strategy adds equity value to an organization resulting in an increase in the organization's financial worth. In addition, the timing and costs of capital investments can have a significant impact on an organization's success IAM (2015).

The asset replacement process is well studied in literature dating back to the early 20th century with Taylor (1923) and Hotelling (1925) incorporating the effects of depreciation into asset replacement problems. Since then, the evolution of asset replacement theory has been well documented. Asset replacement models and methodologies have been developed for a variety of industries and types of assets. Examples from the automotive industry include developing replacement models for buses by Simms *et al.* (1984) and Keles and Hartman (2004), a fleet of vehicles consisting from different classes of vehicles by Weissmann *et al.* (2003), and a single vehicle by Pedraza-Martinez and Van Wassenhove (2013).

Asset replacement applications from the aviation industry can be found in the research of Greenfield and Persselin (2002) focusing on military aircraft replacement, Hsu *et al.* (2011) emphasizing the different options to purchase, buy or lease, and Bazargan and Hartman (2012) focusing on commercial airline fleet acquisition and disposal options. Medical equipment replacement has been investigated by Dondelinger (2004), developing a generic asset replacement and planning methodology, asset replacement planning system in hospitals by Rajasekaran (2005), and a medical asset replacement score system to prioritize replacement actions by Taylor and Jackson (2005). Asset replacement research conducted in the mining industry include surface mining equipment by Hall and Daneshmend (2003), reliability and replacement analysis of a crushing plant by Barabady and Kumar (2008), and generic data-driven decision making by Jardine and Tsang (2013). Asset replacement is also an important decision-making process in the agriculture and livestock industries. Weersink and Stauber (1988) determined the optimal replacement interval and depreciation method for a grain combine, Miranda and Schnitkey (1995) developed an asset replacement model for dairy production, and Rodriguez-Zas *et al.* (2006) investigated the impact of certain factors such as biological variables on the replacement process in swine.

It is noted that replacement theories and optimal life utilization are both important factors in the decision-making process for asset replacement and have been studied by many financial or business experts as a result of the important economic impact it has on the financial performance of an organization including Cooper and Haltiwanger (1990) and Jin and Kite-Powell (2000). Furthermore, optimal life utilization refers to the operation of an asset to its economic life. An asset's economic life is the optimal amount of time to retain and keep an asset in operation, or the time and physical condition which satisfies an objective function for a certain period of time (Hartman and Murphy, 2006). Thuesen and Fabrycky (2001) agree, adding that the economic life of an asset is the age where the Equivalent Annual Cost (EAC) is minimized. Moreover, in the process of determining the optimal life utilization of an asset, it is important to clearly state the scope of variables included in the calculations.

Analogous to AM, asset replacement theory is a broad field and certain limitations are required to prevent scope creep in this research. This research focuses on single asset replacement theory, considering the entire asset and not its sub-

**Table 2.3:** Delineation of asset replacement theory

| Asset replacement variable | Scope of variables |
|---|---|
| Number of assets | Single asset, fleet of assets, individual components |
| Time horizon | Finite, infinite |
| Variables to consider | Quantitative and/or qualitative |
| Replacement asset | Identical asset, technologically advanced asset |
| Costs | Stationary, non-stationary |
| Replacement action | Keep, repair, replace, capacity expansion |

systems or individual components. Furthermore, the time horizon considered in this research is finite. In addition, both qualitative and quantitative variables that affect the replacement process are considered. Moreover, this study excludes the expansion of an asset system thus focusing on keeping and repairing or replacing an asset. Table 2.3 illustrates the scope of asset replacement theory focusing on the generic aspects to consider in the asset replacement process. Interested readers are referred to the work of Wang (2002), Nicolai and Dekker (2008), and Jardine and Tsang (2013) for the areas of research outside the scope of this study.

### 2.3.1 Traditional Asset Replacement

This section provides an overview of what is known as *Traditional Asset Replacement* and investigates the state of the art in asset replacement theory. The traditional factors considered in asset replacement decisions are discussed while gaps in the asset replacement literature are exposed. Hartman (2001) defines a traditional asset replacement analysis as the provision of asset purchase and sale decisions for a defined time period based on selected factors such as initial capital expenditure, OM costs, and salvage value. Furthermore, Hartman and Tan (2014) state that a traditional asset replacement solution aims to provide a replacement policy that minimizes total cost while the interest rate and the cost structure remains constant across an infinite horizon. Zambujal-Oliveira and Duque (2011) agree with the aforementioned definitions and adds that the traditional methodology also assumes similar OM cost structures for replacement assets, an accurate salvage value and certainty in tax regulations. Moreover, the traditional model usually assumes asset performance deterioration with age or operating life. Hartman and Tan (2014) recognize that the operating condition of an asset is likely to be dependent on its usage rate and is therefore not just a function of time.

In addition to the aforementioned aspects, Rogers and Hartman (2005) state that technological advances in the market must also be considered. However, the traditional model does not take into consideration aspects such as changes in tax policies, variable utilization, uncertainty and risks which may affect the financial performance of an organization significantly. Furthermore, Hartman and Tan (2014) state that the basis of the traditional model is based on the cost minimization of assets by using the EAC metric to find the economic life of an asset. The economic life $x$ is therefore the operating life that minimizes the EAC and can be calculated as shown in Equation 2.3.1 (Hartman and Tan, 2014).

$$\mathrm{EAC}(x) = \left(\frac{i(1+i)^x}{(1+i)^x - 1}\right)\left(P + \frac{S_x}{(1+i)^x} + \sum_{t=1}^{x} \frac{\mathrm{OM}_x}{(1+i)^x}\right) \tag{2.3.1}$$

where $i$ is the interest rate, $P$ is the capital expenditure of acquiring a new asset, $S_x$ is the asset salvage value with an operating life of $x$, and $OM$ is the operating and maintenance costs per time period $x$. Hartman and Murphy (2006) determined that the traditional asset replacement model is also valid for a finite time period which implied that it is optimal to replace an asset at the economic life $x$ given the use of traditional replacement theory and assumptions. A typical graph of the costs involved and factors considered in a traditional asset replacement process is illustrated in Figure 2.11. The economic life for the asset under consideration in this example would be at the age of seven years. However, as discussed in Section 2.2.3 with the focus on AM, the optimal organizational performance is not always found at the optimal asset replacement decision. Factors having an influence on this process is uncertainty and various risks as discussed in the following sections.

### 2.3.2 Replacement Solution Approaches

Hartman and Murphy (2006) state that there are two popular approaches to define solutions for asset replacement problems. The first approach is to specify a sequence of *keep* or *replace* decisions for each time period, also known as a decision epoch, under consideration over a time horizon $X$. This approach is also

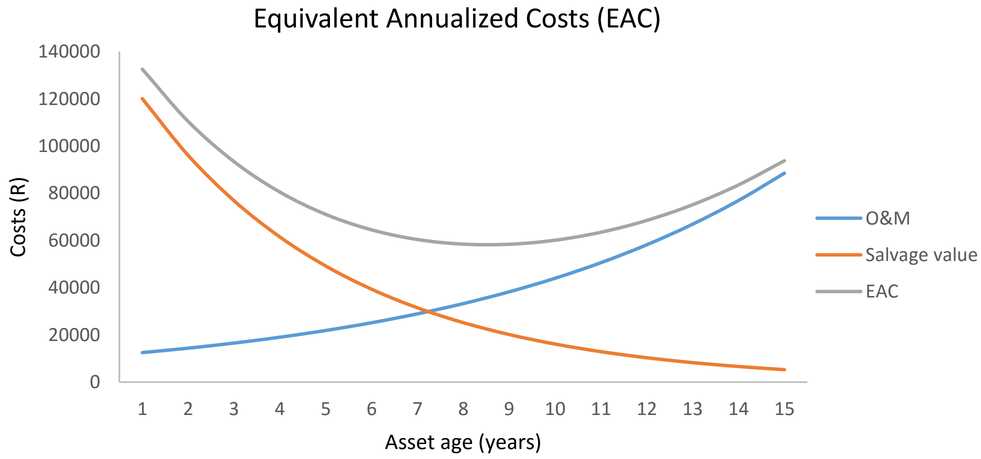



**Figure 2.11:** Determining the economic life of an asset

known as the "time zero" approach. A typical solution output using this approach would be (K, K, R, K, K) which means that the asset should be kept for two decision epochs, replaced at the third decision epoch and retained for the rest of the time horizon. The second approach is to define a sequence of asset service lives, ages, or physical operating conditions which an asset should be retained. The sum of these asset services lives, ages, or physical operating condition should sum to $X$ time periods. A typical solution output using this approach would be to specify (2,3) which is identical to the previous example shown using the *time zero* approach. The latter solution approach guarantees an optimal replacement solution for the current asset, however, the analyst may be more interested in the *time zero* approach depending on the study limitations and assumptions.

A review of asset replacement studies in literature indicate that both solution approaches are popular and used interchangeably across the asset replacement domain. Examples of studies using the *time zero* approach include Hartman (2004) who studied the effect of variable asset utilization and stochastic demand; Regenier *et al.* (2004) who studied the effect of technological change on asset replacement; and Nair and Hopp (1992) who developed a model for equipment replacement due to technological obsolescence. Examples of studies using the second solution approach include Oakford *et al.* (1984) who developed a dynamic replacement economy decision model; Jardine (2001) who developed an optimized component replacement and maintenance model to improve system reliability; and Al-Chalabi *et al.* (2015) who developed a model to calculate the economic lifetime of drilling machines in the Swedish mining industry.

### 2.3.3 Financial Considerations

Gowthorpe (2011) states that there are two main accounting views. The first view is financial accounting, which is Generally Accepted Accounting Principles (GAAP) driven and based on historic costs. The second accounting view is managerial accounting which is not GAAP driven and is based on replacement costs and is driven by decision-making process and finding the best business solution. The Asset replacement studies have to take both accounting views into consideration to find the optimal solution. Therefore asset replacement studies have to take into consideration a broad array of financial factors. Only the most important financial considerations required for the development of the asset replacement decision-making framework in this study are discussed in this section. These factors include relevant economic and performance criteria, tax policies and depreciation structures, Life Cycle Costs (LCC) calculations, valuation methods, and stationary versus non-stationary costs to name but a few. These financial considerations are explored to provide a brief overview of the factors used in asset replacement literature. Regardless of the asset under consideration in the replacement process analysis, certain formats and extent of analysis should be considered and decided on in advance to the study including:

- Objectives and cost variables to be included in the analysis.
- If a sensitivity analysis should be performed. If it is required, what confidence limits should be applied.
- Data requirements of both the current and replacement asset, and the analysis structure.
- Method of accounting for the time value of money and the period of analysis.

The first group of financial considerations for discussion is the identification and use of the relevant economic and performance criteria when replacing an asset. Assets are replaced with the goal of improving organizational performance over a defined period of time. Many different performance metrics for the investment in new assets exist and only the most prominent are introduced here. It should be noted that the identification and use of performance metrics are heavily dependent on the asset under consideration and objectives of the study. The IAM (2015) and Gowthorpe (2011) suggest using the investment performance metrics illustrated in Table 2.4. The selection process of these performance metrics should be treated with caution, because of the advantages and disadvantages associated with each metric (Gowthorpe, 2011). The *discounted payback period* metric's best feature is that it includes the time value of money which incorporates risk into the decision process to some degree. However, this metric does not take into consideration possible cash flows after the payback period.

The *Net Present Value* metric indicates a direct measure of the financial contribution to the stakeholders involved but the size of this contribution is not measured relative to other capital investment options. The *Internal Rate of Return* metric assists in the sensitivity analysis of the changes in cost of capital but may not lead to an optimal decision where multiple investments are considered. *Return On Investment* relates the net profit to the resources required to produce it but does not provide a measure of divisional performance and may lead to dysfunctional decision-making if this metric is considered without the guidance of other performance metric. *Asset turnover* provides the revenue generated relative to its value which is an important ratio for physical assets, however there may be some difficulty in determining the accurate revenue generated associated with a specific asset and its value.

**Table 2.4:** Investment performance metrics

| **Performance metric** | **Definition** |
|---|---|
| Discounted payback period | Period of time to retrieve the funds expected with an investment or to reach a break-even point |
| Net Present Value (NPV) | The difference between the present value of cash inflows and the present value cash outflows |
| Internal Rate of Return (IRR) | Discount rate at which the NPV of an investment becomes zero |
| Return On Investment (ROI) | Measures the gain from an investment relative to the capital expenditure |
| Asset turnover | Organization revenue generated relative to the value of its assets |

The second group of interdependent financial considerations in asset replacement include tax considerations, the financial depreciation structure associated with an asset, and interest expenses. Physical assets are acquired with the primary purpose to generate revenue and are part of the expenses in an organization. This effects the tax considerations for profit-driven organizations because depreciation is accounted for as an expense and therefore affects tax liability and profitability. Furthermore, depreciation expenses of an asset are estimated based on managerial judgment while still complying to financial regulations. Organizations can use this aspect as a strategic initiative to their advantage depending on the organizational performance and economic environment (Gowthorpe, 2011). Therefore an organization that is going through a tough period may choose to overestimate the remaining operating life of an asset to spread out depreciation expenses and thus minimize impact on profits.

Assets are capital expenditures and are therefore subject to a depreciated method complying to Generally Accepted Accounting Principles (GAAP). The two primary GAAP depreciation methods used in industry are: (1) straight-line depreciation and (2) the reducing balance, also known as accelerated depreciation, method. The straight line depreciation method divides the depreciation expense of an asset into equal parts over the accounting period whereas the reducing balance method estimate the depreciation expense as a chosen percentage of its carrying value. Several studies have investigated the optimal choice of depreciation method for various circumstances including Kort *et al.* (2000), Hassler *et al.* (2008), and Kulp and Hartman (2011). In addition, acquiring an asset generates an interest expense. Interest costs occur because an asset ties up capital that an organization may choose to use for other purposes. Therefore if money is borrowed to acquire an asset, interest expenses should also be considered in the asset replacement process.

The third group of financial considerations include *Life Cycle Costing and valuation* and is critical in the asset replacement process. ISO (2008) states that the goal of a LCC analysis is to quantify all life cycle costs associated with an asset to be used in a decision-making or evaluation process. Rose *et al.* (2010) states that two cost concepts are of particular importance to asset replacement. The first concept is the current replacement cost, which is the full cost to replace the current asset in its operating environment. The second costing concept is the calculation of the total LCC associated with an asset. LCC are the total costs associated with an asset throughout its entire life cycle including the following phases: design, acquisition, operations, maintenance, disposal, and salvage value. Sterner (2002) states that many LCC methodologies are available for organizations to use but also have limitations. These limitations include:

- Amounts of data required for the decision-making process.
- Lack of universal methods and standards.
- LCC analyses perform better for certain industries.

Gluch and Baumann (2004) recognize that the practical usefulness of LCC analyses are often constrained by the fact that it converts all costs to a monetary unit. LCC calculations are further bound by the quality of data and the complexity of the economic environment that the organization finds itself in. In the case of limited data, Tan and Hartman (2010) proposed the use of a minimax approach, while Chang (2005) employed the use of fuzzy logic to allow for estimated definitions. Taking the time value of money and opportunity costs into consideration is another essential feature of a LCC analysis although these factors may also complicate the asset replacement process (Hartman and Murphy, 2006). The role of life cycle costing and valuation in a simplified AM plan is illustrated in Figure 2.12.

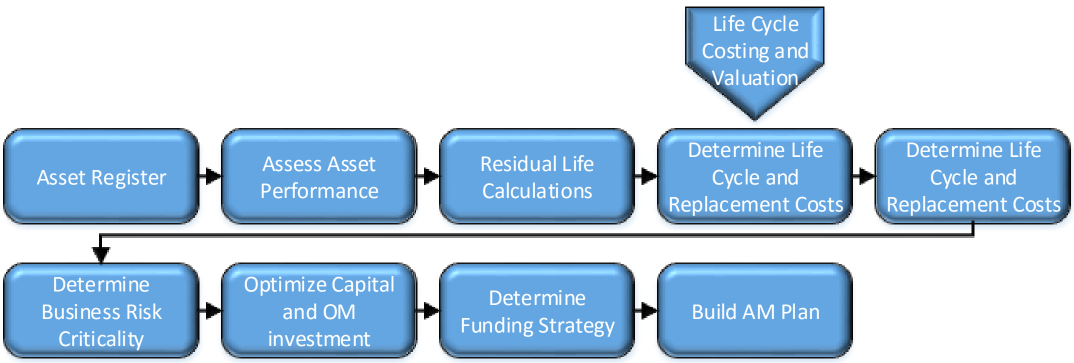



**Figure 2.12:** Contextualization of Life Cycle Costing in AM plan
Adapted from Rose *et al.* (2010)

An important aspect in determining the LCC of an asset is the scope of the calculations. Schade (2007) states that there are five main types of life cycle data. These data types include: (1) occupancy, (2) physical, (3) performance, (4) quality, and (5) cost. In contrast, Sterner (2002) approaches the calculation of LCC by stating that all applicable costs can be categorized into direct and indirect costs. Furthermore, Gu *et al.* (2008) and Ristimäki *et al.* (2013) proposed the combination of traditional LCC with environmental factors to be included in the decision-making process. Therefore, practice varies considerably between analysts as to what costs to include in the LCC calculation process ranging from typical life cycle costs to environmental and societal costs. AM practices typically involve more than just the typical LCC in the process of investigating the total organizational impact of an asset replacement decision.

Another important financial consideration in the asset replacement process is the *valuation* of assets. Rose *et al.* (2010) state the valuation process can be approached from two major perspectives including a macro view and micro view. Using the macro view enables the organization to consider an aggregation of assets with the primary goal of financial reporting. The macro view is also compatible with the financial accounting view which is GAAP driven. The second perspective focuses on individual assets with the main goal of assisting organizational decision-making. The micro view is compatible with the managerial accounting view which is not GAAP driven but rather business-case driven. Three important metrics considered in the valuation of assets are book value, replacement value or salvage value. The book value of an asset is determined using GAAP and is reflected on the balance sheet of the organization. The replacement value is the cost to replace the current asset with an identical new asset with the same operational capabilities. The salvage value of an asset is the value of an asset at the end of its useful life and is greatly affected by market conditions including the supply and demand of the particular type of asset. Furthermore, Rose *et al.* (2010) state that valuating assets are not straightforward and provide the following valuation myths:

- *Quantitative and thus correct.* The valuation of assets are also dependent on qualitative information such as the condition of equipment and market conditions.
- The valuation of assets is a *purely objective* process. Valuating assets is not a purely objective process. Managers need to make estimates on various aspects.
- Valuation of assets has *precision* and only the answer matters. Valuation includes numerous estimates and is therefore not precise.

- Valid over an *extended time*. Valuation of assets needs to be a continuous process in an AM plan.

The final group of financial considerations found in traditional asset replacement literature is *stationary and non-stationary costs*. A stationary asset replacement problem assumes that the asset cost structure and various financial rates remain constant for a period of time whereas a non-stationary problem allow these financial factors to change. Hartman and Murphy (2006) noted that under various stationary cost conditions, it is optimal to an asset at its economic life. Hritonenko and Yatsenko (2008) state that asset replacement problems subject to non-stationary costs are often very challenging as a result of the difficulty in estimating equipment costs and financial rates in volatile economic environments. In the asset replacement literature, non-stationary cost structures are often based on technology change in the market (Hartman and Tan, 2014). Furthermore, Fraser and Posey (1989) showed that replacing an asset under non-stationary costs at its economic life may be sub-optimal, showing that it may be more advantageous to replace before the economic life. However, it is also been proved that under various conditions that assets should be utilized beyond their economic life (Hritonenko and Yatsenko, 2007).

### 2.3.4 Uncertainty and Risk

Hartman and Tan (2014) noted that one of the most prominent obstacles in asset replacement problems is the incorporation of uncertainty, implicit or explicit, and risk. Knight (2012) describes risk and uncertainty as two ends of the same spectrum with risk describing cases of known probability and uncertainty cases of unknown probability. Risk is therefore measurable uncertainty. Stott (2012) states that there are three basic forms of risk and uncertainty including categorizing them as: (1) discrete, (2) continuous, and (3) complex with the following characteristics:

1. Based on uncertainty in discrete variables and defined by discrete probability distributions with no intermediate results or scenarios.

2. Based on uncertainty in continuous variables and defined by continuous probability distributions where intermediate results or scenarios are possible.

3. Combination of discrete and continuous uncertainty. The majority of cases found in industry falls in this category.

Studies conducted by Pulvino (1998) and Banerji (2008) used uncertainty to illustrate the changes is asset salvage value comparing it to market progress. Ierapetritou and Li (2009) illustrated that by not taking uncertainty into account in organizational costs may result in inaccurate budget development, production activities, and strategy execution. Moreover, Zambujal-Oliveira and Duque (2011) investigated how the uncertainty of cash flow influenced managerial decisions on asset replacement by also incorporating a dynamic asset salvage value. Uncertainty is therefore a significant factor that should be included in the asset replacement process. Miller and Park (2002) indicate typical approaches found in engineering applications that address economic uncertainty in decision-making processes.

- Determine the most influential source of uncertainty by conducting a sensitivity analysis.
- Determine the overall level of uncertainty by conducting a scenario analysis. Furthermore, reassess the random variables by conducting a Bayesian analysis.
- Determine the likelihood of possible outcomes by conducting a probabilistic analysis such as a Monte Carlo analysis.

It is noted that authors often aim to find a replacement policy to minimize life cycle costs or to maximize expected NPV when including uncertainty in asset replacement studies. Chang (2005) employed a fuzzy logic modeling approach to include uncertainty in the LCC calculation process. Other causes of uncertainty in asset replacement include technological change and horizon uncertainty which refers to the time that an asset is in operation. These causes of uncertainty are interdependent and affect decision-making significantly. Technological change affects the cost and efficiency considerations in the replacement decision. Technological change therefore refers to the rate at which OM cost and other asset related LCC are increasing or decreasing. Rogers and Hartman (2005) state that the majority of traditional asset replacement models assume that technology stay constant for the duration of the study period. Moreover, authors have studied the effects of both continuous and discontinuous technological change on asset replacement decisions.

Continuous technological change can be modeled as changing in a linear or exponential manner. Hartman and Tan (2014) state that exponential modeling of continuous technological change is mostly implemented in the literature. Furthermore, technological change can be modeled as either accelerating or decelerating. Rogers and Hartman (2005) noted that exponential technological change often lead to a decrease in replacement times. Considering technological change as a discrete process, Nair and Hopp (1992) investigated the problem where a technological breakthrough may occur at an uncertain time during the period of investigation. An asset replacement decision is highly dependent on the length of time that the specific asset is required by the organization. Tan and Hartman (2010) developed a model for the minimization of costs for a replacement problem with an uncertain horizon.

Risk has many industry-specific definitions. However, combining all generic aspects of risk definitions, it is found that risk is the potential of gaining or losing something and can be considered as the combination of the probability of an event occurring and the consequences of the event when it occurs. The major difference between risk and uncertainty is that risk is tangible. A distribution of outcomes may be known for risk, but not for uncertainty (Gifford, 2010). Tversky and Fox (1995) agree, adding that decision theory clearly differentiate between risk and uncertainty where probabilities for uncertain events are not assumed to be known. A common denominator found in all AM standards is the aspect of risk. AM focuses on improving risk management practices while balancing certain organizational drivers.

However, literature indicates that the incorporation of business risk in asset replacement is very limited, if existent. For example, the IAM states in their document, *Asset Management – an anatomy*, that risk should be included in all decision-making processes, yet no instructions are provided on *what* to include nor *how* to implement it. Moreover, PAS 55 states that any asset-intensive organization in the PAM domain should include risk in the entire life cycle management of a business-critical asset but do not provide any tools or methodologies to facilitate this risk implementation. In addition, the literature indicates that risk management with regard to asset reliability is well researched, but taking into consideration the effects of business risks on the timing of asset replacement is non-existent. Furthermore, the ISO 5500X standards state that risk should be incorporated in a SAMP to meet AM objectives but do not provide any details on how to do this. Incorporating the effects of business risks into asset replacement decisions may enable organizations to gain strategic advantage over competitors with the timing of asset replacements and capital investments. Business risk is therefore an integral part of any AM program, and more specifically asset replacement decisions, and is investigated in more detail in Section 2.4.

## 2.4 Business Risk

The concept of business risk management is a broad and complex subject. Business risk management encompasses a much broader scope of activities and methodologies than what is introduced in this section. This section emphasizes the concepts required to develop the framework for this study and is by no means an in-depth analysis, review or discussion of the business risk management field. These concepts include the definition of business risk as well as the management of risk in an AM context, and more specifically, the asset replacement decision-making process. The role of business risk management has changed dramatically in the past three decades. Managing risks in an organization has evolved from a single person investigating insurance options to an entire risk department monitoring, evaluating and controlling various types of risk including strategic, operational, and reputational risk. Every managerial decision has some degree of risk associated with it. Zhuang *et al.* (1998) state that these organizational business risks are generated from both internal and external sources. Steinherr (2000) states that the management of business risk is one the most influential innovations since the 20th century. In addition, McNeil *et al.* (2015) state that business risk management should be approached using a holistic view while considering the effects of all types of business risks on organizational performance and also their interdependency. This section provides a brief overview of the developments that resulted in modern business risk management practices.

Managing risks can be linked to the ancient world where financial cover was used for crop failure and cargo insurance was used to manage risk (McNeil *et al.*, 2015). While business risk management dates further back, it was only in the 20th century that risk management theory was introduced into practice. Sad-

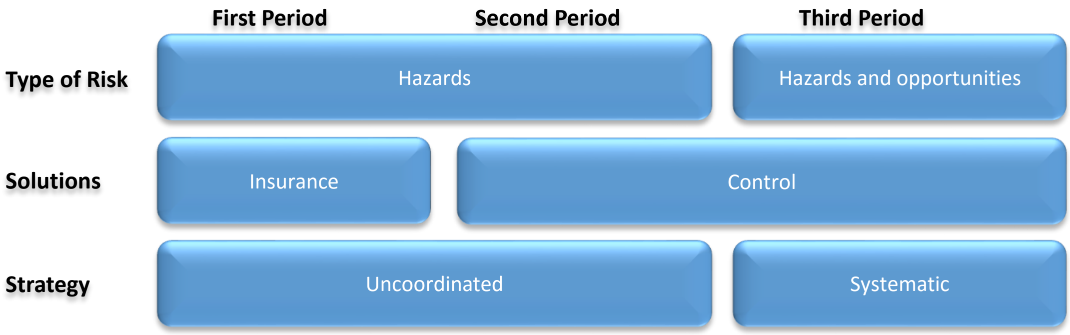



**Figure 2.13:** History of risk management
Adapted from Sadgrove (2015)

grove (2015) states that the first period of risk management, similar to the progression found in AM, before the 1970's was dominated by the reactive actions of organizations to events that had negative financial impacts. This risk management period was succeeded by the second era that saw organizations treat risk in a proactive manner spanning the period of 1970 - 1995. The last, and current, risk management period led to the development of international risks management standards such as the BSI published PAS 56, BS 31100, and the ISO 31000 standard. The three main periods of the development of risk management practices are illustrated in Figure 2.13. Equipped with a brief history of business risk management, Section 2.4.1 explores the various definitions of business risks found in the PAM domain. Section 2.4.2 investigates the important process of business risk management and Section 2.4.3 assesses the impact of business risks on AM, and more specifically, asset replacement.

### 2.4.1 Defining Business Risk

Crouhy *et al.* (2006) recognize that *business risk* is not a new type of risk by stating that this concept has been fundamental in all management practices for a prolonged period of time. Before investigating business risk management and the impacts of business risks on asset replacement decisions, it is important to define the term *business risk.* Doff (2008) states that defining business risk is a complex task as a result of the various contextual uses of it. Literature related to business risk therefore consists of many definitions. Nocco and Stulz (2006) refer to business risk as the aggregate of a number of risks. Furthermore, business risk is sometimes referred to as the residual risk after other types of risks are identified (Kuritzkes and Schuermann, 2006). Also, for strategic management, business risk is often defined as the risk of implementing a suboptimal strategy (Alexander, 2005). Moreover, business risk is sometimes referred to as *strategic*, *systematic*, and *enterprise* risk depending on the organizational context (Sadgrove, 2015). A selected few definitions of business risk are provided to develop a coherent definition to be used for this study. Doff (2004) defines business risk as:

> *"The risk of financial loss due to changes in the competitive environment, which refers to all relations of the organization with clients, competitors, regulators and other economic actors, or the extent to which the organization could timely adapt to these changes."*

Doff (2008) provides numerous definitions for business risk in the banking sector, of which many are similar and contain the same generic aspects. The following definition is an example found in the banking sector, as used by Deutsche Bank:

> *"Business risk describes the risk we assume due to potential changes in general business conditions, such as our market environment, client behavior and technological progress. This can affect our earnings if we fail to adjust quickly to these changing conditions"*

Similar definitions for business risk are found in the volatile mining environment. Hopwood *et al.* (2012) state that several factors influence organizational business risks including competition, economic climate, and governmental regulations. In addition, Doff (2008) notes the presence of a number of generic aspects in all accepted definitions for business risk which includes: (1) the competitive environment, (2) the adaptation capabilities of organizations to changes, and (3) financial consequences. The competitive environment refers to the external dynamic system in which an organization competes and functions (Bierly and Daly, 2007). Moreover, the adaptability of an organization is affected by the state of the external dynamic system. These aspects and the effects of them are illustrated in Figure 2.14.

It is clear from the aforementioned definitions found in literature that business risk is industry-specific and even organization-specific. In addition, authors defining business risk do not explicitly refer to the future implications of an action taken in the present. Considering the deficiencies of the preceding business risk definitions, a coherent and generic definition is formulated to be used throughout this study:


**Figure 2.14:** Main components of business risk
Adapted from Doff (2008)

> *"Business risk is a combination of the probability of an event taking place and the consequences associated with it that might lead to a financial change in an organization taking into consideration both external and internal factors. Furthermore, actions taken presently can lead to future events that might be considered as business risks."*

### 2.4.2 Business Risk Management

Risk management is often perceived as negative and considered as a "necessary evil" such as the maintenance of physical assets once was considered (Culp, 2002). However, risk and opportunity, also known as positive risk, are related subjects and the effective management of risk can be converted to a strategic advantage. A typical risk management process consists of identifying, assessing, and controlling risks that act as a threat to reliable organizational performance (Hopkin *et al.*, 2014). Business risks come in various different forms and is often difficult to identify and therefore manage. Sadgrove (2015) recognizes that there are six main types of business risk including the following:

1. Strategic: These risks require strategic planning and should be managed by senior management. Examples of strategic risk include organizational strategy execution, strategy forecast, and corporate governance.

2. Operational: Risks in this category are associated with the daily organizational activities that responsible for revenue generation and are typically found at lower levels of management. Examples in this category include physical asset reliability and faulty raw materials.

3. People: Risks in this category are caused by employees of the organization. People risk examples include labour relations and interpersonal relationships.

4. Technology: This risk has grown immensely in importance. Failing to manage technology risk may put the organization at serious risk. Examples include cyber-attacks and technological advances in the market.

5. Financial: This category includes both external and internal financial risks. External financial risk examples include exchange rate fluctuations and the global economic environment while internal financial risks may be excessive overheads or non-payments from debtors.

6. Compliance: This category of business risk is considered to one of the most important rising risks. Examples in this business risk category include financial reporting and safety standards compliance.

All organizations face exposure to liability losses. Therefore an important aspect of business risk management is for an organization to determine its *risk tolerance* and *risk appetite*. Risk tolerance refers to the boundaries of risk that excludes certain risks, that are considered to not pose a threat to long term strategic objectives as determined by an organization (Sadgrove, 2015). Risk tolerance therefore provides a clear context and framework to monitor certain risks and to ensure that organizational performance are not achieved at unacceptable high business risk since this is not sustainable in the long term. Nocco and Stulz (2006) state that the levels of risk tolerance are set for short term intervals e.g. annually with static levels and defined confidence limits. Additionally, Culp (2002) notes that risks can be tolerated if the probability of occurrence is low and its effects on the financial performance of the organization is minuscule.

An organization's risk appetite is dependent on the number of risks and also type of risk that it is willing to include in its risk management strategy. Risk appetite is therefore dependent on target levels set by senior management. These risk appetite levels provide guidance for a risk department in terms of mitigation actions and triggers for various risks. It is noted that risk tolerance levels affect risk appetite levels which are context-dependent on aspects such as the organizational performance and the economic environment (Nocco and Stulz, 2006). Furthermore, Hopkin *et al.* (2014) provide a consolidated version of principles of various international risk management standards by stating that an effective business risk management program in any type of organization shall be:

- Proportionate: The amount of resources attributed to the risks management program should be proportionate to risk levels in an organization.

- Aligned: All risk management strategies and practices must be aligned with the daily organizational activities and processes.
- Comprehensive: A risk management program should be systematic and structured which results in comprehensive management of risks.
- Embedded: A risk management program should be embedded within all organizational processes. A risk-aware culture will develop in an organization if it is embedded in all strategies and processes.
- Dynamic: In a volatile and constantly changing economic environment, it is critical that a risks management strategy is iterative and responsive to change.

In addition, Hopkin *et al.* (2014) state that this consolidated list provides the acronym Proportionate Aligned Comprehensive Embedded Dynamic (PACED). These principles provide a comprehensive overview that may act as the foundation of a successful and effective approach to business risk management.

#### 2.4.2.1 Why Implement Business Risk Management?

The main reason for implementing business risk management is to facilitate sustainable financial performance, therefore creating sustainable value. Nocco and Stulz (2006) state that effective business risk management creates shareholder value at both a macro and micro level. Macro benefits are realized at an organizational level where business risk management enables senior management to quantify and therefore measure the risk and performance trade-off for the organization as a whole. Micro benefits are observed at business unit levels where value is created through the risk-conscious behaviour of all employees at various levels of the organization. Hopkin *et al.* (2014) state that effective business risk management enables an organization to take more calculated strategic business risks resulting in an improved financial performance.

Moreover, other key benefits include: (1) an increase in operational efficiency, (2) effective project management, and (3) sustainable business strategy (Hopkin *et al.*, 2014). Also, Amit and Wernerfelt (1990) recognize that business risk management improves the management-shareholder relationship. In addition, Sadgrove (2015) notes that the benefits of business risk management are not easy to quantify but that it does enable organizations to avoid unnecessary costs, disruptions and unhappiness. Sadgrove (2015) identifies several reasons why implementing business risk management is advantageous for organizations including the following:

- Legal and safety regulations are getting more extensive and stringent. Formal risk assessment procedures for safety and finances are becoming ever increasingly part of legislation in several industries.
- Insurance is more expensive and difficult to get. Insurance premiums have risen dramatically in the last decade and pay-outs can be a lengthy process. Furthermore, insurance is a reactive strategy which may lead to dramatic financial losses in certain events.
- The public is getting more critical. The public expect high corporate standards with the emphasis on safety performance, labour relations, and financial fraud.
- Risk management practices force management to incorporate risk awareness throughout the organization resulting in a more professional and efficient working environment.

Hopkin *et al.* (2014) state that the implementation of effective business risk management processes can also help organizations to mitigate the impact of global economic crises or recessions by taking strategically sound actions. Equipped with the benefits and *why* to implement business risk management, the following sections explore certain aspects on *how* to implement business risks management strategies.

#### 2.4.2.2 Business Risk Management Frameworks

Business risk management frameworks are the base documents that all organizations use to implement risks management strategies. The British Standard (BS) states in its risk management standard, BS 31100, that a risk management framework is the following:

> *"It is a set of components that provide the foundations and organizational arrangements for designing, implementing, monitoring, reviewing and continually improving risk management processes throughout the organization" - BS (2008)*

All business risks management frameworks include a number of generic phases. According to Hopkin *et al.* (2014) and BS (2008), these generic phases in the business risk management process include: (1) the identification of risks, (2) assessment of risks, (3) response to risks, (4) reporting the applicable risks, and (5) reviewing risks. A common aspect among all risk management frameworks is the continuous improvement of the process. Many different variations of risk frameworks exist. An example of a more elaborate risk management framework is shown in Figure 2.15 as developed by Hopkin *et al.* (2014).

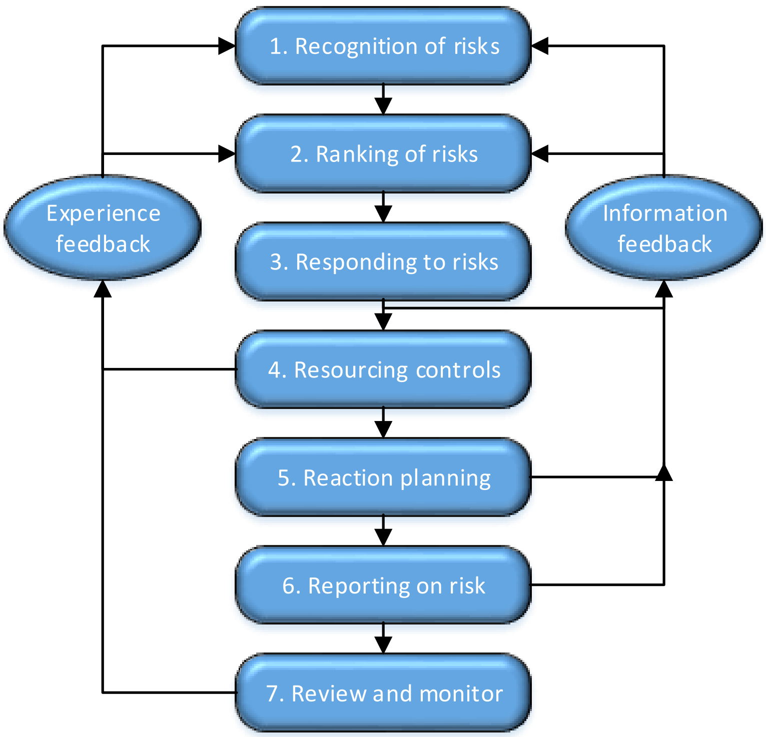



**Figure 2.15:** Typical business risk management framework
Adapted from Hopkin *et al.* (2014)

An overview of the main generic phases present in a business risk management framework is provided to facilitate the development of the framework in Chapter 3 to determine which business risks to include in the asset replacement analysis. The first phase in the risk management process is the *identification* of risks. Culp (2002) states that risk identification is the process of recognizing and, in some cases, detecting financial risks which threatens the normal operations of an organization. The risk identification phase is especially important to organizations with a stable risk profile. These organizations often overlook important risks (Sadgrove, 2015). In addition, it should be noted that the business risk types provided in Section 2.4.2 are used to identify these risks for both the short term and long term. A selected number of qualitative and quantitative risk identification and assessment techniques are illustrated in Table 2.5. The list of risks identified in this phase may all seem important, however, these risks need to be prioritized to focus the attention of senior management on the most important risks. The prioritization of these risks is accomplished by performing a risk assessment and measurement.

**Table 2.5:** Business risk identification and assessment tools

| | **Qualitative** | **Quantitative** |
|---|---|---|
| **Identification techniques** | Focus groups | Historical data |
| | Industry experts | Market research |
| | Employee questionnaires | Influence diagrams |
| **Assessment techniques** | Brainstorming | Scenario analysis |
| | SWOT analysis | Life cycle analysis |
| | Employee questionnaires | Pareto analysis |
| | Checklists | Monte Carlo analysis |
| | Risk matrix | Probabilistic measures |
| | Interaction matrices | Causal at-risk models |

In order to *assess* and *measure* business risks, certain assessment criteria must be developed specific to an organization (McNeil *et al.*, 2015). The primary objective of this phase in the business risk management process is to identify critical risks, measure these risks and prioritize it for the succeeding risks management process phases. Curtis and Carey (2012) state that the risk assessment phase may be completed in two distinct parts. The first part entails an initial screening of risks using qualitative methods and the second part includes using quantitative methods to assess the most important business risks. Measuring risks entail the quantification of organizational risk exposures in order to compare these risks to organization-defined risk tolerances (Culp, 2002). Quantifying these different risks is a critical aspect in the holistic business risks management program of an organization.

Quantifying risks provides an organization with a good measure of whether the correct risks are being managed and how much resources should be attributed to the management of certain risks. Discussions of detailed techniques on the measurement of risks are beyond the scope of this research and interested readers are referred to the following sources in literature including Culp (2002), Nocco and Stulz (2006), Doff (2008), McNeil *et al.* (2015), Sadgrove (2015). Furthermore, business risks should not be considered in isolation. Curtis and Carey (2012) recognized that organizations have, in recent times, realized the importance of analyzing the interaction of business risks. In addition, Curtis and Carey (2012) state that business risks perceived as insignificant in isolation, may develop into a critical-risk when interacting with other business risks. Therefore, organizations are increasingly moving towards an holistic and integrative approach when managing risks using several techniques such as those illustrated in Table 2.5. Practical examples of the interaction of business risks are illustrated in Section 2.4.3. Hopkin *et al.* (2014) state that prioritizing risks is the process of determining an organization's risk management priorities. Furthermore, Curtis and Carey (2012) state that risk should not only be viewed in terms of it economic impact and likelihood of occurrence, but also various other aspects such as: (1) organizational vulnerability, (2) impact on reputation, (3) speed of onset of risk, (4) health and safety impact, and (5) environmental impact. Having prioritized risks, an organization needs to adopt a risk response strategy.

Using the risks that were identified, assessed, and prioritized in the previous risks management phases, a course of action needs to be followed to manage these risks. Starting with the most important and critical risks, a *response* needs to be adopted for each risk. Sadgrove (2015) state that there are four risk responses that can be implemented to manage risks including: (1) avoiding, (2) sharing, (3) accepting, and (4) controlling risks. Many different synonymic uses exist for the treatment or management of risks such as the terms retain, reduce, transfer, and accept to name but a few (Sadgrove, 2015). The type of response for each risk is dependent on the risk severity and probability of occurrence. The four typical risk responses are illustrated in Figure 2.16.

Avoiding a risk implies that an organization should do everything in its power not to accept it. An example in the PAM domain of such a risk may be an aging business-critical asset with very little residual life left. Sharing a risk means that

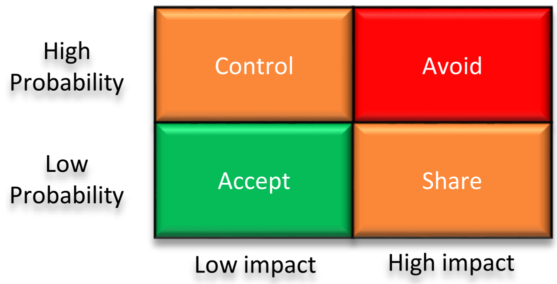



**Figure 2.16:** Risk management responses
Adapted from Sadgrove (2015)

the organization adopts a strategy to transfer the risk such as using methods such as sub-contracting and outsourcing. Accepting a risk applies only to risks that have low impacts and low probabilities of occurring. Risks in this category often seem trivial, but organizations need to apply the correct strategy in order to not waste time and resources. The last risk response category includes controlling risks and it the most populated category. These risks requires active management and to reduce both their impacts and probability of occurring. Sadgrove (2015) states that these risks are controlled by implementing a predefined process, practice or policy and using methods that can be classified as preventative, directive or detective. The succeeding phase in the risk management process is the reporting and documenting of risks.

Risk *reporting and monitoring* is an integral part of the continuous improvement process that is risk management. An organization's risk structure is used a the foundation to communicate, report and monitor risk performance as well as risk issues and events. This phase also includes the documentation of various risk management aspects. Hopkin *et al.* (2014) recognize that there are four categories that need to be addressed in the risk documentation phase including:

- Administrative aspects of the risk management program including the roles and responsibilities of employees in the risk management process.
- Risk improvement and response plans. A critical document in this category is the development of a risk register.
- Risk event reports and recommendations of past and possible future events. Typical documents in this category include continuity plans and simulation results.

- Performance and certification reports including operational and strategic management reports as well as certified risks reports to stakeholders.

Manuj and Mentzer (2008) state that all documentation related to business risk management policies and procedures should include and describe the risk culture of an organization. Effective risk reporting and communication is a pre-requisite for monitoring risks. Risks have to be constantly monitored against certain risk performance metrics, or tolerance levels, to ensure valuable feedback for the risk management process (Manuj and Mentzer, 2008). The last phase in the risks management cycle is the *review* of risks. Reviewing a risk management process enables an organization to update its risk architecture and to improve its risk strategy. This is achieved by conducting audits, both internal and external. Culp (2002) states that a review of the risk management process is critical for continuous improvement and without it an organization would not be able to determine if its risk management process is efficient or not. Equipped with an overview of *why* and *how* to implement business risk management, Section 2.4.3 explores its presence in the PAM domain and its effect on asset replacement decision-making.

### 2.4.3 Business Risk in Asset Management

This section explores the current role of business risk management and integration in AM standards and organizations in the PAM domain. Moreover, examples are introduced to illustrate the effect of business risks on organizational performance and decision-making. ISO (2014) states in its AM standard, ISO 55001, that risk management is an important aspect that should be addressed in the establishment of a SAMP. The IAM (2015) agrees, adding that the time frame of an SAMP could extend beyond an organization's planning time frame, therefore taking the whole life cycle of an asset into consideration. It is noted that all the AM standards introduced in Section 2.2.2 make reference to the incorporation of risks in AM programs, but this is discussed in a vague manner that only focus on the operating and maintenance life cycle phases of a physical asset.

Risk management in AM literature also emphasizes response planning for emergency situations such as unexpected asset failures, again focusing on the effects in the operating life cycle phase and not the acquisition and disposal life cycle phases. Guidelines for the application of ISO 55001, as provided in

ISO 55002, do not state *how* to integrate business risks in asset management decision-making processes. The IAM (2015) does make reference in the AM standard, AM – an anatomy, to the stakeholders that can have an impact on the organizational performance due to their interest in physical assets. These stakeholders include the customer, government, local community, employees, and labour organizations. However, no information is provided on how to incorporate the possible positive and negative effects that these stakeholders can have on organizational performance and AM decision-making.

Business risk identification and assessment is often found in industry where numerous reports are developed by large consulting firms such as KPMG, Ernst & Young, and Deloitte focusing on various industries in the PAM domain. The PAM domain include organizations from the mining, aviation, manufacturing, process, and automotive industries. Furthermore, these industry risk reports often include both qualitative and quantitative business risks that organizations face. Qualitative business risks, that are very important but difficult to quantify, are often omitted in risks analyses. From these industry reports, it is evident that the business risks an organization is exposed to is dependent on various factors including: (1) organizational circumstances, (2) business sector, (3) industry, and (4) the country that the organization is located in.

Invaluable information can be found from these reports, often providing insight on certain trends that are developing or subsiding. Incorporating these business risk insights on business risks into an organization's AM plan, and more specifically asset replacement decisions, may lead to an increase in successful decisions and better planning capabilities. Strategic advantages can also be realized by incorporating business risks into asset replacement decisions by increasing the accuracy of timing in optimal asset replacement and therefore capital investment decisions. In addition, a sensitivity analysis analyzing the effects on organizational performance of controlling business risks in a favorable manner could also yield economic benefits for an organization. Table 2.6 illustrates the top business risks encountered in the mining industry for the period 2014 to 2016 as identified by three major consulting organizations [2]. These reports are developed annually by a number of consulting firms resulting in an abundance of

[2]See industry reports from Hodgkinson (2014), Zweig *et al.* (2015), and Hopwood and Chopra (2015)

available information of the business risks encountered in various business sectors. Literature on these industry reports indicate consistency between various consulting organizations.

**Table 2.6:** Top business risks for mining industry

| Rank | Deloitte 2016 | Ernst & Young 2015 | KPMG 2014 |
|---|---|---|---|
| 1 | Productivity improvement | Switch to growth | Commodity price volatility |
| 2 | Lack of innovation | Productivity improvement | Operating costs |
| 3 | Global economy | Access to capital | Capital costs |
| 4 | Commodity price volatility | Resource nationalism | Resource nationalism |
| 5 | Energy costs | Social license to operate | Liquidity risk |
| 6 | Stakeholder engagement | Price volatility | Permitting risk |
| 7 | Access to capital | Capital projects | Community relations |
| 8 | Social license to operate | Access to energy | Environmental risk |
| 9 | Capital projects | Cyber-security | Capital allocation |
| 10 | Health and safety | Lack of innovation | Life of mine planning |

A business risk in the mining industry, shown in Table 2.6, is used as an example to illustrate the importance and effects of incorporating business risks in decision-making processes. The decline in productivity in the mining industry has been a prominent business risk in the last eight years. With reference to Section 2.4.2, the decline in productivity would be part of the operational business risk category. Mitchell *et al.* (2014) state that the main reason behind the decline in overall productivity is the fact that mines focused on volume output at an unsustainable high commodity price environment. Figure 2.17 illustrates the gradual decline in productivity and the major increase in operating expenditure in the mining industry for the period 2004 to 2012.

Productivity has decline by nearly 30% while operating expenses have increased by 240% from 2004 to 2012. According to Mitchell *et al.* (2014), several other factors contributed to the decline in overall productivity including inexperienced labour teams due to a high personnel turnover and aging workforce. In addition, Mitchell and Steen (2014) recognize other important factors contributing to the decline in productivity including a lack of innovation, labour relations, and suboptimal capital investment decisions. The interdependency between the decline in productivity and other business risks is evident from Figure 2.17.

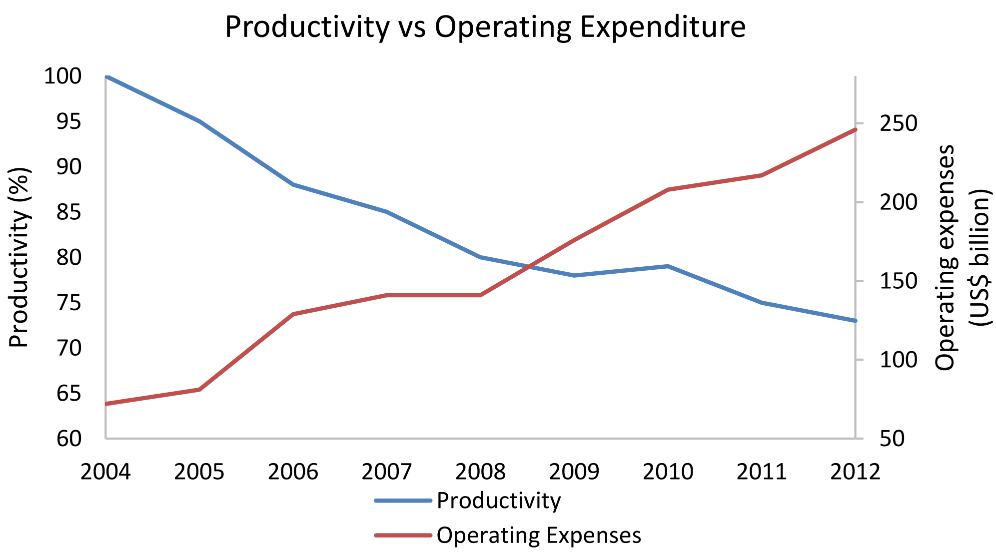



**Figure 2.17:** Impact of business risk in the mining industry
Adapted from Mitchell *et al.* (2014)

Applying the trends from this business risk example as part of an asset replacement process, it might prompt senior management to reconsider investing in new equipment. For example, considering an expensive, business-critical asset that is nearing its replacement time, management may choose to accelerate this investment to curb operating expenses and to increase operating productivity to increase profitability in the medium or long term. However, combining a number of business risks and their trends may be more accurate to improve asset replacement decisions rather than focusing on the effects of a single business risk. The next section explores various techniques to model the decision-making process that allows an analyst to study the effects of business risks on the asset replacement process.

## 2.5 Modeling Techniques

Virtually all managerial decisions require some kind of forecast. To forecast the effects of a decision, a certain modeling technique needs to be employed. According to Quarteroni (2009), mathematical modeling is employed to describe different aspects of the real word, how it interacts, and the dynamics involved by using mathematical principles. In addition, Kulakowski *et al.* (2007) state that modeling techniques are used to illustrate and explain the behavior of an actual system, generate forecasts on certain events and test various ideas. Furthermore, mathematical modeling is often seen as an additional pillar to engineering and science (Quarteroni, 2009). Moreover, Aris (2012) states that modeling is the correspondence of mathematical concepts and another entity which may include physical, biological, conceptual or social aspects. Modeling enables analysts to explore and investigate solutions to a real-world problem in a short time period, resulting in an increase in innovation cycle times. Modeling enables organizations to save time and money in the development of products or conceptual aspects. A typical methodological framework to model an actual system is illustrated in 2.18.

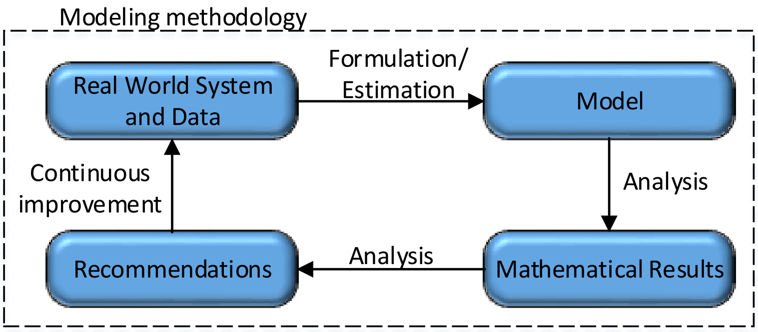



**Figure 2.18:** A methodological framework for modeling a system
Adapted from Carson and Cobelli (2013)

Miller (2014) states that selecting the correct modeling technique is of critical importance to accurately model and analyze a real-world system. The selection of a modeling technique is dependent on many factors including: (1) the context of the study, (2) availability and relevance of qualitative and quantitative data, (3) desired accuracy, and (4) the costs and computational requirements. When selecting a modeling technique, a trade-off needs to be made between interdependent factors including uncertainty, complexity, and validity (Kulakowski *et al.*, 2007). For example, when allowance is made for uncertainty in the results obtained from the model, it is generally found that model complexity decreases and its validity increases. However, the challenge is to find the optimal level of these three factors.

This section aims to review, evaluate, and compare applicable modeling techniques to incorporate business risk in the asset replacement process. More specifically, the modeling technique selected needs to incorporate the ability to predict certain features into the future, find an optimal solution, and integrate actions taken by the analyst into the decision-making process. Therefore, an optimal asset replacement decision should be obtained by focusing on traditional asset replacement factors such as rising OM costs, financial depreciation, performance degradation, while also incorporating the effects of business risks. Several modeling techniques, integrating quantitative and qualitative aspects, are covered and their limits and applicability are investigated. Each modeling technique is contextualized within the asset replacement process by conceptually applying it to solve a typical hypothetical asset replacement problem. The replacement problem is solved conceptually as a result of the data requirements, costs, and time associated with the development of a complete model. This problem entails the determination of the optimal time to replace an asset that is in operation. A replacement decision should be generated on an annual basis for five years into the future and should indicate whether the analyst should (1) keep and repair the asset, or (2) replace the asset with a new asset that is similar in performance and costs. In addition, the modeling technique should integrate traditional asset replacement factors, business risks, and an objective function to maximize the total expected discounted revenue for this finite time period.

The modeling techniques covered in this section were selected based on (1) its ability to meet all previously discussed criteria, (2) implementation in asset replacement literature, and (3) the two previous observations were used to select a single modeling technique from each of the main modeling classes including causal, time-series, artificial intelligence, and hybrid modeling methods. Pure qualitative modeling techniques were not considered since it does not adhere to the aforementioned criteria. The modeling techniques covered in this section include the Markov Decision Process (MDP), Artificial Neural Networks (ANN), Fuzzy Logic, Monte Carlo Analysis, and Bayesian Networks. Lastly, a comparison is made between these modeling techniques to select the modeling technique to be used in the asset replacement decision framework developed in Chapter 3. This is achieved by developing a scoring matrix to assess the capabilities of each modeling technique in relation to the requirements of the decision framework for this study.

### 2.5.1 Markov Decision Process (MDP)

The Markov Decision Process (MDP) is a functional and powerful modeling technique and was popularized by the work of Bellman (1957) and Howard (1960). Givan and Parr (2001) state that the MDP provides a mathematical framework for modeling decision-making systems where the analyst are partly in control of the outcomes of the system. Schaefer *et al.* (2005) and Puterman (2014) agree, adding that the MDP is a suitable modeling technique for solving a multistage planning system where stochastic and dynamic decision-making under uncertainty is involved. An MDP is an extension of Markov chains which is a sequence of events for which the probability of the system entering a certain state only depends on the current and future events (Gilks, 2005). The additions of an MDP compared to a Markov chain is that the analyst can take actions and incorporate rewards for these actions. The MDP therefore satisfies the Markov property, meaning that the conditional probability distribution of future system states only depends on the present state, and not the sequence of events that preceded it. According to Shimkin (2011) an MDP is popular for problems with the following characteristics:

- Systems with deterministic or stochastic characteristics.
- A discrete or continuous time variable is used in the modeling process.
- Problems with a finite or infinite horizon decision.
- The systems has a finite or infinite number of states and actions.
- An additive, total discounted or average expected reward cost structure is applicable to the problem.

The MDP is used in a wide range of optimization and decision-making problems and is often solved using a dynamic programming or reinforcement learning approach (Bertsekas, 2011). White (1993) conducted a survey to illustrate the various applications of a MDP which included robotics, manufacturing, inventory control, risk management, and the inspection and repair of equipment. More recently, applications for the MDP has been focused on physical asset replacement and maintenance applications as illustrated in the research of Chen and Trivedi (2005), Amari *et al.* (2006), and Hartman and Tan (2014). Moreover, the MDP is an important modeling technique in medical applications (Magni *et al.*, 2000; Alagoz *et al.*, 2004; Schaefer *et al.*, 2005). An overview of a finite horizon, discrete MDP is provided here since it is the main focus of this research. An MDP can generally be described using five components including [$T$, $S$, $A_s$, $p_t(s'|s_t,a)$, $r_t(s_t,a)$]. An overview of these components is provided.

1. Decision epoch, $T$, is a set of points in time at which actions are taken (days, months or years).

2. State space, $S$, is a finite set of all possible values and attributes describing the dynamics of the system.

3. Action space, $A_s$, describes the actions or choices available when making decisions for any state $s \in S$.

4. Transition probabilities, $p_t(s'|s_t,a)$, describing the transition probability by which the system state is $s'$ at the next decision epoch $(t+1)$ when the system is in state $s_t$ and action $a$ is taken at decision epoch $t$.

5. Reward function, $r_t(s_t,a)$, is the immediate reward received or penalty incurred as a result of taking action $a$ at state $s_t$ at decision epoch $t$.

When considering a finite horizon where the time value of money is significant, all future rewards must be discounted by the factor $\gamma$. Figure 2.19 illustrates a typical graphical representation of an MDP with three system states and two actions. For example, $p_t(s_2|s_1,a_1) = 0.4$ means that if the system is in state $s_1$ at time $t$ and action $a_1$ is taken, the probability is 40% that the system will be in state $s_2$ at the next decision epoch $t+1$.

The actions in an MDP available to the analyst can be deterministic or stochastic in nature. Furthermore, an MDP assumes full observability which means that a new state resulting from executing an action will be known to the system. Solutions for an MDP is in the form of a policy, $\pi$, which is a sequence of actions at every decision epoch. Solutions for a finite-horizon MDP is obtained by backwards induction, whereas infinite-horizon solutions are obtained through value iteration, policy iteration, and linear programming (Puterman, 2014). In addition, Puterman (2014) provides the set of equations required to solve an MDP as illustrated in Equations 4.4.3 through 2.5.5.

$$V_N^*(s_N) = \max_{a\in A_s} \left\{ r_N(s_N,a) \right\} \text{ for all } s_N \in S \tag{2.5.1}$$

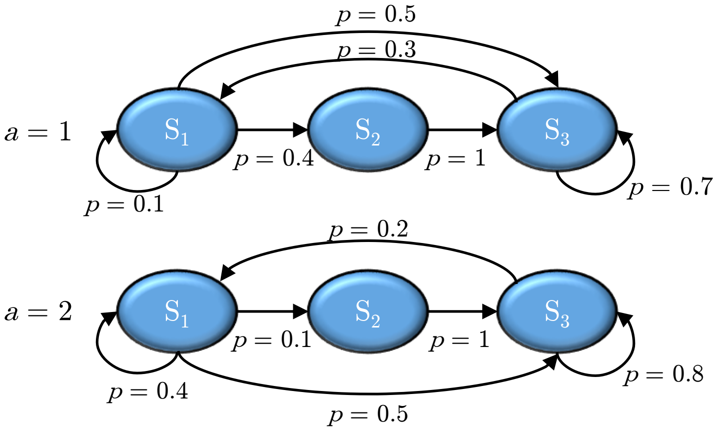



**Figure 2.19:** A typical state transition diagram
Adapted from Shimkin (2011)

$$V_t^*(s_t) = \max_{a\in A_s} \left\{ r_t(s_t,a) + \frac{\sum_{s'\in S} p_t(s'|s_t,a) V_{t+1}^*(s')}{(1+\gamma)} \right\}, \quad t = 1,2,...,N-1 \text{ and } s_t \in S \tag{2.5.2}$$

$$a_{s_t,t}^* \in \arg\max_{a\in A_s} \left\{ r_t(s_t,a) + \frac{\sum_{s'\in S} p_t(s'|s_t,a) V_{t+1}^*(s')}{(1+\gamma)} \right\}, \quad t = 1,2,...,N-1 \tag{2.5.3}$$

where,

$V_N^*(s_N)$ = Terminal rewards obtained at the last decision epoch

$V_t^*(s_t)$ = Maximum expected rewards following the optimal policy

$a_{s_t,t}^*$ = Optimal action that maximizes the total expected reward for state $s$ and time $t$

A state transition probability matrix is developed for all actions and should adhere to the following criteria:

$$0 \le p_t(s'|s_t,a) \le 1 \text{ for } t,...,N-1 \tag{2.5.4}$$

and

$$\sum_{s'\in S} p_t(s'|s_t,a) = 1 \text{ for all } s_t \in S, \ a \in A_s \tag{2.5.5}$$

Asset replacement decisions have to be made sequentially in an uncertain and volatile environment with the primary objective to optimize a specified performance criterion. Schaefer *et al.* (2005) state that the MDP is an appropriate modeling technique for such decision-making processes. Furthermore, Tijms (2003) recognizes other advantages of using an MDP include its flexibility and the fact that an optimal solution can be obtained. However, Schaefer *et al.* (2005) state that there are also drawbacks of using an MDP. These disadvantages include size limitations and data requirements. The computational efforts and data requirements increase dramatically when expanding the size of a system.

Conceptually applying the MDP to the hypothetical asset replacement problem discussed in Section 2.5, the following observations are made. A dynamic programming approach, using a backward induction algorithm that incorporates Equations 4.4.3 to 2.5.5 can be followed to provide an optimal solution to this problem. Firstly, the decision epoch, $T$, would be one year. The state space, $S$, describing the dynamics of the system would include information such as the traditional asset replacement factors and business risks in a discretized format using the same unit of measurement which is the impact on organizational revenue for a specified system state. Next, the action space, $A_s$, would include the replacement decisions in an integer form which describes the replacement action such as 1 to keep the asset or 2 to replace the asset. A corresponding rewards matrix is developed illustrating the revenue effects of taking a certain replacement action for a specified system state. The transition probabilities would be obtained from asset data, expert interviews and industry reports describing various aspects such as performance degradation and business risk evolution. A transition probability matrix, $n \times n$, would be generated from this information with $n$ being the total number of system states. The number of system states depends on the resolution of the problem and is influenced by the number of asset related characteristics and business risks included. The total expected discounted revenue is obtained by implementing a maximization function in the dynamic programming code. The output of the program would be a $n \times n$ matrix indicating the optimal replacement action for each system state over the five years. A corresponding matrix would indicate the total expected discounted revenue. The MDP modeling approach is therefore capable of adhering to all of the specified requirements for the framework in this study.

### 2.5.2 Artificial Neural Networks (ANN)

Dayhoff and DeLeo (2001) and Abraham (2005) state that Artificial Neural Networks (ANN) are modeling techniques used to perform multi-factorial analyses. ANN have emerged as a result of mathematical models being developed simulating biological nervous systems such as the human brain (Abraham, 2005). Additionally, Abraham (2005) recognizes that the human brain has tremendous computational capability for various tasks including parallel information processing, adaptive, and learning capabilities. ANN models may contain multiple layers of computing nodes operating as non-linear summing devices (Elloumi *et al.*, 2015). Focusing on the mathematical model of an ANN, every model has three primary attributes including multiplication, summation, and activation. Connection weights regulate the input data in a similar fashion to the effects of synapses in a brain therefore multiplying input variables with individual weights. The weighted sum of all input signals are then activated and transformed by the transfer functions, analogous to a neuron impulse. In addition, non-linearity of neurons are represented by transfer functions in an ANN model. Krenker *et al.* (2011) state that optimization of an artificial neuron is accomplished by calibrating the weights for a specific learning algorithm.

Dayhoff and DeLeo (2001) and Larochelle *et al.* (2009) state that the successful training of ANN may enable an analyst to perform various tasks including: (1) predict an accurate output value, (2) classify an object for recognition purposes, (3) approximate a function, and (4) complete an established pattern. Furthermore, Zhou *et al.* (2002) and Yegnanarayana (2009) identify four central characteristics of ANN as listed below:

- The ability to learn by example using historical data to train the ANN.
- The ability to produce sensible outputs when presented with new data if training of the original data is successful.
- Robustness to noisy data, often occurring in real-life events and applications.
- ANN performance do not deteriorate significantly if network connections become defective or if outliers are present in the data set.

Applications of ANN are found in various industries. Dayhoff and DeLeo (2001) and (Elloumi *et al.*, 2015) present a few of these applications including financial decision support, physical asset residual life estimations, military target recognition, detection of manufacturing defects, machine monitoring, machine diagnosis, robotics, and control systems. ANN can have a number of different network architectures. Yegnanarayana (2009) and Elloumi *et al.* (2015) state that the most popular and widely used ANN architecture is a Multi-Layered Perceptron (MLP) network which can be trained by the process of back-propagation. ANN using back-propagation minimize the output error by adjusting and calibrating the weights in the network. A graphical representation of the structure of ANN is illustrated in Figure 2.20 and is represented by three layers including the input, hidden, and output layers. The input layer is where the available data is fed into the ANN. The hidden layer is where all the data is processed and calculated. The learned behaviour of the input data is also facilitated in the hidden layer by exposing it to weighted values. Lastly, the output layer is where the results for ANN models are obtained.

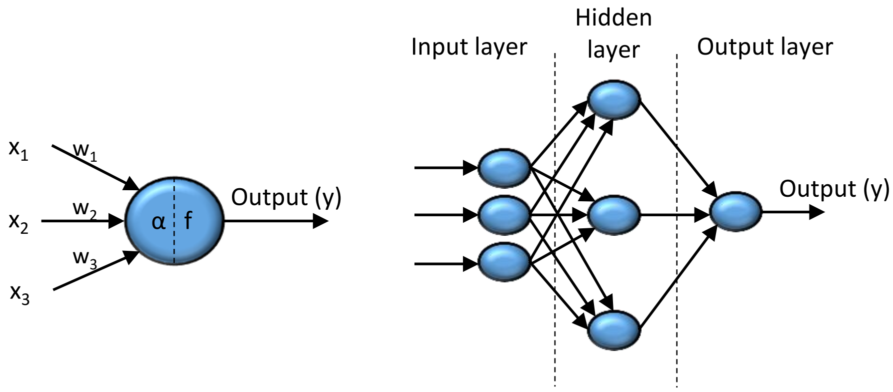



**Figure 2.20:** Architecture of a single artificial neuron and a multi-layered ANN
Adapted from Abraham (2005)

The output of ANN, $y(t)$, is a linear combination of the hidden layer neurons, $\alpha_i$, with an offset, $w_0$, which is expressed mathematically in Equation 2.5.6 (Krenker *et al.*, 2011). The activation function used in ANN scales the output of a node to a value between -1 and 1. There are four major types of activation functions including: (1) hard limiter, (2) threshold, (3) hyperbolic tangent function, and (4) sigmoid. Abraham (2005), Yegnanarayana (2009), and Elloumi *et al.* (2015) unanimously agree that the sigmoid activation function is the most popular in literature as a result of its differentiability.

$$y(t) = f\left(\sum_{i=0}^{m} w_i(t)x_i(t) + b\right) \tag{2.5.6}$$

where,

| | | |
|---|---|---|
| $x_i(t)$ | = | Input data variable in discrete time $t$ |
| $w_i(t)$ | = | Weight value in discrete time $t$ |
| $b$ | = | Bias for ANN model |
| $f$ | = | Transfer function |
| $y(t)$ | = | Output value for ANN in discrete time $t$ |

Applications for ANN in asset replacement domain can be found in the estimation of maintenance costs, macro-economic data, and the residual operating life of a physical asset. Tu (1996) and Krenker *et al.* (2011) identify several advantages and disadvantages associated with ANN. Advantages include the fact that multi-variate analyses can be conducted using ANN models. Furthermore, it is widely acknowledged that less formal statistical training is required, complex non-linear systems can be modeled, and there are many training and optimization algorithms available. However, there are also disadvantages associated with ANN. Results obtained from ANN models are solely dependent on how well the model is trained and the quantity and quality of historical data. Therefore in a volatile environment, ANN tend to provide conservative results. ANN models are also subject to over-fitting which results in greater computation requirements.

Conceptually applying ANN modeling to the hypothetical asset replacement problem discussed in Section 2.5, the following observations are made. An ANN with a MLP network configuration can be used to forecast the objective function which is to maximize the total expected discounted revenue associated with a single asset. The inputs to the ANN model $x_i(t)$ would be traditional asset replacement factors such as performance degradation, financial depreciation, and OM costs. Other input variables include business risk information and the decision to keep or replace the asset with all variables corresponding to the same time-frame. Furthermore, the resolution, referring to the size of the time steps, of these input variables can be chosen as annually or more frequent to increase accuracy. A distinct advantage of ANN models is that all variables do not have to possess the same units. All data on input variables must assume a value between zero and one. The minimum-maximum normalization method can be implemented to transform the input data. A set of input and output data will be used to train the network and determine the optimal connection weights $w_i(t)$. The back-propagation method using a gradient descent optimization algorithm can be implemented to minimize the squared error between the model output and the actual output values.

The forecast horizon of five years can be used to terminate the back propagation process. A sigmoid activation function can be used to define the output of a single node. The trained model is then used to forecast five years into the future. Output values must be transformed back to a predicted value by an inverting process known as de-normalization. Since the output of ANN models will not explicitly indicate the optimal asset replacement choice, the output of the model $y(t)$ can be classified into ordered classes in order to measure the success of an action taken for certain system conditions which will be evident in the revenue $y(t)$. Once the model building, training, and pruning is completed, a sensitivity analysis can be conducted to measure the relative influence that each business risk has on the expected revenue associated with a single asset. A distinct flaw in using the ANN modeling approach is the inability to incorporate transition probabilities of business risks which would unequivocally be valuable to modeling the effect of business risks on the asset replacement process.

### 2.5.3 Fuzzy Logic

The concept of "fuzzy sets" were developed by Zadeh (1965) to take various concepts which are vague and imprecise into consideration as used in human reasoning. Fuzzy sets were used to describe concepts such as length, age, and distance. Zadeh later developed "Fuzzy Logic" as an extension to Boolean Logic to account for the imprecision of natural language quantities and statements. Examples of concepts used in Fuzzy Logic include quantities such as *many* and *numerous* whereas statements included *not likely* and *probably*. Singhala *et al.* (2014) recognize that a statement can be both true or false and also can be neither true nor false in Fuzzy Logic. Furthermore, Intan and Mukaidono (2002) state that Fuzzy Logic excels when defining, formalizing and modeling a complicated system. In addition, Ross (2010) states that the more uncertainty in a system, the less precise the understanding of the system will be into the future. This uncertainty and vagueness have been termed *fuzziness*.

> "It is essential to realize that Fuzzy Logic uses truth degrees as a mathematical model of the vagueness phenomenon while probability is a mathematical model of ignorance." - Bist (2014)

Jarrett and Plouffe (2011) conclude that the connection between classical probability theory and Fuzzy Logic is weak. Moreover, Lee *et al.* (2006) and Jarrett and Plouffe (2011) state that Fuzzy Logic outperforms classical mathematical and statistical modeling techniques for many applications involving real-world data. Lowen and Roubens (2012) and Ross (2010) recognize several central attributes of Fuzzy Logic including:

- Fuzzy sets do not indicate some form of classical probability theory.
- The degree to which a variable belongs to a set is known as the *grade of membership*. Membership grades are not the same as probabilities on a finite universal set. Therefore membership grades are not required to sum to one for an event.
- Fuzzy set theory differs from conventional set theory, because it allows each element of a given set to belong to that set to some degree.
- Fuzzy Logic allows an analyst to incorporate both quantitative and qualitative concepts.

The difference between Fuzzy Logic and classical statistic-based logic is evident when looking at the definitions of a fuzzy set and a crisp (classical) set. Elements in a fuzzy set assume truth values between 0 and 1, while elements in a crisp set assume value of 0 or 1. Dernoncourt (2011) states that Fuzzy Logic is based on fuzzy set theory, which is a generalization of the classical set theory. An example to illustrate the difference. The task is to represent the phrase "Mary is old" using a fuzzy set and a crisp set and assume Mary is 80 years old. Mary may be assigned a 90% truth value. Therefore, using the probability approach, there is a 90% chance that Mary is part of the old people group. Using a fuzzy set approach, Mary's degree of membership within the set of old people is 90%. Lowen and Roubens (2012) state that the difference between crisp and fuzzy sets is established by the introduction of a membership function. Membership functions may take the form of various different mathematical functions including: (1) S-shaped, (2) trapezoidal, (3) Gaussian distributions, (4) exponential, (5) triangular, and (6) cosine to name but a few.

Figure 2.21 illustrate three examples of a membership function for the temperature of an automobile engine for the interval of 0°C to 160°C. Three functions define the degree of membership of any given engine temperature in the sets of

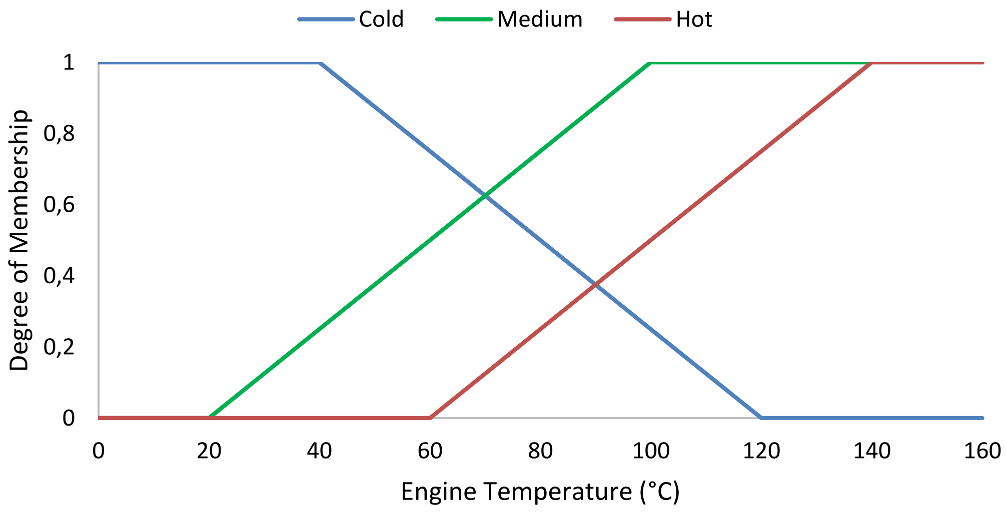



**Figure 2.21:** Membership functions for the concepts cold, medium and hot

cold, medium, and hot temperatures. For example, if the engine is at a temperature of 40°C, the degree of membership to the set of cold is 1, 0.25 for the set of medium, and 0 for the set of hot. If the engine is at a temperature of 100°C, the degree of membership to the set of cold is 0.25, 1 for the set of medium, and 0.5 for the set of hot. Bai and Wang (2006) provide an overview of the Fuzzy Logic process consisting of the following phases:

1. All input values, in a *crisp* form, are *fuzzified* into a fuzzy data set or fuzzy membership functions.

2. Combine membership functions and the available control rules to compute the fuzzy output functions. This phase is also known as the Fuzzy Inference Process.

3. *De-fuzzify* output data obtained from phase two in order to get *crisp* output values using various available methods such as the centroid and weighted average method.

Applications of Fuzzy Logic are found in a wide range of industries. Applications range from control theory, medicine, agriculture, aerospace and decision-making processes (Lowen and Roubens, 2012). Godil *et al.* (2011) and Dernoncourt (2011) identify various advantages and disadvantages of using Fuzzy Logic to model a complex real-world decision-making system. Advantages include accurately resembling human reasoning and decision making as well as integrating qualitative and quantitative information while including uncertainty. Disadvantages associated with Fuzzy Logic include the tedious process of developing fuzzy rules and membership functions. In addition, a great deal of expertise and data are required to develop a fuzzy system.

Conceptually applying Fuzzy Logic to the hypothetical asset replacement problem discussed in Section 2.5, the following observations are made. An important aspect of Fuzzy Logic is accurate qualitative data. Qualitative data required in this asset replacement problem would include all traditional asset replacement factors as well as business risk impacts and transition probabilities. These data requirements would be obtained by interviewing the relevant role players including an asset manager to acquire asset related data and a risk manager or financial manager to acquire the business risk and financial data. Following the Fuzzy Logic process as set out by Bai and Wang (2006), crisp input data is *fuzzified* into a fuzzy data set in the first phase. Various scenarios should be included in the fuzzy data set for this problem. For example, an entry in the fuzzy data set may be the following: If labour relations are bad, the total expected discounted revenue would decrease by $x$ amount. Each input variable requires a separate membership function. The second phase would initiate the fuzzy inference process where the membership functions are combined with system rules. These system rules are at the core of the inference process and is directly related to the intuition of the analyst. An example of a system rule, if the asset is 7 years old, OM costs are high, and a business risk is in a bad state, the total expected revenue would decrease by $y$ amount. Combining various membership functions and system rules, an action to keep or replace the asset should be the output of the model based on the total expected revenue. The last phase of the Fuzzy Logic process requires the *de-fuzzification* which converts the fuzzy data set back to a crisp data set. Using an inverting process such as the center of gravity method, an output graph can be generated which will indicate whether to keep or replace the asset for various system conditions. A distinct disadvantage using the Fuzzy Logic modeling approach for this problem is the tedious process of developing the system rules and membership functions which in turn will not generate an optimal decision. An advantage of using this approach is the incorporation of analyst intuition on the development and impact of business risks on the financial performance and decision making processes of an organization.

### 2.5.4 Monte Carlo Analysis

Before the popularization of the Monte Carlo analysis, simulations were used to test an understood deterministic problem. Statistical sampling was then employed to investigate uncertainties in the simulation results (Kroese *et al.*, 2013). The primary object of the introduction of Monte Carlo simulations was to invert this classical approach by using a probabilistic approach to solve deterministic problems. Kroese *et al.* (2014) state that Monte Carlo methods, in principle, may be used to solve any problem having a probabilistic interpretation. There is no consensus in literature on the definition of Monte Carlo analysis techniques. Sawilowsky (2003) states that a clear distinction should be made between simulation, Monte Carlo methods, and a Monte Carlo simulation. Simulation is the imitation of a real-world process or system over a defined period of time. Furthermore, Sokolowski and Banks (2011) state that the process of simulation is used to resemble real-world system characteristic that are difficult to express in mathematical terms, inaccessible or does not exist. Sawilowsky (2003) defines Monte Carlo methods as techniques that are used to solve mathematical or statistical problems. Lastly, Kroese *et al.* (2014) define a Monte Carlo simulation as the repeated random sampling of a system to determine a significant property and behaviour. Kalos and Whitlock (2008) recognize that distinguishing between the various Monte Carlo definitions is not always easy and it is often found that these definitions are used interchangeably.

This section on the Monte Carlo analysis emphasizes the role of Monte Carlo simulation as a potential modeling technique for the asset replacement process. Various sampling methods exist and the selection of the correct method is dependent on the context of the study, type of data available, length of forecast horizon, and the degree of accuracy required. Binder and Heermann (2010) introduces various sampling methods for a Monte Carlo simulation including random walk methods, the Ising model, and multi-canonical sampling methods. Kroese *et al.* (2014) recognize several key attributes of a Monte Carlo simulation including:

- Easy and efficient; Monte Carlo simulation techniques are often simple, flexible, and scalable. Furthermore, it can reduce the complexity of models to a basic set of equations and interactions.
- Random nature; The inherent randomness of Monte Carlo simulations is

essential for the simulation of real-life events and systems. The random nature also greatly benefits the deterministic numerical computation process.

- Understanding randomness; Monte Carlo simulations facilitate the exploration and understanding of the behaviour of random systems and occurrences. In addition, Monte Carlo simulations are capable of handling large data sets.

- Theoretical justification; An extensive body of mathematical and statistical knowledge exist that underpins Monte Carlo simulations therefore justifying the accuracy and efficiency of results and algorithms.

Kroese *et al.* (2014) state that Monte Carlo simulations are mainly used in three distinct problem classes including: (1) optimization, (2) numerical integration, and (3) generating graphs from probability distributions. The implementation of Monte Carlo simulations are found in a wide range of applications including finance, engineering, and science. Hubbard (2009) notes that Monte Carlo simulation is emphasized in calculating risk in business decision-making processes where uncertainty is significant. In addition, Monte Carlo simulations are often more accurate than human intuition or other qualitative methods when predicting failure and cost overruns (Hubbard, 2009). Mooney (1997) states that although many variations of the Monte Carlo procedure exist, a basic procedure consists of the following steps:

1. A set of all possible inputs required to resemble the real-world system is defined.

2. Random inputs are generated from probability distributions over the set defined in the previous step.

3. A deterministic computation is performed on all inputs using a sampling method.

4. All results are aggregated, processed, and analyzed.

Kalos and Whitlock (2008) and Kroese *et al.* (2013) recognize several advantages and disadvantages associated with Monte Carlo simulations. The most notable advantages include the ability to conduct a scenario analysis which contributes to risk management decisions and the flexibility of the time horizon. A sensitivity analysis can be performed using Monte Carlo simulation and the process of developing a simulation model often clarify the understanding of a real system. However, Monte Carlo simulations can be very expensive and time consuming and do not provide exact results such as analytical modeling techniques.

Conceptually applying a Monte Carlo simulation to the hypothetical asset replacement problem discussed in Section 2.5, the following observations are made. Following a generic Monte Carlo simulation process to model a real-world system as proposed by Mooney (1997), the first step is the define a set of all possible inputs. These inputs should resemble the real-world system and will include the traditional asset replacement factors such as performance degradation, salvage value, organizational revenue, and rising OM costs to name but a few as well as the business risks influencing organizational decision making. The second step is to generate random inputs by using probability distributions to model the input variables defined in the previous step as best as possible. Typical discrete input distributions include Bernoulli, binomial and Poisson distributions whereas continuous distributions such as the Weibull and Laplace distributions are often implemented. Historic data for all of the input variables should be used for asset related information, whereas industry reports and the intuition of the analyst can be used to accurately model business risks. A number of aspects can be included in this step for input variables to accurately resemble the real-world system such as starting values, growth rates, volatility, forecast horizon and the resolution of the system. The third step is the deterministic computation on all inputs using a sampling method such as the Brownian motion or random walk method. The last step in the process is where all results are aggregated, processed, and analyzed. Analyzing the objective function of the problem, total expected discounted revenue, the optimal replacement time must be identified. A distinct advantage of Monte Carlo simulation is to perform sensitivity analyses which in turn can be used to establish confidence intervals for the output of the model, however large quantity of historical data is required to accurately model input variables.

### 2.5.5 Bayesian Models

Geweke and Whiteman (2006) state that Bayesian models provide a formal and coherent methodology to combine statistics and subjective judgments of experts with empirical data. Bayesian models therefore share numerous characteristics with Fuzzy Logic. Koski and Noble (2011) state that a model is classified as Bayesian when probability distributions can be used to describe uncertainty of unknown parameters. Furthermore, for a model to be Bayesian, it must adhere to Bayes theorem. Bayes theorem describes the computation of the conditional probability of a set of possible causes for an observed outcome. The conditional probability is calculated by combining the information on the probability of each cause and the conditional probability of the outcome of each cause (Congdon, 2014). Bayes theorem is applied in Bayesian models to update a *prior* distribution into a *posterior* distribution by integrating information provided by the observed data (De Alba *et al.*, 2007). The application of Bayesian models to real-world systems emphasize qualitative judgments, rather than the historical data of a similar system but also incorporate quantitative data and theoretical justification. Geweke and Whiteman (2006) state that the most popular Bayesian models include the Vector Auto Regression (VAR) and Auto Regression and Moving Average (ARMA) methods which are often used in economic decision-making processes. Bayesian modeling is used in a wide range of applications including business, social, and scientific applications (Trucco *et al.*, 2008). In addition, Draper (2011) describes the versatility of the Bayesian modeling approach with the following quote:

> "All forms of uncertainty are in principle quantifiable with this approach." - Draper (2011)

Geweke and Whiteman (2006) state that Bayesian models all derive from two basic principles including: (1) the principle of explicit formulation and (2) the principle of relevant conditioning. Bayesian models adhere to both principles whereas non-Bayesian models often adhere to the first principle but violate the second principle. The principle of explicit formulation requires the formal expression of assumptions about all relevant aspects in the model using probability statements. The principle of relevant conditioning requires the use of distributions of future events which are conditional on observed events therefore using prior knowledge of relevant structures and parameters. In addition, an explicit loss function must also be included. Ghahramani (2012) provides key attributes of Bayesian models including: (1) the ability to accurately represent uncertainty and risk in a decision-making process, (2) models are automated and adaptive, and (3) the ability to scale to large data sets and exhibit robustness.

Geweke and Whiteman (2006) recognize that Bayesian inference occur in the context of one or more models describing the attributes and behaviour of a vector, $p \times 1$, consisting of observable and random variables $y_t$ for a time period $t = 1, 2, ...N$. Furthermore, $Y_t = \{y_s\}_{s=1}^{t}$ illustrates the history of a sequence at time $t$. The sample space for $y_t$ is designated as $\omega_t$, and $\Omega_t$ for $Y_t$. A corresponding sequence of probability density functions is specified by a model, $M$ consisting from prior and likelihood concepts. Equation 2.5.7 illustrate the sequence of generic probability density functions.

$$p(y_t|Y_{t-1}, \theta_M, M) \tag{2.5.7}$$

where $\theta_M$ is a $k_M \times 1$ vector of unobservable variables and $\theta_M \in \mathbb{R}^k$. The vector $\theta_M$ includes all the available variables required to formulate the model. The probability density function for $Y_T$ is conditional on the model $M$ and the vector $\theta_M$, and is calculated using Equation 2.5.8.

$$p(Y_T|\theta_M, M) = \prod_{t=1}^{T} p(y_t|Y_{t-1}, \theta_M, M) \tag{2.5.8}$$

Expressions such as $y_t$ and $Y_T$ denote random vectors if used on its own. In Equations 2.5.7 and 2.5.8, $y_t$ and $Y_T$ denote arguments of model functions. Observed values are designated in a different manner. To explicitly distinguish between the observed values and and random value, $y_t^o$ denotes the observed value of $y_t$ and $Y_T^o$ indicates the observed value for $Y_T$. Readers interested in a more detailed discussion on Bayesian model formulation are referred to Geweke and Whiteman (2006). Furthermore, Ghahramani (2012) and Congdon (2014) indicate several advantages and disadvantages associated with Bayesian models. Advantages of Bayesian models include the fact that it is coherent, conceptually straightforward, and modular in design. Limits and criticisms of Bayesian models often include its subjective nature, difficulty in selecting the optimal prior, and the demanding computational efforts associated with it. Moreover, Bayesian models are often inferior to traditional analytical models for long term modeling.

Conceptually applying Bayesian modeling to the hypothetical asset replacement problem discussed in Section 2.5, the following observations are made. A Bayesian model can be developed by following three major steps. The first step is to developed a full probability model which includes probability distributions for all variables in the problem. Variables in this asset replacement include all traditional asset replacement variables and the applicable business risk variables.

Probability distributions have to be developed to show the transition probability of each variable over a period of five years into the future. The second major step is to condition on the observed historic data. This is used to calculate and interpret the appropriate posterior distribution which forecasts the output of the model, total expected discounted revenue in this case. Interested readers are referred to Geweke and Whiteman (2006) who illustrated the development of a Bayesian model by using a VAR model providing a full set of the required equations. The last major step in the Bayesian modeling process is to evaluate the fit of the model and to analyze its implications. Expert interviews and intuition should be employed in this step to ensure that the model provide meaningful outputs for the expected revenue based on all input variables. A distinct advantage of Bayesian modeling is the forecasting of business risk data, however integrating this information with asset data to analyze the effects on the asset replacement process is not as straightforward as with the other modeling techniques discussed in this section. In addition, Bayesian models are known to have inferior performance when the forecasting horizon is more than two years.

### 2.5.6 Comparison of Modeling Techniques

This section compares the modeling techniques discussed in Sections 2.5.1 to 2.5.5 in order to identify the most applicable modeling technique to incorporate the effects of business risks in the asset replacement process. The chosen modeling technique should integrate the traditional quantitative asset replacement considerations such as OM costs, financial depreciation, salvage value, and performance degradation as well as business risks which can be quantitative or qualitative in nature in order to find an optimal decision policy for five years into the future to maximize an objective function, and it should facilitate user-input.

It was found that the MDP is a functional and powerful modeling technique which provides a mathematical framework to model decision-making systems where the analyst are partly in control of the outcomes of the system. Furthermore, the MDP is an effective modeling technique for solving a multistage planning system where stochastic and dynamic decision-making under uncertainty is involved. In addition, an MDP model is capable of integrating both qualitative and quantitative data therefore making it an acceptable choice to use in the framework for this study. Next, ANN were reviewed. It was found that ANN models possess exceptional ability to learn by example using historical data to train the ANN architecture. However, ANN are very data intensive and do not provide optimal results. Furthermore, projections are made into the future without facilitating analyst input or integrating qualitative data.

Next, Fuzzy Logic was discussed. Fuzzy Logic was found to be a powerful modeling technique to represent uncertainty or risk by integrating both qualitative and quantitative data in its mathematical approach to develop fuzzy sets. The most significant feature of Fuzzy Logic is the ability to provide a definite output from vague of fuzzy input values. However, Fuzzy Logic does not combine multiple variables to determine an output as is the case for MDP and ANN models, which is a prerequisite for the model in this study. Monte Carlo simulation were then reviewed. Monte Carlo simulations solve deterministic problems by using a probabilistic approach. Simulation has many benefits over traditional analytic modeling techniques but can be time consuming and expensive. Monte Carlo simulations are not capable of providing an optimal answer by integrating various actions in the decision-making process. Lastly, Bayesian models were reviewed. Bayesian models provide a formal and coherent methodology to combine statistics and subjective judgments of experts with empirical data. The most significant factor prohibiting the use of Bayesian models in this study is its inferior long term performance compared to the other analytical modeling techniques.

**Table 2.7:** Modeling techniques scoring matrix

| Modeling Techniques | Quantitative data | Qualitative data | Multi-variable | Forecasting | Decision-making | Analyst input | Optimality | Score |
|---|---|---|---|---|---|---|---|---|
| | **Model Requirements** | | | | | | | |
| Markov Decision Process | 8 | 8 | 7 | 8 | 8 | 8 | 7 | 54 |
| Artificial Neural Networks | 8 | 5 | 8 | 7 | 6 | 6 | 7 | 47 |
| Fuzzy Logic | 5 | 8 | 7 | 5 | 8 | 8 | 5 | 46 |
| Monte Carlo Analysis | 8 | 6 | 8 | 8 | 5 | 8 | 6 | 49 |
| Bayesian Models | 8 | 8 | 7 | 7 | 5 | 6 | 7 | 48 |

The literature review and the conceptual solutions to the hypothetical asset replacement problem are used to score each modeling technique as illustrated in Table 2.7 in order to identify the most appropriate modeling approach for this study. Several criteria are considered when comparing and scoring the modeling techniques in order to adhere to all requirements for the framework developed in Chapter 3. Each of the model requirements is scored out of a maximum of 10 and the results are summed to arrive at a final score. It is evident from Table 2.7 that an MDP modeling approach scores the highest for this specific study and will be used in Chapter 3 as part of the decision framework for incorporating business risks into asset replacement. This decision is validated by the fact that the majority of studies in the asset replacement literature use the MDP modeling approach for asset replacement applications.

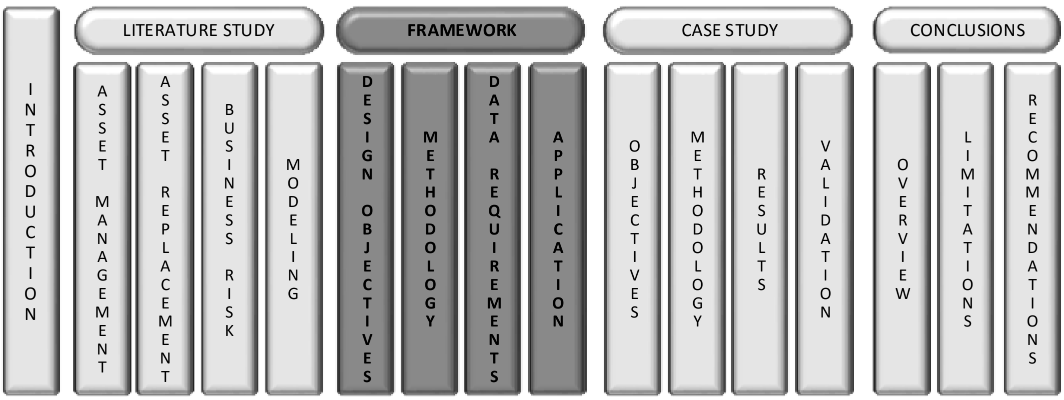
## 2.6 Chapter Summary

The primary focus of this chapter is to review and contextualize the main concepts in this study. These main concepts include AM, asset replacement, business risks, and modeling techniques. The literature review indicate that AM is a holistic management approach and is a necessity in the modern competitive economic environment. Different asset replacement concepts are emphasized including the traditional approach to asset replacement, various replacement solution approaches, financial considerations, and the impact of uncertainty and business risk on asset replacement. Next, business risk is defined and reviewed. Furthermore, business risk in AM is investigated and its potential effects on the asset replacement decision process are emphasized. Lastly, five modeling techniques are reviewed and evaluated, resulting in the identification of the MDP as the best modeling approach to be used for the framework developed in this study. The next chapter uses the literature review and contextualization of the study presented in this chapter as a foundation to develop a decision-making framework to facilitate the incorporation of business risk in asset replacement.

# Chapter 3

# Design and Development of Framework

*"As far as the laws of mathematics refer to reality, they are not certain, and as far as they are certain, they do not refer to reality"* - Albert Einstein (1879 - 1955)




### Chapter Outcomes:

- Comprehension of general framework design principles.
- Description of framework scope, objectives, and development methodology.
- Development of the framework to incorporate business risk in asset replacement.
- Presentation of the framework application methodology to be used as a template for the case study in Chapter 4.
- An understanding of the data requirements for the case study presented in Chapter 4.

## 3.1 Introduction

This chapter uses the literature review and contextualization of the study presented in Chapter 2 as well as information obtained from practice as the foundation to develop a decision-making framework to facilitate the incorporation of business risks in asset replacement. The framework incorporates the three main concepts of this research including asset replacement, business risks, and the Markov Decision Process (MDP). Chapter 2 illustrates that senior management responsible for asset replacement decisions in the PAM domain is faced with the need for a framework with the following characteristics: (1) quantify overall risk using a holistic approach, (2) provide a level of certainty associated with an asset replacement decision, (3) create consistency and repeatability in the asset replacement process, and (4) make defensible decisions by considering the evolution of asset performance and business risks.

The framework developed in this chapter should therefore assist senior management in their asset replacement decisions and as act as a guide and reference for managers to defend their actions. The framework incorporates the fundamental aspects of any risk-based decision making process used by organizations in the PAM domain including the following:

- The context of the process is defined that describes the business environment for the company focusing on factors such as political, social, environmental and technical issues.
- The system and its interaction with the business environment is defined.
- Top business risks are defined, identified, and categorized.
- A risk assessment is undertaken and feedback is provided to implement risk mitigation measures.

The layout of Chapter 3 is as follows: Section 3.2 discusses general framework design principles found in literature which provide the foundation for the framework developed in this study. Next, the boundaries and objectives of the framework to incorporate business risk in asset replacement are introduced in Section 3.3. Then, the framework is developed in Sections 3.5 to 3.7 by implementing the methodology stated in Section 3.4, which is also used as a template in the case study presented in Chapter 4.

## 3.2 Framework Design

According to Anderson *et al.* (2015), senior management of large organizations are constantly searching for structured and logical decision-making processes to assist the organization in meeting its objectives. These structured and logical decision-making processes are often found in the form of a framework. Mishra and Mohanty (2012) describe frameworks as reusable designs that consist of a set of abstract classes. These abstract classes collaborate in an effective way to fulfill certain functions and to solve a problem. Carson and Cobelli (2013) state that a framework should describe the context of a system, consider various stakeholders, generate possible solutions, and provide instructions on how to implement certain actions recommended by the results. Moreover, decision-making frameworks can be used for orientation, planning, implementation, communication, and evaluation. In addition, Hunter (2006) states that a decision-making framework should: (1) enable identification and articulation of goals and objectives, (2) support the prediction of outcomes, (3) be transferable across different applications, and (4) be modular, flexible, and scalable. Moreover, Menzel *et al.* (2011) recognize that any decision-making framework is a combination of internal and external information, a decision-making or modeling method, application of the method, and the communication of results. Frameworks can be developed following various distinct approaches including:

1. Deriving a framework from a review of theoretical and empirical literature and combining that knowledge with industry experience (Jacobson *et al.*, 2003).

2. Developing a framework as a combination of various frameworks, or the evolution of a single, existing framework (Menzel *et al.*, 2011).

3. Developing a framework based upon a clear set of assumptions and beliefs about a subject that are drawn from evidence (Webber *et al.*, 2008).

4. Developing a framework through an iterative process that involves a series of systematic steps to combine two or more existing conceptual frameworks derived from empirical studies (McCormack and McCance, 2006).

5. Developing a framework that consists of assumptions, a priori knowledge, a mathematical model that resembles a real-world system, and data (Carson and Cobelli, 2013).

Taking the aforementioned concepts of framework design into consideration, the decision-making framework in this study is developed from a review of the relevant theoretical and empirical literature combined with expert advice. It consists of a series of structured and logical flow of decisions and tasks and facilitates interaction between the analyst and the client, which is all the relevant key stakeholders. It employs an MDP as a mathematical model to represent a real-world system which is flexible, scalable, and modular. Furthermore, a sensitivity analysis is integrated in the framework and provision is made for the selection of communication strategies aimed at specific audiences for the results obtained.

## 3.3 Framework Scope and Objectives

As part of the development of a framework, the scope and objectives of the framework should be explicitly stated. The scope of the framework, as stated in Section 1.4, is summarized and recited in Table 3.1. The framework only considers a single, entire, business-critical asset for a finite time horizon. The business risks included in the analysis are determined as part of a risk identification process in the framework. The replacement asset is considered to be identical to the asset under consideration in terms of performance and costs. Costs included in the analysis are dependent on the context of the asset and typical costs influencing asset replacement decisions are illustrated in Table 3.1. Lastly, when replacing an asset, it can be kept and repaired or replaced with a new asset.

**Table 3.1:** Delineation of asset replacement framework

| Framework component | Scope of framework components |
|---|---|
| Number of assets | A single, whole, business-critical asset |
| Time horizon | Finite horizon |
| Business risks | Quantitative and qualitative variables are integrated as determined by framework |
| Replacement asset | Identical asset in terms of performance and costs |
| Costs | Stationary costs, financial depreciation, OM costs salvage value, capital expenditure, inflation |
| Replacement action | Keep and repair, or replace |

The objectives of the framework as stated in Section 1.5 are elaborated in this section. The main objective of the framework is to provide the analyst with a systematic and structured process for integrating business risk into asset replacement decisions. Overall features and objectives, not in any order of significance, of the framework include:

- Practical – The framework should be a practical tool that can be applied in industry to supplement existing decision-making processes.
- Holistic – The framework should employ a holistic and integrated view to emphasize the importance of the whole and the interconnectivity of its parts.
- Logical and structured – The flow of the decision-making process and instructions in the framework should be logical and structured.
- Interactive – The framework should facilitate communication and interaction between the analyst and client to ensure that significant and accurate results are obtained.
- Generic – The framework should provide a generic decision-making process to incorporate business risks in asset replacement decisions.

More specifically, the framework aims to be a generic process that can be applied to any business-critical physical asset in a capital-intensive organization in the PAM domain. A map of replacement decisions are provided for a finite time period into the future with expected values that are dependent on the objective function of the analysis. Equipped with an overview of general framework design principles and the scope and objectives of the study, the proposed solution is developed in the following sections.

## 3.4 Framework Development

The development of the proposed solution is based on the literature review conducted in Chapter 2 combined with expert advice obtained from various sources ranging from experienced industry asset managers in the AM and asset replacement fields to high-level strategic decision-makers in capital-intensive organizations. The literature review indicates that no framework exists to incorporate business risks in physical asset replacement decisions. A holistic view of the framework is presented in Figure 3.1. The popular *Input-Black Box-Output* structure is used as suggested by Kulakowski *et al.* (2007). This structure is usually implemented when modeling and calculations are important to supplement other decision-making steps in a framework. The main concepts of the framework illustrated in Figure 3.1 are followed chronologically when implementing the decision-making framework starting with the *Inputs*-phase. The Inputs-phase is important to contextualize the analysis, set the boundaries of the analysis, identify the correct factors and to acquire all the required data elements. The analyst-client interaction is facilitated throughout this phase to ensure that the correct concepts are used in the analysis. The four main concepts of the research is prominent throughout the decision-framework and include AM, asset replacement, business risk, and the MDP.

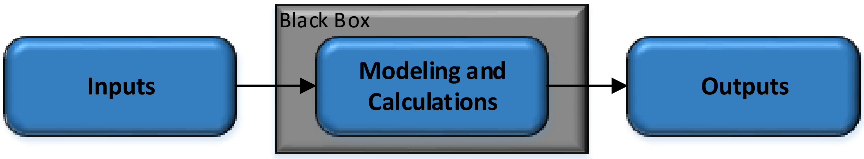



**Figure 3.1:** Holistic view of proposed solution

The second phase of *modeling and calculations*, also known as the *Black Box*-phase, is used to model a real-world system and obtain the results which is a map of replacement policies for a finite period of time into the future. The second phase is conducted by the analyst, thus seeming like a Black Box to the client. A set of mathematical equations and modeling assumptions are implemented in this phase to develop a dynamic program in order to obtain results for the asset replacement problem. In addition, a sensitivity analysis is integrated in this phase for two reasons. The first is to investigate the effect of changing a parameter on the outcomes of the model, therefore obtaining a level of confidence in the accuracy of the results. The second reason is to investigate the effect of controlling business risks in a favorable manner in order to make informed business decisions.

The last part of the framework is the *Outputs*-phase. The main objective of this phase is to select the most appropriate communication strategy to convey the results to the client. Clients may have different skills sets and technical backgrounds, therefore prompting the use of different communication strategies to convey the results in an effective and comprehensible manner. The Outputs-phase, like the Inputs-phase, also facilitates analyst-client participation. Furthermore, the steps in each phase are numbered. The function of the numbering configuration is to provide a sequential guideline for the analyst when implementing the framework. The roles and responsibilities of the analyst and client are also indicated. Equipped with an overview of the framework structure as the proposed solution to integrate business risk into asset replacement, each phase and step is discussed in detail in the following sections. Typical objectives and outcomes are indicated for each step and examples in the PAM domain are introduced for certain steps to accentuate its importance. The Inputs-phase is developed in Section 3.5. Then, the MDP model is developed in Section 3.6. Section 3.7 illustrates the development of the results and recommendations phase. Lastly, the three phases are combined to develop the complete framework.

## 3.5 Phase 1: Inputs

The detailed discussion on the development of the proposed decision-making framework and how to implement it starts with the Inputs-phase. The primary objective of this phase is to contextualize the analysis and obtain the required data for the business risks and asset involved. A Graphical User Interface (GUI) is developed to aid the data acquisition process in order to collect data from people with different skills sets and experience. The Inputs-phase is the foundation to the development of the MDP model developed in the second phase. A graphical representation of Phase 1 is presented at the beginning of this section, in Figure 3.2, for the reader's convenience to use as a reference throughout the development of Phase 1.

### 3.5.1 Business Risks

The identification of the appropriate business risks follows a top-down approach. This approach is illustrated in Figure 3.3. Although a country cannot have specific business risks, it has a great influence on the business risks that an organization faces. For example, an iron ore mine situated in the Northern Cape, South Africa will have different business risks from an iron ore mine situated in Brazil due to political, economic, and other factors. However, some risks will be similar due to certain generic aspects of an iron ore mine. Therefore, a need exists to follow a top-down approach to identify and use the correct business risks that an

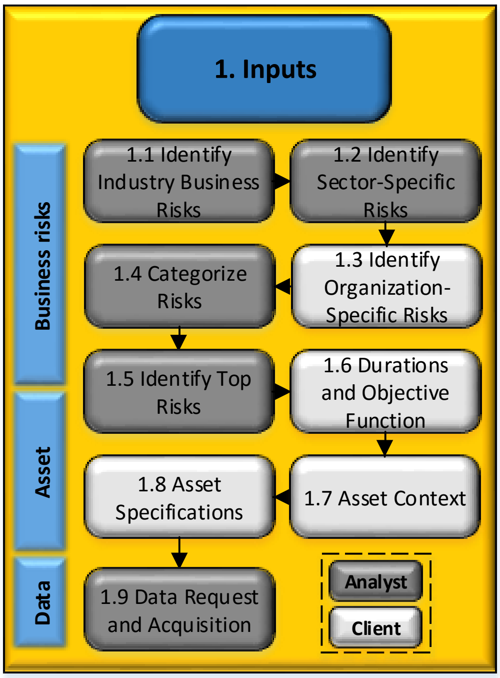



**Figure 3.2:** Inputs-phase of decision-making framework

organization faces. The business risk definitions introduced in Section 2.4.2 are used throughout the risk identification process in Phase 1.

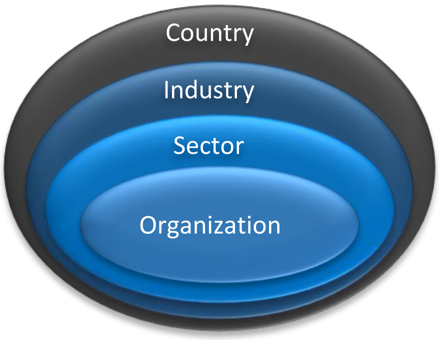



**Figure 3.3:** Risk management responses

#### 3.5.1.1 Step 1.1: Identify Industry-Specific Business Risks

The framework starts with the identification of industry-specific business risks in Step 1.1. Industry-specific business risks are factors that impact the financial and operational performance of an industry such as the mining or manufacturing industries. Organizations typically do not have control over these risks. From the literature analysis, four primary sources of industry-specific business risks were

identified with the root causes being external influences, technology evolution, legislation changes, and commodity price fluctuations. Having established the context of the country that the organization is located in, industry-specific business risks are identified and assessed using several tools and methods. These tools and methods include industry reports, risk matrices, scenario analysis and other methods introduced in Table 2.5. Furthermore, it is noted that the analyst performs this step although the client may add risks if it is deemed necessary. Examples of industry-specific business risks include commodity price fluctuations and labour concerns in the mining industry or a secure and efficient supply chain in the manufacturing industry.
**Objective:** To identify industry-specific risks that are affecting or may affect the organization's performance in the future.
**Outcome:** Having established the industry-specific risks, sector-specific risks can be identified.

#### 3.5.1.2 Step 1.2: Identify Sector-Specific Risks

Sector-specific business risks are identified in this step. It is often different from industry-specific risks in the sense that many sectors exist in an industry and these sectors do not necessarily share the same risks. For example, the iron ore, gold, and diamond mining sectors all form part of the mining industry, yet organizations in each mining sector have many distinctly different business risks. Similarly, organizations in the manufacturing industry and in the automobile sector could face different business risks as organizations in the food manufacturing sector. The tools and methods to identify and assess sector-specific risks include industry reports and as well as the tools illustrated in Table 2.5. Analogous to the previous step, the analyst performs this step although the client may add risks if it is deemed necessary. Examples of sector-specific business risks include commodity price fluctuations, technology change, and more extensive and stringent legislation.
**Objective:** To identify sector-specific risks that are affecting or may affect the organization's performance in the future.
**Outcome:** Industry and sector specific business risks are now determined. The next, more detailed, level of organization-specific risk identification conducted by the client can take place.

#### 3.5.1.3 Step 1.3: Identify Organization-Specific Risks

The final step in the identification of the appropriate business risks is to identify organization-specific risks. Organization-specific risks are those that occur due to unique circumstances associated with an organization and are independent of industry and sector business risks. A typical business risk-management framework such as the one illustrated in Figure 2.15 is used to identify and assess risks. This step in the framework is performed by the client and is usually executed by the risk department in an organization. Strategic risks are often the most prominent in this risk identification phase. Other typical organization-specific risks include workers health and safety, labour relations and operational performance.
**Objective:** To identify organization-specific risks that are affecting or may affect the organization's performance in the future.
**Outcome:** All the required business risks have now been identified and assessed, the next steps is to categorize these risks and identify the most important risks to include in the MDP model.

#### 3.5.1.4 Step 1.4: Categorize Risks

This step in the framework combines all the business risks identified in the preceding steps to categorize it into three risk categories. These three risk categories include operational, strategic, and external risks. These categories were identified in the literature review, specifically in Section 2.4.2, as encompassing all business risks identified in risk management processes. The purpose of categorizing business risks is to ensure that the analyst include risks from the most probable sources that may influence organizational performance or decision-making processes. This step in the framework is performed by the analyst and paves the way to identifying the top risks to be included in the MDP model.
**Objective:** Categorize all identified business risks into operational, strategic, and external risks.
**Outcome:** Use risk categories to ensure that risks from various sources are considered.

#### 3.5.1.5 Step 1.5: Identify Top Risks

In order to identify the top business risks, the categorized risks from Step 1.4 should be ranked using a tool or methodology used within the organization or a process found in risk management standards. From the literature review, in Section 2.4, it was found that a risk map, or heat map, is the most popular tool to rank business risks, however, any tool or methodology can be used that can be justified. A risk map is developed by assigning a risk a score for both the likelihood of it occurring and the consequences associated with it. These scores are multiplied and plotted on a graph similar to Figure 3.4. This step is performed by both the analyst and client, combining the expertise and knowledge gained in the previous steps to determine the most important risks to include in the MDP model. A trade-off should be made at this point between the number of risks to be included, its data requirements, and the computational efforts of the MDP model.

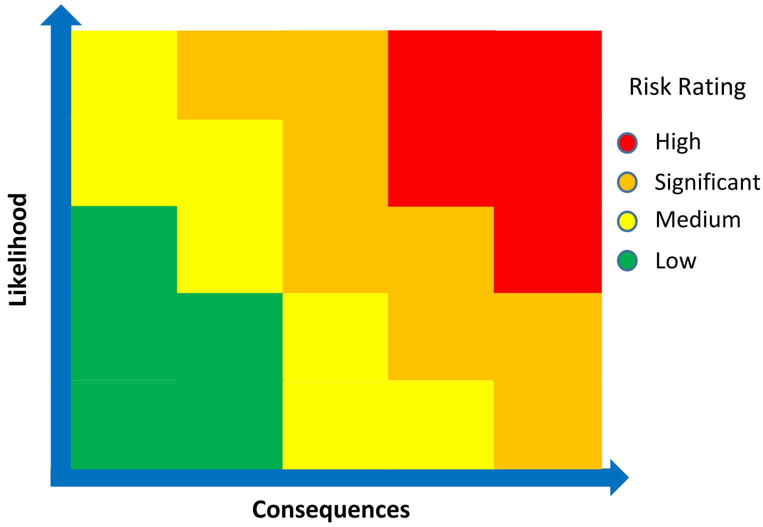



**Figure 3.4:** Risk map to determine top business risks

**Objective:** To identify the top $x$ number of business risks.
**Outcome:** The top $x$ number of business risks determined in this step are used in the MDP model.

### 3.5.2 Asset Context

This primary objective of this section of the framework is to provide context for the business-critical asset under consideration and other variables included in the MDP model. More specifically, the duration and frequency of the replacement decision are to be specified along with the resolution of the entire system. Similar to the business risks, a trade-off has to be made between the analyst and client taking into consideration the data requirements, cost, and computational effort when deciding on the resolution of the model.

#### 3.5.2.1 Step 1.6: Analysis Decisions

This step in the framework is used to determine certain factors that concerns both business risks and the asset under consideration and is performed by the client. First, the time horizon for the MDP model is established. The literature review, in Section 2.3, and consultation with industry experts revealed that the average managerial period of responsibility for an asset system is three to five years. However, due to the flexibility of the model, this parameter can be changed. Therefore this step aims to specify the time horizon of the study and the objective function. The objective function is the variable in the study which should be maximized or minimized. Furthermore, the level of detail for the business risks in the MDP model has to be specified. For example, five business risks are included with five levels of detail ranging from bad to excellent. This describes the current and expected condition of the business risks identified in Step 1.5.
**Objective:** To specify the resolution of the system.
**Outcome:** The time horizon, objective function, and level of detail for business risks are specified.

#### 3.5.2.2 Step 1.7: Provide Asset Context

Step 1.7 in the framework aims to provide the necessary context of the asset under consideration. This step is important for both the analyst and client in order to model the system accurately and often affects the objective function of the study. To contextualize the asset operating environment, information is required on several factors including the main purpose of the asset, where it fits in the organizational set-up and how it influences organizational performance. This step is performed by the client. An example of providing context for an asset's operating environment follows: Considering a power shovel which is a business-critical asset in many mining organizations that is used to extract minerals. If a shovel is not in operation, fragmented rocks cannot be moved, thus stopping the entire mineral extraction process and halting the supply chain. This has significant effects on production and therefore revenue generation. Based on this information, an objective function can either be to maximize asset availability and therefore revenue, or to minimize OM and other related costs.

**Objective:** Contextualize the business-critical asset within the organizational set-up.
**Outcome:** Clarity on asset context and how it affects the objective function.

#### 3.5.2.3 Step 1.8: Asset Specifications

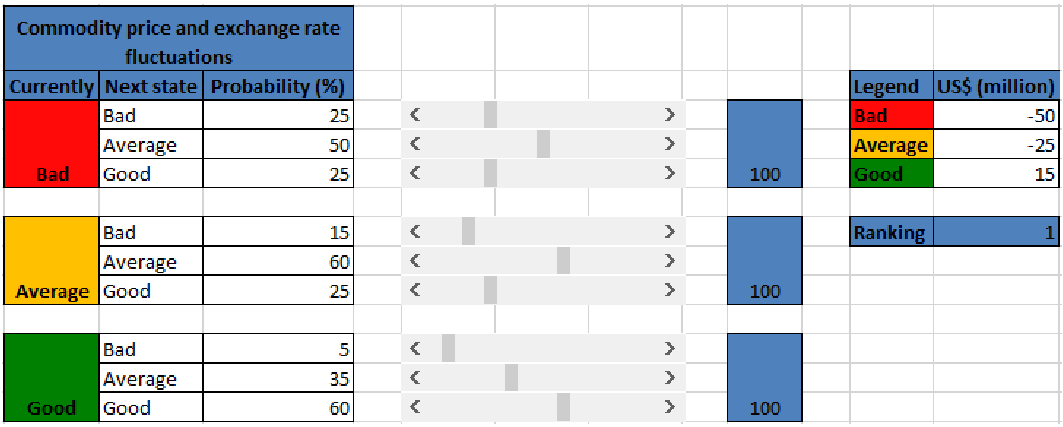
This step in the framework aims to establish the relevant asset specifications that are required for the model in Phase 2. The client and analyst work together to identify all the influential factors to be included in the MDP model. These factors include traditional asset replacement considerations such as capital expenditure, performance degradation, OM costs, financial depreciation, and salvage value. An important concept to be clarified in this step is how the organization, or client, calculate these considerations. Furthermore, the resolution of the asset specifications have to be specified in this Step 1.8. This may required the discretization of several asset specifications. An example of asset specifications follows: Considering a business-critical asset, performance degradation is based on an engineering availability graph which is discretized into five levels of availability. OM costs are calculated as 10% of the capital expenditure and increase by 5% per annum. Financial depreciation is incorporated with the straight-line method over 10 years and the asset's salvage value is based on market prices.
**Objective:** To specify the required asset considerations to be included in the model.
**Outcome:** The appropriate considerations that affects asset replacement decisions are identified and the overall system resolution is specified.

### 3.5.3 Data

The data acquisition part of Phase 1 is focused on requesting data in a certain format to aid the analyst's model requirements and to develop a Graphical User Interface (GUI) to simplify this data acquisition process. In addition, the data for the MDP model is obtained from the client in this step. The GUI enables clients with various technical backgrounds to understand the transition probabilities of certain variables without requiring the theoretical knowledge behind the MDP mathematics.

#### 3.5.3.1 Step 1.9: Data Request and Acquisition

The last step in Phase 1 of the framework facilitates analyst-client participation in the data request and acquisition process. A GUI is developed by the analyst to capture data on the relevant factors identified in the previous steps of Phase 1. The client uses the GUI to provide the required data. The GUI illustrated with an example in Figure 3.5 is developed in Microsoft Excel, but any software package can be used to aid this process. The example illustrates the transition probabilities of a business risk, commodity price and exchange rate fluctuations, from one decision epoch to the next. The scroll bars are coded to assist the client in adhering to model requirements.



Commodity price and exchange rate fluctuations

| Currently | Next state | Probability (%) | |
|---|---|---|---|
| Bad | Bad | 25 | |
| | Average | 50 | |
| | Good | 25 | 100 |
| Average | Bad | 15 | |
| | Average | 60 | |
| | Good | 25 | 100 |
| Good | Bad | 5 | |
| | Average | 35 | |
| | Good | 60 | 100 |

| Legend | US$ (million) |
|---|---|
| Bad | -50 |
| Average | -25 |
| Good | 15 |
| Ranking | 1 |

**Figure 3.5:** GUI for data request and acquisition

**Objective:** Develop a GUI to obtain the required data for the MDP model.
**Outcome:** Data is obtained for all the relevant factors to be included in the MDP model. The MDP model can now be developed in Phase 2.

## 3.6 Phase 2: MDP

Using the information and data obtained in Phase 1, the primary objective of this phase is to develop the mathematical Markov Decision Process (MDP) model. More specifically, a systematic process is introduced to develop the MDP model and how to present the results obtained from the analysis to various stakeholders. The MDP mathematics presented in this phase elaborate on the basic information provided in Section 2.5.1. Phase 2 of the framework is entirely performed by the analyst. A graphical representation of Phase 2 is presented at the beginning of this section, in Figure 3.6, for the reader's convenience to use as a reference throughout the development of Phase 2.

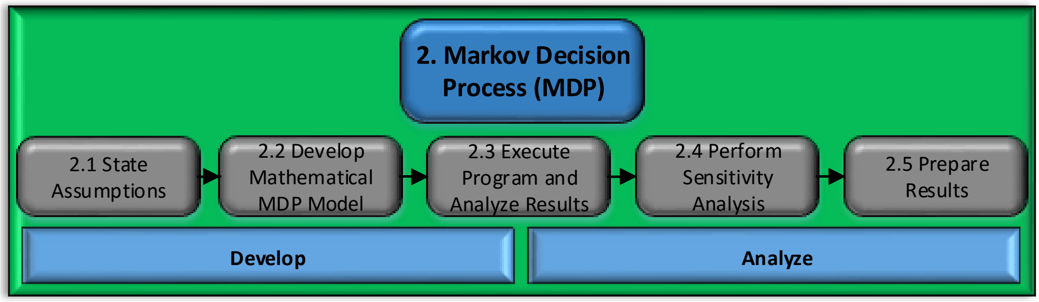



**Figure 3.6:** Markov Decision Process (MDP) phase of framework

### 3.6.1 Model Development

The model development part of Phase 2 aims to develop an MDP model to resemble the real-world system introduced in Phase 1 of the framework. The model is developed using a structured and logical process by first stating all assumptions. Next, a set of mathematical equations is developed to resemble the real-world system using Section 2.5.1 as the basis for the discussion. Lastly, the optimization method of backward induction is introduced to obtain the results for the model. An example is presented in Section 3.6.1.4 to illustrate the MDP model for a typical decision-making process.

#### 3.6.1.1 Step 2.1: State Model Assumptions

The first step in Phase 2 of the framework aims to establish and explicitly state all assumptions with regards to the development of the MDP model. In addition, all parameters and variables identified in Phase 1 are stated in this step with the required detail to model it. First, specific assumptions associated with an MDP include:

- First-order Markovian dynamics apply which means that the next system state solely depends on the current state and action and is therefore independent of historic states and actions as recognized by Schaefer *et al.* (2005) in Section 2.5.1.

- State-dependent rewards: The system rewards is a deterministic function of the current state and action taken by the analyst as stated by Gilks (2005) in Section 2.5.1.

- Full observability: This implies that the next state the system takes is fully known after an action is taken, even though the new state is not always predictable as suggested by Puterman (2014) in Section 2.5.1.

Next, all parameters and variables included in the MDP model are stated with their associated assumptions. For example, a replacement decision, or action, is assumed to take place at the start of each decision epoch and a replacement asset is available immediately if required. Equipped with all parameters, variables and their associated assumptions, the mathematical MDP model can be developed in Step 2.2.
**Objective:** State all assumptions that affects the development and outcomes of the MDP model.
**Outcome:** All parameters, variables, and their associated assumptions are conveyed to the client therefore enabling the analyst to develop the mathematical MDP model.

#### 3.6.1.2 Step 2.2: Develop MDP Model

This step in the framework aims to develop the MDP model to resemble the real-world system described in the previous steps of the framework. A review of the information provided in Section 2.5.1 is given to introduce the terminology used to formulate the model and to provide an overview of a typical MDP. The analyst is faced with a problem of influencing a probabilistic system that evolves with time by choosing certain actions at specific times to satisfy an objective function. Actions taken at a certain point in time only considers the future system states to anticipate expected opportunities and costs, thus adhering to the Markov property. At each time period $t$ the system state $s$ provides the decision maker with all the information necessary for choosing an action $a$. As a result of choosing an action, the decision maker receives a reward $r_t(s_t, a)$ and the system evolves to a (possibly different) state $s'$ with a probability $p_t(s'|s_t, a)$. A summary of the MDP model components is provided in Table 3.2.

Decision epochs $T$ are the points in time where decisions are made to keep and repair the asset or to replace it. In a finite system, decisions are made at all

**Table 3.2:** Components used to describe Markov Decision Process model

| Component | | Description |
|---|---|---|
| $T$ | = | A set of points in time at which actions are taken $t \in T = [1, 2, ..., N]$ |
| $N$ | = | Total number of decision epochs, e.g., for a decision forecast of five years with action taken on an annual basis, $N = 5$ |
| $S$ | = | A finite set of all possible values and attributes describing the dynamics of the system. $S = \{s_1, s_2, ..., s_x\}$ |
| $x$ | = | Total number of system states used to describe system characteristics |
| $p_t(s'\|s_t, a)$ | = | Describes the transition probability by which the system state is $s'$ at the next decision epoch $(t+1)$ when the system is in state $s_t$ and action $a$ is taken at decision epoch $t$. |
| $A_s$ | = | Describes the actions or choices available when making decisions for any state $s \in S$ with $A_s = [a_1, a_2, ..., a_y]$ |
| $y$ | = | Number of asset replacement actions available to analyst |
| $M_t(s'\|s_t, a)$ | = | An $x \times x$ transition probability matrix describing the system transition dynamics for each action at a decision epoch |
| $r_t(s_t, a)$ | = | Reward function is the immediate reward received or penalty incurred as a result of taking action $a$ at state $s_t$ at decision epoch $t$. |
| $\pi$ | = | Policy is a set of decision rules $\pi = [d_1, d_2, ..., d_{N-1}]$, optimal policy is denoted as $\pi^*$ |
| $\gamma$ | = | Discount factor to discount future rewards $0 < \gamma \leq 1$ |
| $V$ | = | Total expected value for a certain policy $\pi$, $V^*$ denotes optimal value |

decision epochs. Time is divided into equal periods as identified in Step 2.1. The MDP decision epochs and time periods are graphically illustrated in Figure 3.7. The last decision is made at decision epoch $N-1$.

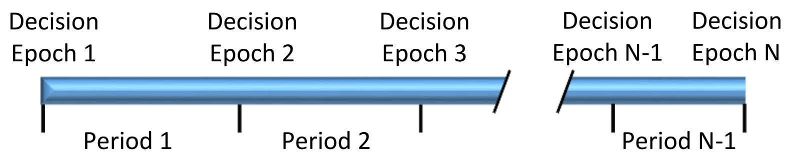



**Figure 3.7:** MDP decision epochs and periods

The system reward at the last decision epoch is known as the terminal reward, which represents the asset salvage value and is illustrated in Equation 3.6.1. The system assumes a state $s$ at each decision epoch. The system state is described by all variables included in the MDP model to describe the systems dynamics.

These variables are identified in the preceding steps in the framework and include factors such as asset condition, business risks, and financial depreciation.

$$V_N^*(s_N) = \max_{a \in A_s} \left\{ r_N(s_N, a) \right\} \text{ for all } s_N \in S \tag{3.6.1}$$

When an action $a$ is taken at a decision epoch for a specific system state $s$, a reward $r_t(s_t, a)$ is received which may be positive or negative. This is also known as the immediate reward. The total discounted expected rewards is a combination of the immediate rewards and future discounted expected rewards and is illustrated in Equation 3.6.2. To maximize the total expected rewards, an optimal decision must be made at every decision epoch as indicated in Equation 3.6.3. The total rewards for each action taken is a sum of the rewards associated with the system variables that is defined in Step 2.1 as shown in Equation 3.6.4.

$$\begin{aligned} V_t^*(s_t) = & \max_{a \in A_s} \left\{ r_t(s_t, a) + \frac{\sum_{s' \in S} p_t(s'|s_t, a) V_{t+1}^*(s')}{(1+\gamma)} \right\}, \\ & t = 1, 2, ..., N-1 \text{ and } s_t \in S \end{aligned} \tag{3.6.2}$$

$$a_{s_t,t}^* \in \arg\max_{a \in A_s} \left\{ r_t(s_t, a) + \frac{\sum_{s' \in S} p_t(s'|s_t, a) V_{t+1}^*(s')}{(1+\gamma)} \right\}, \quad t = 1, 2, ..., N-1 \tag{3.6.3}$$

$$R_t(s_t, a) = \sum_{t=0}^{N-1} r_t(s_t, a) \tag{3.6.4}$$

In order to calculate the maximum expected rewards, which is also the objective function, a transition probability matrix $M_t(s'|s_t, a)$, describing the entire system transition dynamics, must be developed that satisfies certain conditions. The transition probability matrix is developed for each action as illustrated in Equation 3.6.5.

$$M_t(s'|s_t, a) = \begin{bmatrix} p_{11} & p_{12} & p_{13} & \cdots & p_{1x} \\ p_{21} & p_{22} & p_{23} & \cdots & p_{2x} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ p_{x1} & p_{x2} & p_{x3} & \cdots & p_{xx} \end{bmatrix} \tag{3.6.5}$$

The transition probability matrix must satisfy the two conditions given in Equations 3.6.6 and 3.6.7. The decision policy $\pi$ provides an action for every decision epoch and is one of the model's outputs along with total expected discounted rewards that is of interest to the client. A simple MDP problem is discussed in Section 3.6.1.4 to provide an example of solving a decision-making system with the MDP and also to validate the code developed for this study.

$$0 \leq p_t(s'|s_t, a) \leq 1 \text{ for } t, ..., N-1 \tag{3.6.6}$$

and

$$\sum_{s' \in S} p_t(s'|s_t, a) = 1 \text{ for all } s_t \in S,\ a \in A_s \tag{3.6.7}$$

For simple MDP problems all policies can be evaluated by hand to find the optimal policy, however for MDP problems with a large state space, dynamic programming principles have to be implemented to perform computational activities. Shimkin (2011) defines dynamic programming as a general approach to solve systems that possess multi-stage decision-making and optimal planning characteristics. The underlying idea is to use backward induction in order to reduce computational complexity. Backward induction is the process of determining a sequence of optimal decisions by reasoning backwards in time, therefore starting at the last decision epoch of the time horizon. The backward induction algorithm is described below.

1. Set t = N in Equation 3.6.1.
2. Substitute $t-1$ for $t$ and calculate $V_t^*(s_t)$ for each $s_t \in S$ by using equation 3.6.2 and set $a^*_{s_t,t}$ in equation 3.6.3.
3. If $t = 1$, stop. Otherwise return to step two.

**Objective:** To formulate a generic MDP model for an asset replacement problem.
**Outcome:** MDP model is formulated and can be executed in Step 2.3 to obtain the results.

#### 3.6.1.3 Step 2.3: Execute MDP Model

This step in the framework is focused on executing the MDP model to obtain results for an asset replacement problem. As discussed in Section 3.2, the model is flexible, scalable, and modular. The model can therefore be altered with minimal effort to obtain results for various time horizons and other model parameters and variables. In addition, the analyst in conjunction with the client need to ensure that realistic results are obtained. The results obtained in this step need to be processed and analyzed in the subsequent steps of the framework.

**Objective:** Execute MDP model to obtain results for an asset replacement problem.

**Outcome:** Results are obtained and can now be analyzed to present meaningful information to the client.

#### 3.6.1.4 MDP Example

An MDP example from Bauerle and Rieder (2011), which is known as the *Howard's toymaker*[1] problem in literature, is used as the basis in this example to illustrate a typical MDP problem and to validate the MDP code developed for this study. The toymaker aims to maximize the total discounted rewards for a system with two states, two actions, and four decision epochs. The problem is illustrated graphically in Figure 3.8 indicating the transition probabilities for both actions. The system can take two states $S = [s_1, s_2]$ with the following immediate rewards: $r(s_1, a_1) = 6$, $r(s_2, a_1) = -3$, $r(s_1, a_2) = 4$, $r(s_2, a_2) = -5$. The planning horizon $N$ is four periods with terminal rewards of $r_n(s_n, 1) = 104$ and $r_n(s_n, 2) = 102$ for both actions $A = [a_1, a_2]$. In addition, future rewards are discounted by 2%. The

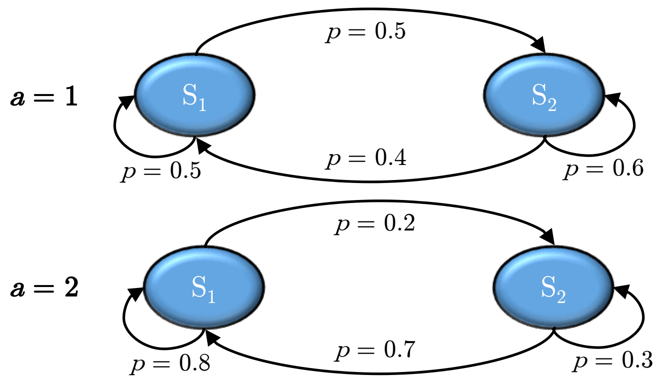



**Figure 3.8:** Markov Decision Process toymaker example
Adapted from Bauerle and Rieder (2011)

transition probability matrices for both actions are as follows, with $M(.|.,1)$ representing the transition probability matrix for action 1 and $M(.|.,2)$ representing the transition probability matrix for action 2.

[1]The Howard's toymaker problem is a popular numerical problem used in literature to illustrate and test backward induction algorithms.

$$M(.|.,1) = \begin{bmatrix} 0.5 & 0.5 \\ 0.4 & 0.6 \end{bmatrix} \text{ and } M(.|.,2) = \begin{bmatrix} 0.8 & 0.2 \\ 0.7 & 0.3 \end{bmatrix}$$

Executing the MDP code with the aforementioned data, the following results are obtained as illustrated in Table 3.3. The results indicate a total expected value and optimal action for each state at every decision epoch. For example, for decision epoch 1, the optimal decision is action 2 for system state 1 with total discounted expected rewards of 106.82.

**Table 3.3:** Computational results of backward induction algorithm

| **n** | $V_n(1)$ | $V_n(2)$ | $\pi_n^*(1)$ | $\pi_n^*(2)$ |
|---|---|---|---|---|
| 1 | 106.82 | 96.84 | 2 | 2 |
| 2 | 106.92 | 96.95 | 2 | 2 |
| 3 | 106.99 | 97.10 | 2 | 2 |
| 4 | 106.94 | 97.74 | 1 | 1 |
| 5 | 104 | 102 | NA | NA |

The results obtained for the data inputs correlate to Howard's toymaker example found in literature, thus validating the dynamic programming approach implementing the optimization algorithm of backward induction. The development of the framework is continued in the next section which aims to analyze the results obtained from the MDP model.

### 3.6.2 Analyze

The *analyze* part of Phase 2 aims to examine the results obtained in the preceding steps and to convert these results into value-adding information for the client. A sensitivity analysis aids the processes of analyzing results, but can also potentially add value to the client by identifying certain business opportunities with regards to controlling business risks. Moreover, results should be prepared in a manner that efficiently conveys the results to the various stakeholders involved.

#### 3.6.2.1 Step 2.4: Sensitivity Analysis

A sensitivity analysis is performed to analyze the effects of changing certain model parameters on the results. Some information concerning business risk forecasts in the MDP model are subjective and therefore open to interpretation. Performing a sensitivity analysis on the transition probabilities and effects of business risks would therefore provide an indication on the accuracy of the results. In addition, a sensitivity analysis can also be used to provide the client with useful information on the control of business risks. For example, managing a business risk such as labour relations and forcing it into a good state may decrease downtime and improve productivity. A sensitivity analysis would therefore illustrate the effects over a finite period of favorably managing a business risk which may assist and add value to certain organizational initiatives and strategies.
**Objective:** Perform a sensitivity analysis on the results obtained from the MDP model.
**Outcome:** The effects of parameter alteration are investigated and value is added to the client feedback process.

#### 3.6.2.2 Step 2.5: Prepare Results

The last step in Phase 2 of the framework is to prepare the results to be communicated to the client. Once the data is analyzed and a sensitivity analysis is performed, the results have to be transformed into meaningful information for the various stakeholders involved in the study. The study may have stakeholders with different technical skills, interests and objectives. Therefore, preparing the results using a certain communication strategy is of the utmost importance. Typical methods of preparing results include detailed reports, case studies, simulations, charts and figures, and verbal presentations. Step 2.5 is performed in parallel with Step 3.1 when selecting the communication strategy for the results.
**Objective:** Transform results into meaningful, value adding information.
**Outcome:** Results are transformed into meaningful information and can now be communicated to the client.

## 3.7 Phase 3: Results and Recommendations

Phase 3 of the framework aims to communicate the information, assumptions, and results obtained from the previous phases in an affective manner to the various stakeholders involved in the study. Effective communication strategies in this framework assist the analyst in providing the correct information to the applicable stakeholders to improve the asset replacement decision-making process. A graphical representation of Phase 3 is presented at the beginning of this section, in Figure 3.9, for the reader's convenience to use as a reference throughout the development of Phase 3.

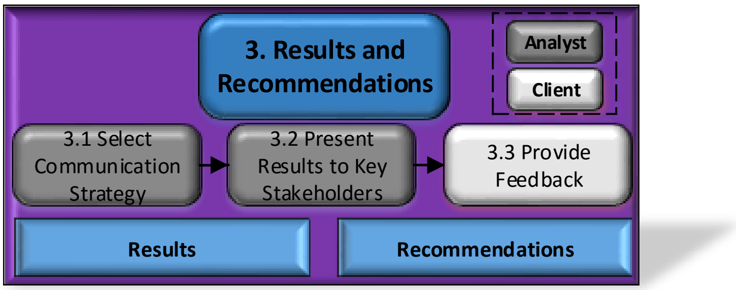



**Figure 3.9:** Results and recommendations phase of framework

### 3.7.1 Results

The first part of Phase 3 in the framework is aimed at selecting the correct communication strategy and using this strategy to communicate the results of interest to all key stakeholders involved in the study.

#### 3.7.1.1 Step 3.1: Select Communication Strategy

Selecting a strategy to communicate the results and other information obtained in previous steps of the framework the, analyst must consider what the clearest way is to present information to the key stakeholders. For example, in an asset replacement process there are multiple stakeholders including the asset manager, financial manager, and maintenance manager. Each of the aforementioned stakeholders is interested in different aspects of the asset replacement process. The asset manager is interested in the replacement policy, life cycle management and operating performance of the asset under consideration. The financial manager is interested in all financial considerations, whereas the maintenance manager is interested in the maintenance schedule of the asset. The analyst should therefore consider the specific needs of all the key stakeholders when selecting the results communication strategy. Step 3.1 and Step 2.5 are therefore performed simultaneously.

**Objective:** Select a strategy to effectively communicate the results to key stakeholders.
**Outcome:** Results can now be communicated to the key stakeholders.

### 3.7.2 Recommendations

The second part of Phase 3 in the framework aims to present the results and recommendations using the communication strategy selected in Step 3.1 and to invite all stakeholders to discuss and review results. Feedback from stakeholders often results in important realizations between departments in an organization to improve a process.

#### 3.7.2.1 Step 3.2: Present Results to Key Stakeholders

This step in the framework focuses on the actual process of communication the results to stakeholders. Typical aspects to be included in this step include a summary of the scope and objectives of the study, methods of data collection and evaluation, results, limitations, conclusions and recommendations. It is crucial to be objective during the presentation of the results. Both positive and negative results should therefore be communicated to the stakeholders. A variety of techniques can be implemented to present the results to stakeholders including written reports, simulations, oral presentations, and short videos. No one technique is sufficient to satisfy the requirements of all the stakeholders and an integrative approach is required. A critical aspect of this step is to invite stakeholders to review the results and provide feedback which is the main focus of Step 3.3.
**Objective:** Present results to key stakeholders in an effective manner.
**Outcome:** Results and recommendations are presented satisfying all key stakeholders' needs.

#### 3.7.2.2 Step 3.3: Provide Feedback

The last step in the framework aims to invite key stakeholders to discuss and review the results and recommendations provided by the analyst. Feedback from the stakeholders are integrated in future iterations of the framework to incorporate business risks in the asset replacement process. The feedback and discussions often lead to important realizations between stakeholders which improves organizational performance as a result of the holistic approach followed. For example, the asset manager may want to replace an asset with residual life left to improve long-term profitability considering an expected increase in commodity prices, whereas the financial manager aims to minimize all capital expenditure focusing on short-term targets. Facilitating this discussion may result in an increase in organizational performance.

**Objective:** Invite stakeholders to discuss and review the results and recommendations.

**Outcome:** Feedback is integrated in the framework for future iterations to incorporate business risks in asset replacement decisions.

Equipped with detailed information, objectives, and outcomes for all steps in phases one to three of the decision-making framework, these phases are combined to develop the final framework for incorporating business risks in asset replacement decisions in capital-intensive industries. A graphical representation of the complete version of the framework is illustrated in Figure 3.10 which is implemented on the case study presented in Chapter 4. A feedback-loop is incorporated in the final framework to facilitate the updating of variables and parameters according to the feedback obtained from the client in Phase 3.

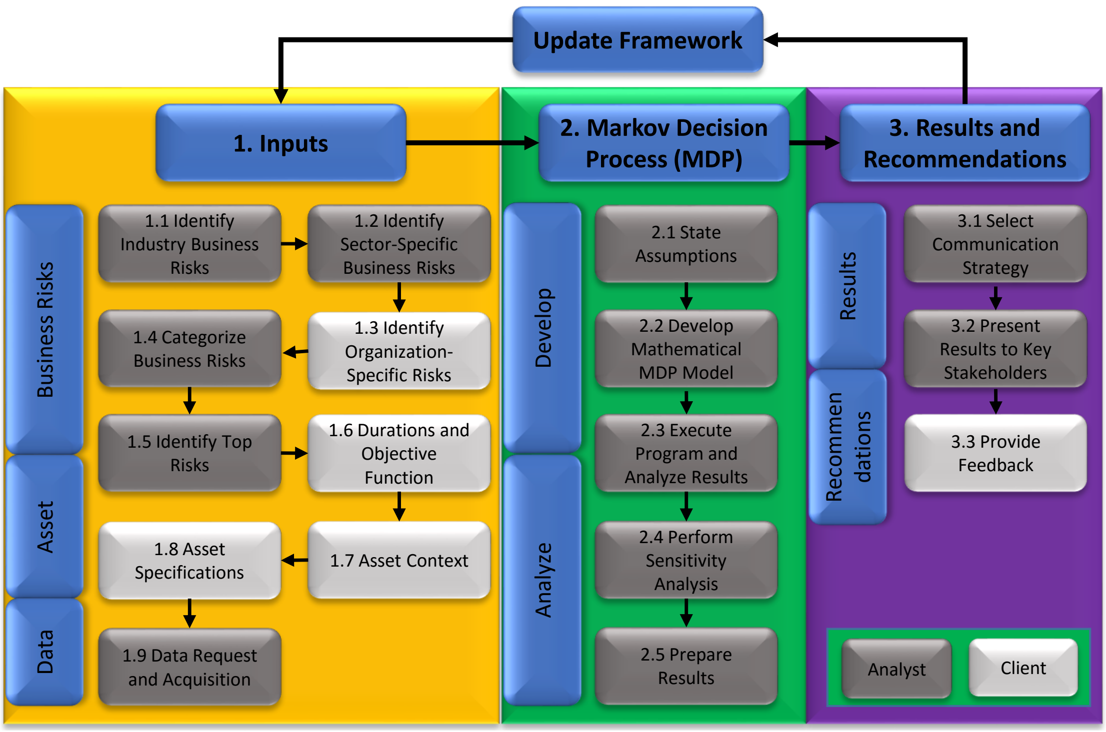



**Figure 3.10:** Framework incorporating business risks into asset replacement decisions

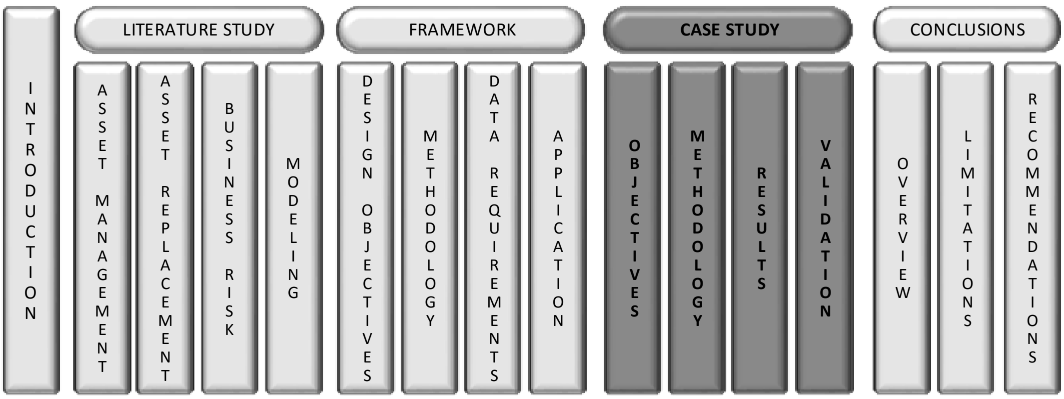
## 3.8 Chapter Summary

The primary focus of Chapter 3 is to design and develop the decision framework incorporating business risks into the asset replacement process. First, general framework design principles are discussed to provide a holistic structure to develop the framework for this study. Next, the scope and objectives of the framework developed in this chapter are introduced. Using the general framework design concepts, scope and objectives, a framework is developed to incorporate business risks into the asset replacement process. The framework is developed in three main phases including the Inputs, Markov Decision Process (MDP) model, and Results and Recommendations phases. The framework meets the requirements of a good decision-framework, as stated by Hunter (2006) in Section 3.2, which is: (1) it enables the identification and articulation of goals and objectives, (2) supports the prediction of certain outcomes, (3) is transferable across different applications, and (4) is modular, flexible and scalable. The framework developed in this chapter is used in the case study presented in Chapter 4 to incorporate business risks in the asset replacement process for a case in the mining industry.

# Chapter 4

# Case Study and Results

*"Given mounting levels of volatility and change, miners need to take a broader view of risk management and scenario analysis. This includes taking a much greater range of variables into account to inform their decision making."* - John Woods, Mining Leader, Deloitte Southern Africa




**Chapter Outcomes:**

- Introduce and contextualize case study within this research.
- Conduct a case study in the PAM domain by applying the framework for asset replacement decisions incorporating business risks as developed in Chapter 3.
- Validate the framework and case study results and perform a sensitivity analysis.
- Discuss and interpret results to be used as a basis for the conclusions drawn in Chapter 5.

## 4.1 Introduction

The primary objective of this chapter is to apply and validate the decision-making framework, developed in Chapter 3, to incorporate business risks into asset replacement decisions. This is achieved by conducting a case study at a diamond mine located in Southern African. The application of the decision-making framework follows the format of a retrospective case study for the period 2008 to 2013. The global financial crisis in 2008 brought the turmoil of unprecedented uncertainty to the mining sector. Mining organizations across all mining sectors were severely impacted, reliant on the bloated commodity prices of the super-cycle which plummeted to record-lows. Mining organizations now, in 2016, face similar economic and industry circumstances due to low commodity prices and a volatile business and operating environment.

Physical Asset Management (PAM) and more specifically, asset replacement decisions, is an important aspect in the mining industry where capital expenditure on physical assets form a large part of an organization's financial and operational strategies. Moreover, the mining industry operates within a volatile business environment with business risks constantly influencing boardroom decisions and strategies. A diamond mine is a prime example of an asset-intensive organization due to the fact that its revenue and operating performance is largely dependent on its physical assets. The mining industry is a good representation of a capital-intensive industry facing evolving business risks and is therefore a suitable environment to conduct the case study and validate the proposed solution.

The layout of Chapter 4 is as follows: The case study is formulated in Section 4.2 in which the contextual background, asset replacement in the mining industry, and the case study objectives are discussed. Next, the data collection procedure and instruments used to obtained the case study data are discussed in Section 4.3. The decision-making framework, developed in Chapter 3, is then applied to the case study at the diamond mining organization in Section 4.4. The delineation of the case study, results discussion, and sensitivity analysis form an integral part of the framework and is therefore incorporated in Section 4.4 and not discussed in separate sections. Lastly, the framework and the results obtained in the case study are validated in Section 4.5.

## 4.2 Case Study Formulation

This section aims to communicate the required information on the case study conducted at a diamond mine in Southern Africa. Contextual background is provided in Section 4.2.1 detailing the origin of the case study and the key role players involved. Section 4.2.2 introduces the asset under consideration for replacement in this case study as well as the operating and business environment of the organization and its current asset replacement strategies. Lastly, Section 4.2.3 discusses the key case study objectives in relation to this research.

### 4.2.1 Contextual Background

This study was conducted in collaboration with the Anglo American Corporation (AAC), the Asset Care Research Group (ACRG), and the Operational Excellence Research Group (OERG) at Stellenbosch University. The Anglo American Corporation is one of the world's leading mining organizations and operates with a diverse portfolio of commodities. These commodities include diamonds, iron ore, manganese, copper, coal, and platinum. The AAC operates in many continents including Africa, Europe, Asia, Australasia, North America, and South America. The ACRG facilitates interaction between theoretical research studies and industry in PAM and other AM related concepts. The ACRG investigates several aspects of PAM such as investment decision-making, reliability modeling, and organizational change in companies implementing PAM. The OERG is dedicated to solving advanced management problems preventing organizations reaching the state of operating excellence through the integration and exploitation of innovative engineering concepts with contemporary management sciences. A representative from the AAC agreed that a framework incorporating business risks into asset replacement decision would be an area worth exploring to improve both operational and strategic decision making. The representative directed the case study towards one of the AAC diamond mines located in Southern Africa for further investigation. For confidentiality reasons, the mine will consistently be referred to as *Mine X* for the remainder of this thesis.

When carbon is exposed to extreme pressures and high temperatures deep within the crust of the earth, diamond crystals are formed. Volcanic rock formations such as Kimberlite pipes facilitate the conveyance of diamond crystals from deep within the earth's crust to the surface. Kimberlite pipes, shaped like an inverse triangle, is considered to be the richest source of mined diamonds worldwide and is in abundance in Southern Africa. These volcanic rock formations can extend as deep as two kilometers underground. Diamonds can be mined using one of the following mining techniques: (1) open-pit, (2) underground, (3) alluvial, and (4) off-shore. The type of mining technique implemented by mining organizations depends on the location of the diamond deposits. Open-pit and underground mining methods are used for diamond deposits found deep in the earth, while alluvial mining methods are implemented to extract diamonds on the earth's surface from deposits of gravel, sand, and clay. Off-shore mining techniques are employed to mine diamonds located in the seabed.

Mine X is an open-pit diamond mine which means that the earth's crust is burrowed into layer-by-layer until diamond deposits are found. The diamond mining process at Mine X consists of six distinct steps and is described below:

1. Ore extraction: This mining step consists of three stages including excavation, extraction, and transport. Excavating ore requires drilling and blasting the overburden or top rock layers to extract the diamond ore. The excavated and extracted ore is then transported by haul trucks to the disposal or processing sections of the mine.

2. Comminution: Diamonds are liberated and ore particles are reduced to a manageable size in this step. This is achieved by crushing and scrubbing the ore.

3. Concentration: The crushed ore is mixed into a ferro-silicon and water mixture to separate the diamonds from the Kimberlite ore. Heavy diamonds sink to the bottom of the mixture and is extracted for further sorting and polishing processes. This process is also known as Dense Media Separation (DMS).

4. Recovery: Small traces of diamonds are recovered that were not separated from the Kimberlite ore in the previous step. Diamonds are recovered using techniques such as fluorescent lights, grease adhesives, and laser lights.

5. Sorting and sales: Diamonds are sorted, cleaned, packaged, and weighed. These finished diamonds are then sold to various stakeholders in different markets.

6. Waste disposal: The waste resulting from the concentration, recovery, and sorting phases are disposed of.

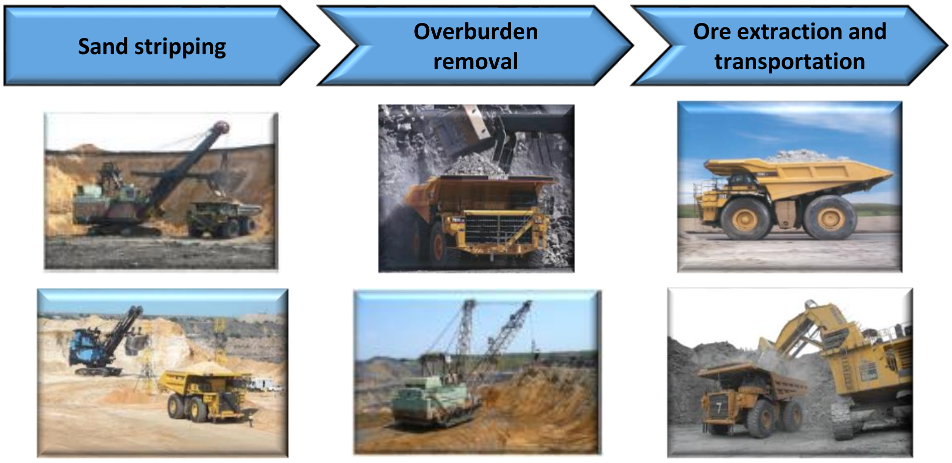



**Figure 4.1:** Mining process at Mine X
Image courtesy of Mine X

As illustrated in Figure 4.1, it is evident that haul trucks are critical in the first step of the mining process for excavation and transport purposes. More specifically, haul trucks transport the stripped sand, overburden, and diamond ore to various locations on Mine X. Equipped with an overview of the mining process at Mine X, Section 4.2.2 investigates the business-critical asset considered in this study and current asset replacement practices at Mine X.

### 4.2.2 Replacing Haul Trucks at Mine X

Organizations across all mining sectors are constantly aiming to improve operational performance in order to increase revenue and meet organizational objectives. Furthermore, economic globalization is responsible for the increasing competition among mining organizations as well as difficult operating conditions and fluctuating macro-economic factors. The equipment used in mining organizations are subject to performance degradation therefore increasing OM costs and reducing operating performance, resulting in a negative economic effect. What is more, mining organizations are often plagued by evolving business risks such as labour strikes, unreliable third party infrastructure, fluctuating commodity prices, stringent mining regulations, and political influences that dents investor confidence. In order to stay competitive, mining organizations are required to use the most reliable and efficient equipment. Reliable and efficient equipment in the mining industry is extremely expensive and capital investment strategies should therefore be optimal. Taking the aforementioned information into consideration, asset managers are faced with challenging questions such as the following:

- When should business-critical assets be replaced in order to minimize costs while maximizing organizational performance?
- How will the asset manager convince the finance and production managers to replace business-critical assets at a specified time?
- How to incorporate business risk forecasts into the equipment replacement process?

Jardine and Tsang (2013) provide an answer to the first question by stating that the optimum replacement time of equipment is the time at which LCC are at a minimum value. This strategy is employed throughout the mining industry, including Mine X, by using several tools and methods to aid the decision process such as failure statistics and detailed life cycle cost models. However, none of these methods take business risks and their evolution over time into consideration when making asset replacement decisions. The status quo for making asset replacement decisions at Mine X is to consider equipment condition and equipment LCC, therefore focusing on the traditional asset replacement factors. The decision to keep or replace a haul truck is performed on an annual basis. The business-critical asset under consideration in this case study is a Caterpillar 793C haul truck. These haul trucks are extremely expensive, in the order of US $ 5 million, and is critical in the diamond mining process. A haul truck comprises of numerous subsystems such as the power unit, undercarriage, body, and the drive-train. However, all subsystems are required to work simultaneously to achieve the desired function.

The Caterpillar 793C is used across all mining sectors to transport ore. The truck has a nominal payload of 240 tons with a gross operating weight of more than 383 tons (Caterpillar, 2016). It has a Caterpillar 3516B engine capable of delivering 1.71 MW of power. Figure 4.2 provides an indication of the sheer size of these haul trucks. The overall body length of the truck is 13.3 m as indicated by dimension 1. The inside body length, indicated by dimension 2, is 8.7 m while

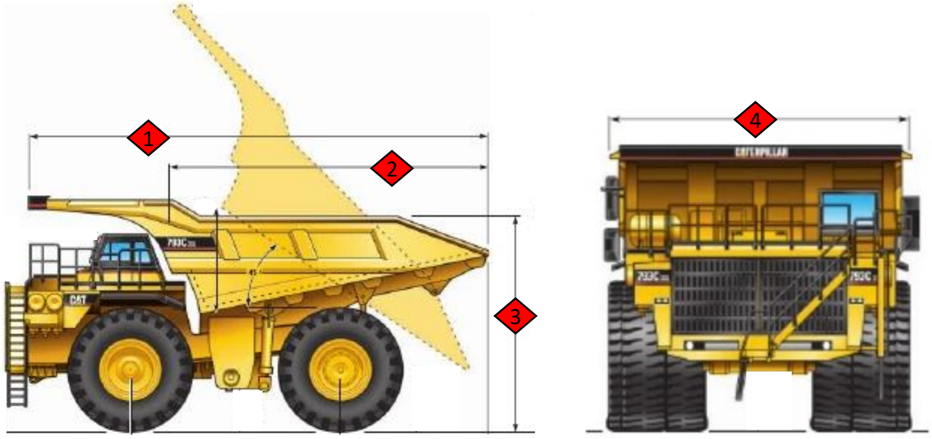



**Figure 4.2:** Caterpillar 793C haul truck
Adapted from Caterpillar (2016)

the loading height is 5.8 m as indicated by dimension 3. Dimension number 4 indicates the overall width of 7.7 m. Equipped with an overview of the mining process at Mine X, current haul truck replacement strategies and the asset under consideration for this case study, Section 4.2.3 discusses the case study objectives.

### 4.2.3 Case Study Objectives

The case study conducted at Mine X aims to incorporate business risks into the asset replacement process by focusing on a single business critical asset, a Caterpillar 793C haul truck. The scope and assumptions for the case study are inherently part of the framework and are therefore not explicitly discussed in this section. The application of the decision-making framework follows a retrospective case study format considering the period 2008 through 2013 to aid the validation process described in Section 4.5. The main objectives of the case study are listed below:

1. Implement the decision-making framework developed in Chapter 3 with a case study at Mine X.

2. Incorporate business risks in the asset replacement process of a Caterpillar 793C haul truck for the period 2008-2013.

3. Generate optimal replacement decisions for various system states and calculate the Total Expected Discounted Revenue (TEDR) associated with these decisions.

4. Validate the framework application methodology and results analysis.

5. Demonstrate that the decision-making framework is practical, holistic, logical, and structured.

In addition, the case study aims to illustrate certain features of the framework including: (1) it enables the quantification of business risks using a holistic approach, (2) provides a level of certainty associated with asset replacement decisions, (3) creates consistency and repeatability in the asset replacement process, and (4) enables management to make defensible decisions by considering the evolution of asset performance and business risks on a medium to long-term basis. The framework aims to generate a map of optimal replacement decisions for various organizational states on an annual basis for the period 2008-2013 by specifying whether to repair or replace the selected Caterpillar 793C haul truck in operation at Mine X. The organizational state is determined by the condition of the variables included in the framework such as the various business risks, financial and asset information. A typical question the framework aims to provide a maps of solutions to is:

> *Should a Caterpillar 793C haul truck be kept and repaired or replaced, taking into consideration the evolution of asset condition and business risks, given that the asset and organization is currently in the following state: asset's engineering availability is 85%, the condition of labour relations are bad, overall productivity is bad, Social License to Operate (*SLTO) *is good, and the global economy is average?*

In addition, the framework aims to specify the TEDR associated with the replacement actions, incorporating all identified and specified factors by the analyst and Mine X.

## 4.3 Data Collection Instruments

The successful application of the framework incorporating business risks into the asset replacement processes is reliant on quantitative and qualitative information from Mine X and several other sources. For the purpose of the case study, quantitative data used in the framework is retrieved from information management systems implemented by Mine X, organizational reports, industry reports, technical reports, the GUI developed as part of the framework in Step 1.9, and other electronic sources such as case studies for analogous situations. Qualitative information used in this case study is obtained through interviews and discussions with different stakeholders including the lead asset manager at Mine X, organizational reports from Mine X, reports from the mining industry, and electronic sources. The three main data requirements are illustrated in Table 4.1 together with the data collection instruments used to obtain the information.

**Table 4.1:** Data collection instruments

| **Data Requirement** | **Data Collection Instruments** |
|---|---|
| Business risks information | Interviews and discussions, organizational and industry reports, information management system |
| Asset information | Technical reports, information management system, electronic sources, discussions, electronic sources |
| Financial information | Organizational reports, discussions, electronic sources |

Equipped with an overview of the case study formulation that includes contextual background, information on replacing haul trucks at Mine X, and objectives for the case study, Section 4.4 illustrates the application of the decision-making framework to the case study at Mine X.

## 4.4 Application of Framework

This section illustrates the application of the framework, developed in Chapter 3, incorporating business risks in physical asset replacement decisions to the case study conducted at Mine X. The framework is applied sequentially from Phase 1 to Phase 3 for the period 2008 to 2013, focusing on a Caterpillar 793C haul truck in operation at Mine X and aims to meet the objectives of each step as described in Chapter 3. The procedural nature of the framework (see Figure 3.10, also illustrated for convenience in Figure 4.3) facilitates the straightforward application of the framework to the case study. Moving sequentially through the three phases of the framework, the following subsections describe the application of each step and illustrates the data used, assumptions made, and the results obtained.

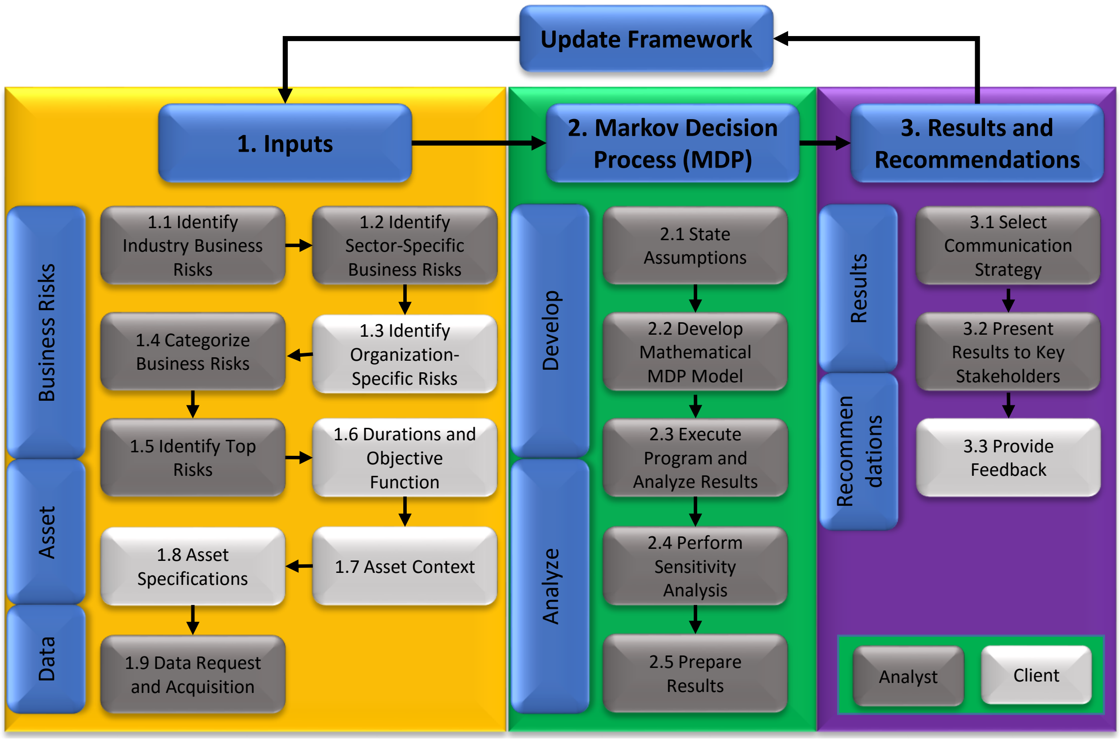



**Figure 4.3:** Framework incorporating business risks into asset replacement decisions

## 4.4.1 Phase 1: Inputs

The first phase of the framework, known as the Inputs-phase, focuses on three aspects including the identification and ranking of business risks, specification of Caterpillar 793C haul truck features and attributes and other significant study variables, as well as the data acquisition process. The Inputs-phase is the foundation to the development of the MDP model developed in the second phase. The primary objective of this phase is to contextualize the analysis and obtain the required data for the business risks and asset involved in the study.

### 4.4.1.1 Step 1.1: Identify Industry-Specific Business Risks

The framework starts with the identification of business risks specific to the mining industry as a whole. Referring to Figure 3.3, it is seen that the geographic location influences the industry-specific business risks. Therefore business risks applicable to the Southern African mining industry in 2008 are identified using industry reports from various sources. Although Southern Africa is home to developing countries, the mining industry as a whole essentially faces similar business risks across all mining sectors worldwide. In any mining sector, if the market is flooded with a commodity or the demand is low, prices will decrease significantly. The underlying fundamentals are therefore the same which is that material and talent shortages are still present in an environment where rising operating costs and stringent regulatory compliance threatens the sustainable development and operation of mining organizations. However, the political and regulatory instability in developing countries, including the country where Mine X is located, poses additional business risks.

Considering the aforementioned information, the top 10 industry-specific business risks are identified for Mine X using industry reports from KPMG, Ernst and Young, and Deloitte illustrated in Section 2.4.3. The top 10 risks are identified based on their frequency of occurrence in these mining industry reports. It is found that these reports often contain similar business risks resulting in a concurrence between consultation companies, adding to the credibility of these results. A concise discussion of each business risk, in no particular order, is presented below:

1. Skills shortage: The mining industry often utilizes staff from other industries yet to experience an upturn. In addition, it is often unattractive for young professionals to work at mines that are located far from urban life. There is also a large number of workers retiring or seeking other work opportunities due to the financial crisis, adding to the loss of skilled workers and their knowledge.

2. Commodity price volatility: Commodity prices are dependent on numerous factors including the supply and demand patterns as well as the global economic environment. In addition, operating costs are often incurred in foreign currencies putting additional financial strain on organizations.

3. Infrastructure access and reliance: The development of infrastructure projects is dependent on a number of stakeholders including the mining organizations, communities, governments, and financial institutions. Achieving the required coordination between all these stakeholders to develop infrastructure, is a great challenge. In addition, relying on third party infrastructure in everyday operations adds to this problem.

4. Social License to Operate (SLTO): There are numerous issues that can affect an organization's SLTO including environmental performance, worker's safety, community engagement, and land disputes.

5. Fraud and corruption: Fraud and corruption is often caused by political instability and it is noted that many mining organizations are seeking alternative investment destinations as a result thereof. Fraud and corruption therefore decreases organizational reputation and dents investor confidence.

6. Rising costs and decreasing productivity: The significant rise in costs and decline in productivity is interconnected to the commodity price cycles. The decline in productivity is a result of over investment during the so called *super-cycle* where organizations pursued volume-growth at all costs.

7. Capital allocation and access: Effective capital allocation is a continuous process that is dependent on a variety of external and internal factors. Capital access presents a significant threat to smaller mining organizations subject to risk averse investors.

8. Resource nationalism: Governmental regulations are resulting in shrinking returns for mining organizations while a greater share is flowing to national treasuries due to changes in mining, tax and royalty policies.

9. Increased regulation: Mining organizations are constantly expanding their global footprint, therefore exposing themselves to a greater diversity and magnitude of regulations. The consequences of adhering to these regulations are both extremely costly and burdensome.

10. Access to water and energy: Accessing water and energy is a critical part of mining operations and have become increasingly difficult. Electricity load shedding occurs due to a greater demand than supply of electricity and a water scarcity in Southern Africa have led to organizations adjusting strategic and practical responses to this business risk.

#### 4.4.1.2 Step 1.2: Identify Sector-Specific Risks

Business risks specific to the diamond mining sector in Southern Africa are identified in this step. These risks are additional to the risks identified in Step 1.1 and are obtained from industry and organizational reports as well as other electronic sources such as case studies in the diamond mining sector. These sector-specific risks are listed and discussed below (Bain and Company, 2014):

- Creating sustainable long term demand: Polished diamonds are often considered as luxury items. Therefore creating a long term demand for polished diamonds is more challenging than creating demand for rough diamonds, which is used in industrial tools. To ensure long term demand all stakeholders in the value chain must emphasize the emotional appeal of diamonds.

- Synthetic diamonds: Synthetic diamonds are produced in a laboratory with a process simulating the natural condition of high temperatures and pressure in the earth. Synthetic diamonds are mainly used in industrial tools, although it has become possible in recent years to produce high quality polished diamonds at a very high cost.

- Illegal and fake diamonds: Illegal and fake diamonds present the risk of flooding a market that is dependent on a delicate balance between supply and demand. To prohibit the illegal mining and trade of diamonds, including fake diamonds, the Kimberley Process Certification Scheme was introduced in 2002 by the United Nations. However, corruption in the mining industry may lead to the certification of illegally mined and fake diamonds.

The business risks identified in Steps 1.1 and 1.2 are presented to the representative of Mine X in the next of the framework step to consider and add organization-specific risks to the list before categorizing and ranking the risks.

#### 4.4.1.3 Step 1.3: Identify Organization-Specific Risks

Step 1.3 is performed by Mine X to identify organization-specific business risks that are unique to the organization that is not necessarily present in other diamond mining companies. The following risks were specified as important by the risk department at Mine X additional to the business risks identified in the previous steps of the framework:

- Physical asset performance: The operational performance of Mine X is critical to generating the maximum revenue and minimizing costs.

- Labour relations: Labour relations refer to workforce availability, retention, and engagement. Relations with the workforce is essential to the performance of Mine X and its ability to achieve organizational objectives. Unstable labour relations may result in strikes and ultimately a loss in productivity. Industry reports from Ernst and Young, Deloitte and KPMG indicate that overall productivity decreased as much as 15% from 2004 to 2008.

- Resources and reserves uncertainty: Uncertainty in resources and diamond reserves threatens the sustainable development and operating capabilities of Mine X. In addition, declining ore grades leads to an increase in costs.
- Lack of price transparency: A lack of price transparency prevents the development of a diamond investment market to a great degree and therefore threatens long-term growth and demand.

Having identified all significant business risks in Steps 1.1 to 1.3, these risks can now be categorized into operational, strategic, and external risks in Step 1.4.

#### 4.4.1.4 Step 1.4: Categorize Risks

Step 1.4 categorizes the business risks identified in the previous steps into three categories including operational, strategic, and external business risks. Section 2.4.2 indicated that categorizing these risks is an all encompassing approach to include business risks from the most probable sources that may influence organizational performance or decision-making processes and is performed in Table 4.2.

**Table 4.2:** Categorizing influential business risks

| **Strategic** | **Operational** | **External** |
|---|---|---|
| SLTO | Physical asset performance | Commodity price volatility |
| Fraud & corruption | Skills shortage | Resource nationalism |
| Capital allocation & access | Infrastructure access | Increased regulation |
| Creating sustainable demand | Decrease in productivity | Access to water & energy |
| Resources uncertainty | Labour relations | Synthetic diamonds |
| Price transparency | Rising costs | Illegal & fake diamonds |
| Reserves uncertainty | | |

It is evident from Table 4.2 that the risks identified in previous steps are present in all three categories indicating that business risks from all probable sources were considered and identified. The framework proceeds to determine the top business risks for Mine X in Step 1.5.

#### 4.4.1.5 Step 1.5: Identify Top Risks

Step 1.5 is performed by both the author, or the individual using the framework in practice, and the representative from Mine X, combining the expertise and knowledge gained in the previous steps to determine the most important risks to include in the MDP model in Phase 2. A trade-off is made between the number of risks to be included, its data requirements, and the computational efforts of the MDP model. It is decided to include the top five business risks in the MDP model. These top risks and other significant risks are illustrated in the risk map in Figure 4.4.

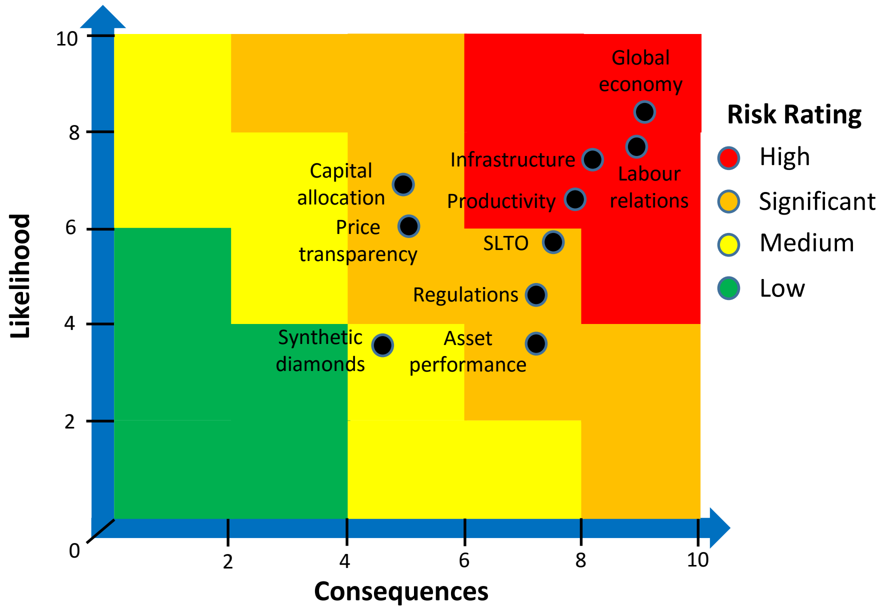



**Figure 4.4:** Risk map for top business risks

The top five business risks, in order of risk priority, include: (1) global economic circumstances and commodity price volatility, (2) labour relations, (3) reliance on third party infrastructure, (4) overall productivity, and (5) SLTO.

#### 4.4.1.6 Step 1.6: Analysis Decisions

The main objective of Step 1.6 is to specify the resolution of the system by specifying the time horizon, objective function and level of detail for the top five business risks. A trade-off is made between the author and the representative from Mine X taking into consideration the data requirements, cost, and computational effort when deciding on the resolution of the model. The following is a summary of the decisions made with regards to a number of variables and parameters:

- Replacement decisions are made on an annual basis for five years for the period 2008-2013.
- The objective function of the MDP model is to maximize the total expected discounted revenue for the period 2008-2013 associated with the Caterpillar 793C haul truck. A detailed discussion on how the total expected discounted revenue is calculated, is provided in Phase 2 of the framework.
- Each business risk is discretized into three levels that a business risk may evolve to over a certain time period. The business risk levels are labeled as *Bad*, *Average*, and *Good*. These labels describe the effect on the organizational revenue if the business risk is in a certain condition.

The costs associated with each condition of a business risk is obtained in the data acquisition process in Step 1.9. The next step in the framework provides the necessary context of the asset under consideration.

#### 4.4.1.7 Step 1.7: Provide Asset Context

The main objective of this step is to provide clarity on the asset context and how it affects the objective function specified in Step 1.6. Adding to the discussion in Section 4.2.2, Step 1.7 describes where the haul truck fits in the organizational set-up and how it influences organizational performance. The Caterpillar 793C haul truck is instrumental at Mine X throughout the diamond mining process. It is critical in the sand stripping, overburden removal, and the ore extraction process to shift large volumes of substance. The entire value chain at Mine X is therefore dependent on haul trucks to transport ore, sand, and overburden in order to generate revenue. Adding to Step 1.6. the objective function is therefore to maximize asset availability and revenue, while minimizing operating costs.

#### 4.4.1.8 Step 1.8: Asset Specifications

This step specifies the appropriate considerations that affects the asset replacement decisions for the Caterpillar 793C haul truck at Mine X and the overall system resolution. It was decided to consider the asset as a whole, even though a Caterpillar 793C haul truck consists of numerous subsystems. The performance degradation, and therefore the revenue associated with the truck, is based on an engineering availability graph, illustrated in Figure 4.5, which is discretized into five levels of availability for the MDP model. Engineering availability refers to the degree to which the haul truck is in an operable state at any point in time when it is needed expressed in a percentage measure. OM costs are calculated as 10% of the initial capital expenditure with an increase of 5% per annum. OM costs include preventive and corrective maintenance costs, as well as labour costs.

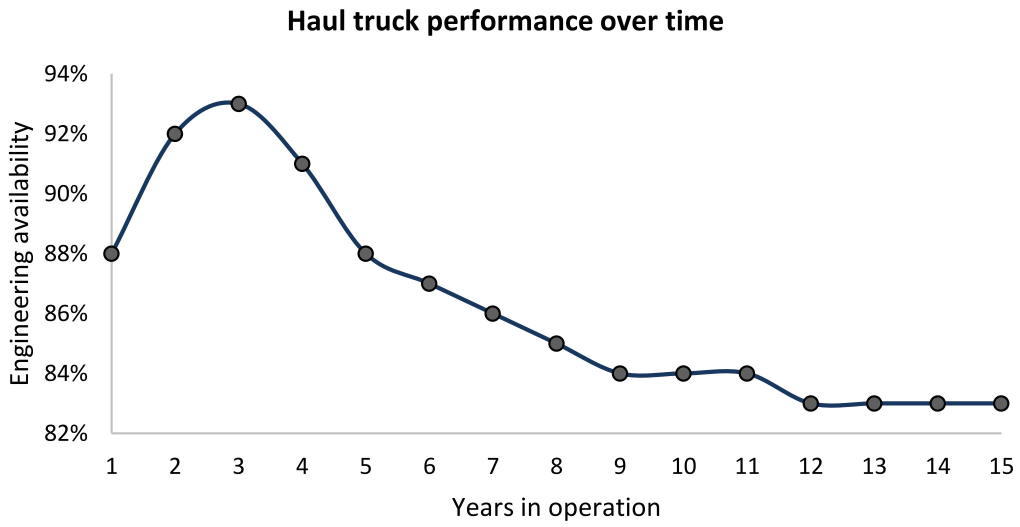



**Figure 4.5:** Engineering availability of Caterpillar 793C haul truck at Mine X

Financial depreciation is incorporated with the accelerated method and the asset's salvage value is based on market prices. The representative from Mine X highlighted that the market for used mining equipment is very limited. Haul trucks sell for far below its theoretical market value. It is therefore assumed that the salvage value of a used haul truck older than 10 years is negligible in financial calculations. Considering the resolution of the business risks and the haul truck, it is evident that the system size is 1215 states depending on the condition of each variable and is discussed in more detail in the MDP model in Phase 2.

#### 4.4.1.9 Step 1.9: Data Request and Acquisition

The last step in Phase 1 facilitates participation between the author and Mine X in the data request and acquisition process. The primary outcome of this step is to obtain data for all the relevant factors to be included in the MDP model. A GUI is developed in Microsoft Excel, as illustrated in Figure 3.5, to capture data on all the business risk and asset information required to model the system as specified in the preceding steps of Phase 1. For each business risk, transition probability and cost information is acquired from Mine X by using the GUI. The time value of money is also incorporated in the five year period by using a discount factor of 5%. Equipped with information on the context and scope of the analysis, and having obtained all the required data elements, the MDP model is developed in Phase 2.

### 4.4.2 Phase 2: MDP

Using the context, information and data obtained in Phase 1, the mathematical Markov Decision Process (MDP) model is develop in Phase 2. More specifically, a systematic process is followed to develop the MDP model to resemble the real-world system introduced in Phase 1 of the framework. The MDP mathematics presented in this phase elaborate on the generic equations introduced in Section 3.6.1. The results obtained in Phase 2 is used as the basis for the communication of the results and recommendation in Phase 3.

#### 4.4.2.1 Step 2.1: State Model Assumptions

All parameters, variables, and their associated assumptions are discussed in this step before developing the MDP model in Step 2.2. Specific assumptions associated with an MDP, discussed in Section 3.6.1, apply to the case study and include: (1) first-order Markovian dynamics, (2) state-dependent rewards, and (3) full observability of the system at each decision epoch. Assumptions specific to the system of the case study include the following:

1. A replacement decision takes place at the start of each decision epoch for the five years and an identical replacement asset (Caterpillar 793C haul truck) is immediately available if required.

2. Inflation, or the discount factor, remains constant throughout the period of investigation and is therefore not affected by macro-economic circumstances.

3. Installation costs when replacing the haul truck are not included as an independent parameter in the MDP model.

4. Taxes are not included as an independent parameter in the MDP model. Taxes are included in the purchase price, and all other expenses such as OM costs as specified by Mine X.

5. The revenue associated with the haul truck in the case study is calculated as the average revenue associated with a haul truck at Mine X. The same ratio is used to incorporate the effects of the business risks on the TEDR.

6. The Caterpillar 793C haul truck considered in the case study has an operational age of five years at Mine X at the start of 2008.

An important concept incorporated in the MDP model is the assumption that a business risk does not change condition between decision epochs. Replacement decisions are made annually and therefore incorporates the annual transition probabilities of business risks and the haul truck's engineering availability profile. The next step illustrates the parameters, variables, equations and methodology used to develop the MDP model for the case study.

#### 4.4.2.2 Step 2.2: Develop MDP Model

Using the information and data from the preceding steps in the framework, the MDP model is formulated and developed in Step 2.2 by using a systematic and logical process. The primary objective of the MDP model is to maximize the TEDR associated with the haul truck considering the traditional asset replacement factors including OM costs, financial depreciation, salvage value, and performance degradation as well as the impact of the forecasted evolution of business risks faced by Mine X as identified in Phase 1 of the framework. The calculation of the TEDR at each decision epoch is illustrated in Equation 4.4.1 and consists of the immediate rewards and the forecasted, or expected, rewards. A summary of the MDP follows: at each time period $t$ the system state $s$ provides the decision maker with all the information necessary for choosing a replacement action $a$. As a result of choosing an action, the decision maker receives an immediate reward $R_t(s_t, a)$, consisting of the combined effects of the asset related and business risk related immediate rewards illustrated in Equation 4.4.3, and the system evolves to a (possibly different) state $s'$ with a probability $P_t(s'|s_t, a)$.

A series of optimal replacement actions must be made to maximize the objective function for the finite period of five years in this case as illustrated in Equation 4.4.4. The system for the case study may inhibit any one of 1215 states at a decision epoch, illustrated in Equation 4.4.2, at any time depending on the asset condition and the condition of the various business risks that Mine X faces.

$$V_t^*(s_t) = \max_{a\in A_s}\left\{R_t(s_t,a) + \frac{\sum_{s'\in S} P_t(s'|s_t,a)V_{t+1}^*(s')}{(1+\gamma)}\right\}, \quad t = 1,2,...,5 \text{ and } s_t \in S \tag{4.4.1}$$

$$\begin{aligned} x_{\text{total}} =& x_{\text{asset}} \times x_{\text{SLTO}} \times x_{\text{economy}} \times x_{\text{labour}} \times x_{\text{productivity}} \\ &\times x_{\text{infrastructure}} \\ =& 5\times3\times3\times3\times3\times3 \\ =& 1215 \text{ states} \end{aligned} \tag{4.4.2}$$

Elaborating on the description of the system state, an example is provided to clarify what the system state entails. A consistent process is used to describe and calculate various MDP concepts. Considering system state $s_{1215}$, this refers to (1) the asset operating with an engineering availability of 93%, therefore being in the best operating state, (2) the business risk global economic circumstances and commodity price volatility is in a *good* condition, (3) labour relations are in a *good* condition, (4) reliance on third party infrastructure is in a *good* condition, (5) operational productivity is in a *good* condition, and (6) SLTO is in a *good* condition. A similar convention is followed to calculate the associated system rewards and system transition probabilities. Selected parts of the code used to develop the MDP model in the software package Matlab is illustrated in Appendix A.

$$\begin{aligned} R_t(s_t,a) &= \sum_{s_t\in S} r_t(s_t,a) \\ &= \sum_{s_t\in S} r_t(s_t,a)_{\text{asset}} + \sum_{s_t\in S} r_t(s_t,a)_{\text{business risks}} \end{aligned} \tag{4.4.3}$$

The generic components used to describe an MDP model, introduced in Table 3.2, is applied to the case study system and illustrated in Table 4.3. A description, value or equation used to calculate a component is provided for each MDP component. A decision policy map, a 1215 × 5 matrix, is generated as the recommended replacement actions for each decision epoch. This matrix recommends the optimal replacement action for each system state using Equation 4.4.4.

$$a_{s_t,t}^* \in \arg\max_{a\in A_s}\left\{R_t(s_t,a) + \frac{\sum_{s'\in S} P_t(s'|s_t,a)V_{t+1}^*(s')}{(1+\gamma)}\right\}, \quad t = 1,2,...,N-1 \tag{4.4.4}$$

To calculate the system transition probability matrix $M_t(s'|s_t,a)$ as illustrated in Equation 4.4.7 certain statistical concepts, specifically probability theory, is employed. The individual transition probabilities of the business risks and asset

**Table 4.3:** Components for the case study Markov Decision Process model

| Component | | Description |
|---|---|---|
| $T$ | = | A set of points in time at which actions are taken $t \in T = [1, 2, ..., 5]$ |
| $S$ | = | A finite set of all possible values and attributes describing the dynamics of the system. $S = \{s_1, s_2, ..., s_{1215}\}$ |
| $x$ | = | Total number of system states used to describe system characteristics, $x = 1215$ for the case study as illustrated in Equation 4.4.2. |
| $P_t(s'\|s_t, a)$ | = | Describes the transition probability by which the system state is $s'$ at the next decision epoch $(t+1)$ when the system is in state $s_t$ and action $a$ is taken at decision epoch $t$, illustrated in Equation 4.4.5. |
| $A_s$ | = | Describes the replacement actions for any state $s \in S$ with $A_s = [a_1, a_2]$ with $a_1$ – keep and repair asset, and $a_2$ – replace asset |
| $M_t(s'\|s_t, a)$ | = | An $1215 \times 1215$ transition probability matrix describing the system dynamics for each action at a decision epoch, illustrated in Equation 4.4.7. |
| $R_t(s_t, a)$ | = | Reward function is the immediate reward received or penalty incurred, illustrated in Equation 4.4.3. $r_t(s_t, a)_{\text{asset}}$ includes all asset related financial considerations, analogous to $r_t(s_t, a)_{\text{business risks}}$ |
| $\pi$ | = | Policy is a set of decision rules $\pi = [d_1, d_2, ..., d_5]$, optimal policy is denoted as $\pi^*$ |
| $\gamma$ | = | Discount factor to discount future rewards, $\gamma = 0.05$ |
| $V$ | = | Total expected value, or TEDR, for a certain policy $\pi$, $V^*$ denotes optimal value for TEDR as illustrated in Equation 4.4.1. |

condition is independent, therefore employing Equation 4.4.5 enables the calculation of the transition probability of each system state. It is evident from Equation 4.4.5 that each state transition probability for the system is dependent on the current state and the replacement action taken. A sample calculation is provided in Equation 4.4.6 to calculate $P(2|1,1)$, which refers to the system transition probability from state $s_1$ to $s_2$ when taking action 1 (keeping and repairing the haul truck). It is therefore the product of all the transition probabilities of the variables influencing the system state. Using the data from Mine X collected in Step 1.9, it is evident that the system state transition probability from $s_1$ to $s_2$ for action $a_1$ is 8%.

$$P_t(s'|s_t, a) = \prod_{s' \in S} p_t(s'|s_t, a) \tag{4.4.5}$$

$$\begin{aligned} P(2|1,1) =& p(2|1,1)_{\text{asset}} \times p(2|1,1)_{\text{SLTO}} \times p(2|1,1)_{\text{economy}} \times p(2|1,1)_{\text{labour}} \\ & \times p(2|1,1)_{\text{infrastructure}} \times p(2|1,1)_{\text{productivity}} \\ =& 0.25 \times 0.8 \times 0.84 \times 0.7 \times 0.85 \times 0.8 \\ =& \ 0.08 \end{aligned} \tag{4.4.6}$$

$$M_t(s'|s_t,a) = \begin{bmatrix} p_{11} & p_{12} & p_{13} & \cdots & p_{1\ 1215} \\ p_{21} & p_{22} & p_{23} & \cdots & p_{2\ 1215} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ p_{1215\ 1} & p_{1215\ 2} & p_{1215\ 3} & \cdots & p_{1215\ 1215} \end{bmatrix} \tag{4.4.7}$$

More detailed equations and matrix algebra used to calculate the various parameters can be found in Appendix A. From the overview of the development of the MDP model provided in Step 2.2, the model is now executed and results are obtained in Step 2.3.

#### 4.4.2.3 Step 2.3: Execute MDP Model

The MDP model developed in Step 2.2 for the case study system is executed in this step to obtain results for the Caterpillar 793C haul truck replacement problem for the period 2008 to 2013. The results obtained in this step are analyzed to present meaningful and value-adding information to the client in the following steps. The primary objective of the model is to incorporate business risks in the asset replacement process for a finite period of five years at Mine X. With this in mind, the outputs of the model that is of interest to Mine X is the TEDR and the replacement policy for various system states, but specifically for the conditions of the haul truck under consideration. The TEDR and replacement policy are generated for all 1215 system states to provide a decision-making tool for Mine X for various organizational, or system, conditions. Three sample systems, illustrating the range of system states, are shown along with the case study system state of the Caterpillar 793C haul truck. The actual system state that is of importance to Mine X is state 894, labeled as CAT 793C, and is explained in Table 4.4.

Focusing on the system state for the haul truck in this case study, labeled CAT 793C, the following observations are made at the start of 2008 which is the start of the period to find the optimal replacement policy for the haul truck aiming to maximize the TEDR: (1) the engineering availability of the haul truck is 90.5%,

**Table 4.4:** System state definitions

| System state | Asset | SLTO | Economy | Labour | Productivity | Infrastructure |
|---|---|---|---|---|---|---|
| CAT 793C | 90.5 % | Good | Bad | Average | Good | Average |
| 1 (Worst) | 83 % | Bad | Bad | Bad | Bad | Bad |
| 608 (Average) | 88 % | Average | Average | Average | Average | Average |
| 1215 (Best) | 93 % | Good | Good | Good | Good | Good |

(2) the SLTO is in a *good* condition, (3) the global economy is in a *bad* condition, (4) labour relations are in an *average* condition, (5) overall productivity is in a *good* condition, and (6) the access to infrastructure and reliance on third party infrastructure is in an *average* condition. The MDP model then uses these inputs to generate the TEDR for the five year period, illustrated in Figure 4.6, and the optimal replacement policy shown in Figure 4.7. It is evident from these results that for the haul truck considered in this case study, the associated TEDR for the period 2008 to 2013 is US $ 113,17m if the optimal policy is followed. The optimal policy is to replace the haul truck in 2009. The TEDR for the year 2013 is the predicted salvage value of the Caterpillar 793C haul truck, also known as the terminal rewards in the MDP model. It is evident that the limited resale value of mining equipment, the haul truck in this case, is almost negligible compared to the costs and revenue associated with it.

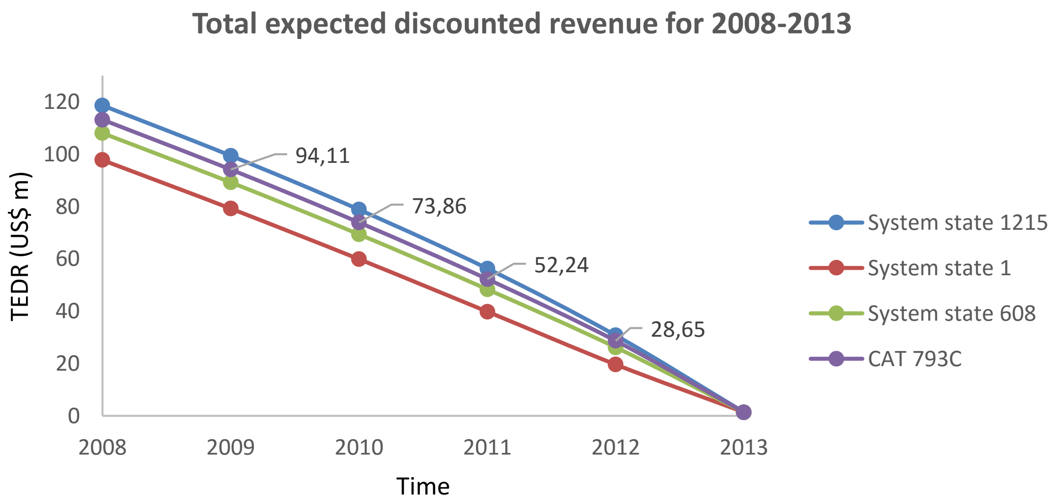



**Figure 4.6:** Total Expected Discounted Revenue (TEDR)

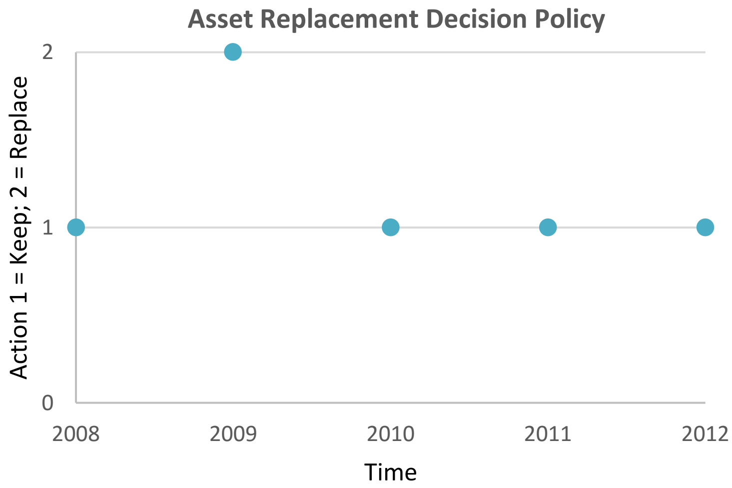



**Figure 4.7:** Replacement policy for CAT 793C

A real strength of the framework, MDP model, and results generated in this section is that it incorporate the expected volatilities associated with the business risks and the performance degradation of assets, using transition probabilities, in the mining industry. Moreover, the map of solutions provide numerous possible system states which can be updated at each new decision epoch (annually in this case study), as illustrated in Figure 4.3. Therefore if conditions change at the next decision epoch, a new forecast is generated that can be followed. The validation of the framework in Section 4.5 investigates the recommended replacement policy and TEDR from this section to the actual results and conditions obtained from Mine X. The next step in the framework is to perform a sensitivity analysis to investigate the variation in results due to a change in the value of certain parameters.

#### 4.4.2.4 Step 2.4: Sensitivity Analysis

Step 2.4 facilitates the process of performing a sensitivity analysis on the results obtained for the Caterpillar 793C haul truck from the previous step. More specifically, the sensitivity analysis investigates the effect of using a different condition of a business risk at the beginning of the analysis period (2008) while all other variables follow their original forecasted path. The average effect over the five year period on the TEDR is analyzed with two primary objectives. The first objective is to analyze the variational effect on the outcome, being the TEDR, when using a different variable condition. An example of the first objective: if the condition of labour relations are incorrectly identified as being in a *good* condition at the start of the analysis period, what is the average effect on the TEDR for the study? The second objective is to possibly identify certain opportunities to make informed business decisions. For example, what is the effect on the five-year TEDR if the organization can control the business risk SLTO in a favorable manner to improve organizational performance? The sensitivity analysis uses the conditions of the Caterpillar 793C used in the previous step to analyze the various objectives. The magnitude of the variation is primarily influenced by two factors as is evident from Equation 4.4.1 which is used to calculate the TEDR. These two factors are: (1) the costs associated with the business risk condition for Mine X, and (2) the transition probabilities for the five year period. The results for the sensitivity analysis are summarized in Table 4.5.

**Table 4.5:** Sensitivity analysis results for TEDR

| | **% Change in TEDR** | | |
|---|---|---|---|
| **Business risk** | **Bad** | **Average** | **Good** |
| SLTO | -0.066 | -0.026 | N/A |
| Labour relations | -4.972 | N/A | +2.469 |
| Global economy | N/A | +0.603 | +1.976 |
| Infrastructure | -0.070 | N/A | +0.047 |
| Overall productivity | -11.291 | -5.286 | N/A |

It is evident from Table 4.5 that labour relations and overall productivity have the most significant effect on the TEDR over the five year period. This was confirmed in discussions with Mine X. Feedback from Mine X reaffirmed that overall productivity which includes operational, labour, and capital productivity was the most influential business risk for the period 2008 to 2013. Several factors contributed to this decrease in productivity including labour issues, declining ore grades, lack of innovation, and economies of scale brought about by the mining super cycle just before 2008. The final step in Phase 2 is facilitates the preparation of result for the applicable stakeholders.

#### 4.4.2.5 Step 2.5: Prepare Results

Step 2.5 is performed in parallel with Step 3.1 when selecting the communication strategy for the results generated in Phase 2. Step 2.5 identifies the relevant results as obtained in Steps 2.3 and 2.4 to present to key stakeholders from

Mine X. For this case study, there is primarily one key stakeholder from Mine X which is the Asset Manager. The Asset Manager may use the results to facilitate discussions with other relevant stakeholders within Mine X including representatives from the finance, production, and maintenance departments. Therefore, preparing the results using a certain communication strategy is of the utmost importance. The methods used in this case to generate the results include figures, tables, and a written report. The results that are of interest to Mine X is a $1215 \times 5$ map of the TEDR and its associated replacement policy for each system state for the five year period as generated in Step 2.3. More specifically, Figures 4.6 and 4.7 are emphasized for the Caterpillar 793C haul truck considered in this case study, however, the generated maps can be used for many other haul trucks in operation at Mine X by simple selecting the corresponding system state. Moreover, the sensitivity analysis performed in Step 2.4 is used to present recommendations on the management of business risks as well as the deviations in the results such as the TEDR for the five year period. Next, Phase 3 is performed to communicate the results and recommendations obtained in Phase 2 for the system that was specified in Phase 1.

### 4.4.3 Phase 3: Results and Recommendations

Phase 3 of the framework communicates the information, assumptions, and results obtained from the previous phases in an affective manner to the stakeholders from Mine X. Effective communication strategies in this framework assist the process for providing the correct information to the applicable stakeholders to improve the asset replacement decision-making process in Mine X by taking into consideration the effect of business risks.

#### 4.4.3.1 Step 3.1: Select Communication Strategy

Step 3.1 selects a strategy to effectively communicate the relevant value-adding results identified in Step 2.5 to key stakeholders. Considering the primary (Asset Manager) and secondary (finance and production departments) stakeholders, the communication strategy selected to communicate the results is a formal presentation. The presentation includes an overview of the framework and the entire process followed to obtain the results along with all assumptions and limitations. The most significant results included in the presentation is Figure 4.6 showing the TEDR for the analysis period, Figure 4.7 illustrating the recommended replacement policy, and Table 4.5 explaining the sensitivity analysis results.

#### 4.4.3.2 Step 3.2: Present Results to Key Stakeholders

Step 3.2 implements the communication strategy selected in Step 3.1 to convey the results and recommendations as determined in the preceding steps of the framework. A meeting was arranged with the Lead Asset Manager from Mine X to present the framework, results and various other aspects. The aspects include a summary of the scope and objectives of the study, methods of data collection and evaluation, results, limitations, conclusions and recommendations.

#### 4.4.3.3 Step 3.3: Provide Feedback

The final step in the framework is for Mine X to provide feedback on the aspects presented in Step 3.2. Feedback from Mine X was received in the form of a discussion and interview at the presentation. Some parts of the feedback obtained from Mine X is discussed in more detail in the validation of the framework in Section 4.5. The main outcome of Step 3.3 is to integrate the feedback and recommendations from Mine X in the framework for future iterations to improve the process of incorporating business risks in asset replacement decisions. The feedback received from Mine X is illustrated in Appendix B in the form of an interview that took place during the meeting as mentioned in Step 3.2. Having applied the framework to the case study at Mine X in Section 4.4, the framework is validated in the next section.

## 4.5 Validation

The purpose of Section 4.5 is to validate or ascertain whether the framework incorporating business risk into physical asset replacement decisions in capital-intensive industries has any value from both a theoretical and practical point of view. The framework is validated by means of a retrospective case study that is applied to the diamond mining sector in Southern Africa at Mine X. The framework is built on the foundation of a thorough literature base incorporating the most significant concepts in asset replacement in capital-intensive industries. These concepts include AM, asset replacement, business risks and modeling techniques. This holistic approach to asset replacement ensures that the framework can be applied to various types of physical assets in numerous capital-intensive industries. Moreover, the framework incorporates a structured and logical approach to decision making as is evident in the application of the framework to the case study. What is more, the framework builds on the work of Hartman and Tan (2014) and van Wyk *et al.* (2016), adding to the asset replacement literature by following a dynamic programming approach to determine the optimal replacement time of a business-critical physical asset.

Validating the framework through the retrospective approach for the Caterpillar 793C haul truck used in the case study, the following results are obtained. Figure 4.8 illustrates the TEDR for the five year period as forecasted by the framework and the actual revenue generated at Mine X associated with the haul truck for the period 2008 to 2012 for the system conditions illustrated in Table 4.6. The five-year estimate for the framework is 4.48% higher than the actual revenue at Mine X. This difference can be attributed to the limited number of business risks included in the study and the uncertainty associated with forecasting the transition probabilities and the effects of business risks as well as the assumptions made to simplify the asset's operating condition.

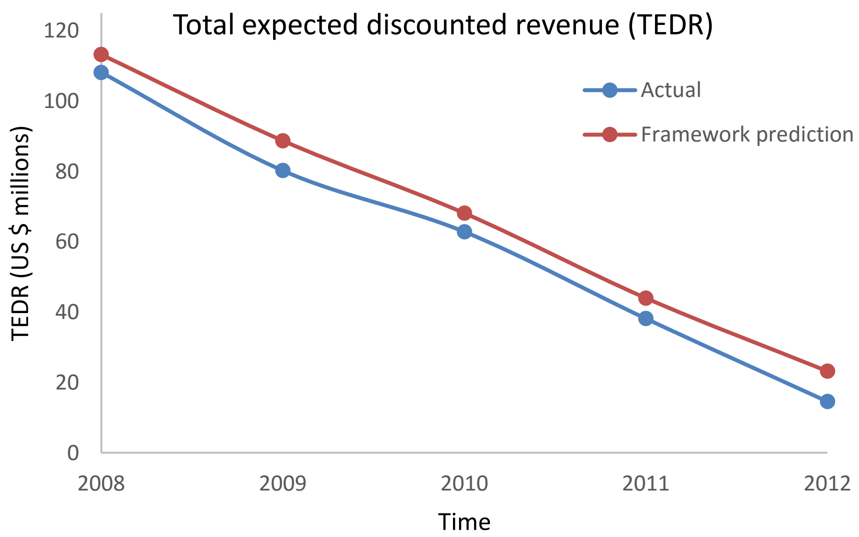



**Figure 4.8:** Forecasted TEDR versus actual revenue

Figure 4.9 illustrates the recommended replacement policy versus the actual followed policy by Mine X. The framework indicates that the haul truck should have been replaced in 2009 with an operating age of seven years. This replace-

**Table 4.6:** Actual system states for MDP model

| System variable | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|
| Asset operating condition | 4 | 3 | 2 | 2 | 2 |
| SLTO | Good | Average | Average | Average | Average |
| Global economic conditions | Bad | Bad | Bad | Average | Average |
| Labor relations | Average | Average | Average | Average | Average |
| Overall productivity | Good | Average | Average | Bad | Bad |
| Infrastructure | Average | Bad | Bad | Bad | Average |

ment age is further validated by conducting an Equivalent Annual Cost (EAC) analysis using the same parameters as used in the framework for the Caterpillar 793C haul truck. The optimal replacement age from the EAC analysis is 7.5 years, illustrated in Figure 4.10, and correlates well with the framework recommendation of 7 years considering the annual decision-making resolution of the framework. The EAC is the annual cost of owning and operating an asset over its entire lifespan. An EAC analysis therefore aims to minimize the EAC of an asset by focusing on the traditional asset replacement factors including capital expenditure, OM costs, depreciation, and salvage value.

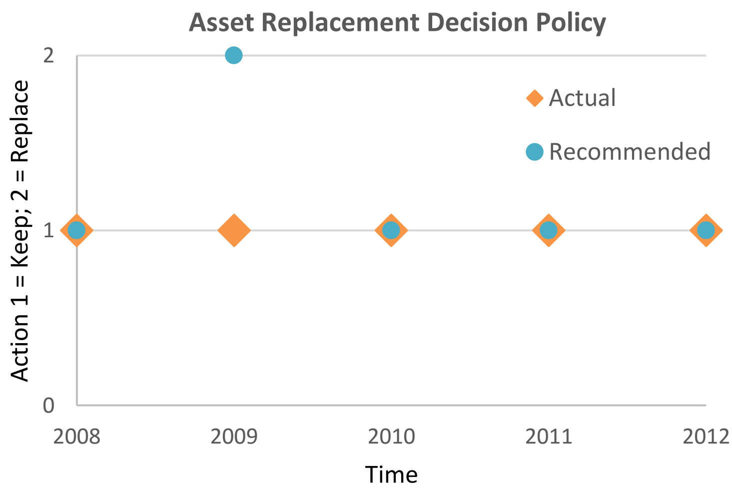



**Figure 4.9:** Recommended replacement policy for CAT 793C haul truck

The framework and the results obtained was presented to, and discussed at length with, a representative in a senior managerial role at Mine X. In retrospect, management from Mine X agreed that the decision to minimize capital investments in the period considered for this case was not optimal. Management agreed that major factors that led to the dramatic decrease in overall productivity, evident from the plant availability at Mine X, was caused by deferring capital expenditure, worsening labour relations, tough global economic circumstances, and reliance on third party infrastructure, similar to the business risks considered in the case study. These important lessons to incorporate the effect and evolution of business risks are expected to be of significant importance in the next few years (2016 - 2020) since the economic outlook and business risk conditions are in line with the crisis faced by the mining industry in 2008.

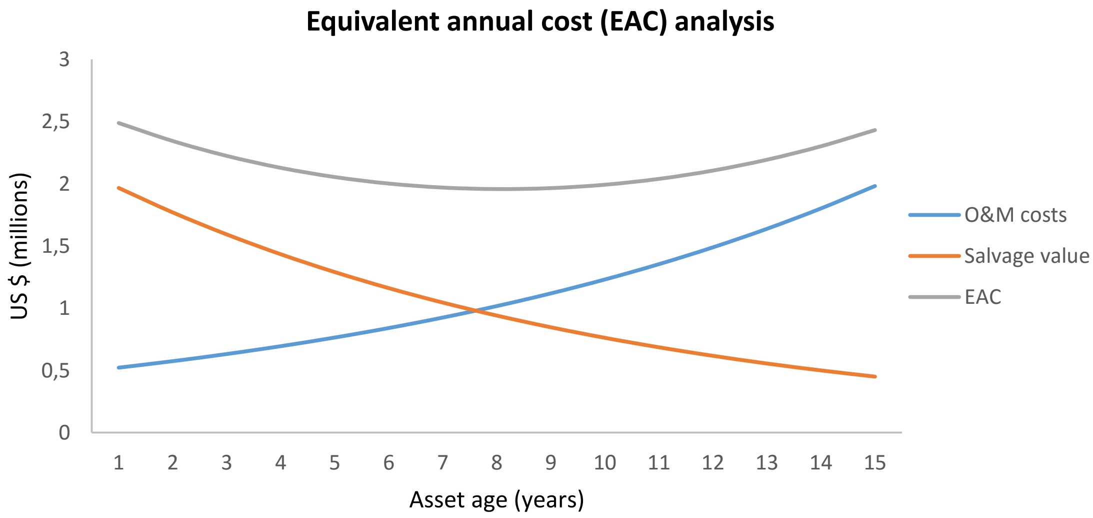



**Figure 4.10:** Equivalent Annual Cost (EAC) analysis for CAT 793C haul truck

In addition, the interview conducted with the Lead Asset Manager at Mine X on the framework is provided in Appendix B. The positive feedback on the framework from the interview illustrates both the theoretical and practical value of incorporating business risks into asset replacement decisions. When asked if the framework could assist analysts in the asset replacement process in industry to: (1) quantify overall risk, (2) provide a level of certainty associated with asset replacement decisions, (3) create consistency and repeatability in the decision-making process, and (4) enable the process of making defensible decisions by considering various types of business risks the response from Mine X was: *"Absolutely. I absolutely believe in your model."*

## 4.6 Chapter Summary

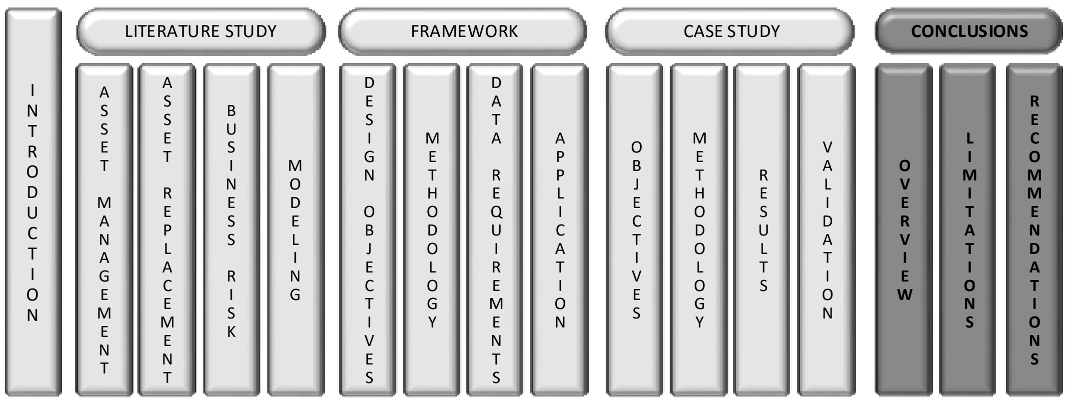
The primary objective of Chapter 4 is to implement and validate the framework incorporating business risks in asset replacement decisions in capital-intensive industries developed in Chapter 3. To implement and validate the framework, a case study was conducted in collaboration with the AAC at a diamond mine located in Southern Africa. The case study is formulated in Section 4.2 in which the contextual background, asset replacement in the mining industry, and the case study objectives are discussed. Next, the data collection procedure and instruments used to obtained the case study data are discussed in Section 4.3. The framework, developed in Chapter 3, is then applied to the case study at Mine X in Section 4.4. More specifically, the case study focuses on a Caterpillar 793C haul truck at Mine X for the period 2008 to 2013 incorporating the following business risks in the asset replacement process: (1) global economic circumstances, (2) labour relations, (3) overall productivity, (4) reliance on third party infrastructure, and (5) SLTO.

The framework applied to the case study maximized the TEDR and generated a replacement decision policy associated with the maximum TEDR for the haul truck. The optimal policy was to replace the haul truck in 2009 with a TEDR of US $ 113.17m for the five year period. In addition, a map of optimal replacement policies with their associated TEDR was generated for various other haul trucks at Mine X depending on their operating condition. The delineation of the case study, results discussion, and sensitivity analysis form an integral part of the framework as discussed in Section 4.4. Lastly, the framework and the results obtained in the case study are validated in Section 4.5. The forecasted TEDR was found to be 4.48% higher than the actual revenue associated with the haul truck at Mine X for the five-year period, a very accurate prediction for financial budgeting purposes. The replacement of the asset at an operating age of 7 years recommended by the framework, was validated by conducting an EAC analysis illustrating the optimal replacement age is 7.5 years focusing only on traditional asset replacement factors.

The framework was further validated by Mine X illustrating both the theoretical and practical value of the framework. Moreover, the application and validation of the framework illustrates certain features of the framework including: (1) it enables the quantification of business risks using a holistic approach, (2) provides a level of certainty associated with asset replacement decisions, (3) creates consistency and repeatability in the asset replacement process, and (4) enables management to make defensible decisions by considering the evolution of asset performance and business risks on a medium to long-term basis. The proposed framework is therefore validated and the research proposition is evaluated. The following chapter, Chapter 5, discusses the conclusions drawn from this case study, its limitations and the recommendations for future research.

# Chapter 5

# Conclusions




**Chapter Outcomes:**

- Overview and summary of research conducted.
- Discussion of central research questions, evaluation of the research proposition and final conclusions.
- Discussion of limitations to this study.
- Recommendations for future research.

## 5.1 Introduction

Chapter 5 serves the purpose of bringing closure to the research conducted in this study. More specifically, an overview and summary of this thesis in its entirety is provided. This is followed by final conclusions on the research conducted with specific emphasis on answering the central research questions and evaluating the reserach proposition. Next, the limitations of the study, in particular the framework incorporating business risks in physical asset replacement decisions in capital-intensive industries, are acknowledge with the aim of thoroughly understanding both the theoretical and practical value of the research. The chapter ends with a discussion on the identification of possible areas of improvement and elaboration for future research.

## 5.2 Overview

Economic globalization has resulted in an ever-increasing competitive operating environment among capital-intensive organizations. Organizations in the mining, manufacturing, and process industries are required to achieve higher production rates at lower costs in order to stay competitive in a challenging economic and operating climate. Staying ahead of competitors requires the use of every effort and resource at an organization's disposal including the process of innovative thinking. Certain alternatives such as technological advances in equipment or economies of scale are not often implemented by organizations due to the high risks and low returns associated with it. The more sustainable and controllable approach to create competitive advantage is from a strategic management point of view. This refers to the analysis, decisions, and actions taken by an organization in order to create a sustainable competitive advantage.

Organizations are therefore forced to use more reliable equipment with higher performance capabilities which in turn may be more expensive. Compounding the aforementioned challenges is a harsh operating environment which leads to performance degradation and a volatile socio-economic climate with evolving business risks to contend with. Given all, capital-intensive organizations can combine these aspects in the asset replacement process to create competitive advantage. Organizations in capital-intensive industries tend to focus on *traditional asset replacement factors* and do not consider the effects of evolving business risks which may significantly influence strategic initiatives such as operating and capital expenditure decisions. The primary objective of this study is therefore to create a framework to incorporate business risks in the physical asset replacement process in capital-intensive industries. Chapter 1 introduced the main concepts of the research including AM, asset replacement, and business risks and indicated the intricate interdependency between these concepts. Additionally, the possible benefits and importance of including business risks in asset replacement decisions in capital intensive industries were emphasized. Furthermore, a problem statement was defined which led to the development of research delimitations and research objectives to pursue in order to evaluate the research proposition.

A literature study was conducted in Chapter 2 which explored and reviewed, in detail, the opportunities to integrate the effects of business risks into asset replacement decisions. The literature study focused on the main concepts in the study including AM, asset replacement, and business risks. The chapter was concluded by comparing five suitable modeling techniques in order to model a real-world asset replacement decision process. It was found that the Markov Decision Process (MDP) is the best modeling technique to incorporate business risks into physical asset replacement decisions. Next, a framework was developed in Chapter 3 to incorporate business risks into asset replacement decisions by implementing general framework design principles and communicating the objectives, methods, and outcomes of each step. The framework was developed to adhere to all specified research objectives and questions as stated in Chapter 1.

Lastly, Chapter 4 applied the framework, developed in Chapter 3, to a case study conducted at a diamond mine in Southern Africa. More specifically, the case study focused on a Caterpillar 793C haul truck in operation at Mine X for the period 2008 to 2013 incorporating the following business risks in the asset replacement process: (1) global economic circumstances, (2) labour relations, (3) overall productivity, (4) reliance on third party infrastructure, and (5) SLTO. Traditional asset replacement factors incorporated in the asset replacement analysis included capital expenditure, financial depreciation, OM costs, asset salvage value, and performance degradation. An optimal replacement policy with its associated Total Expected Discounted Revenue (TEDR) for the period 2008 to 2013 was obtained. These results were discussed, a sensitivity analysis was performed, and the framework was validated from both a theoretical and practical perspective. Next, the final conclusions of the research are discussed.

## 5.3 Final Conclusion

As defined by the central research question in Chapter 1, the primary objective of the research conducted in this thesis was to determine whether business risks could be incorporated into the physical asset replacement process in capital intensive industries. Several research objectives were developed, summarized in Table 1.3, to answer the central research question and evaluate the research question as illustrated in Table 5.1. Leading from the discussion in the previous section and considering the research in its entirety, it can be confirmed that all the research objectives were met at the completion of this thesis.

In addition, the application and validation of the framework illustrated certain features of the framework including: (1) it enables the quantification of business risks using a holistic approach, (2) provides a level of certainty associated with asset replacement decisions, (3) creates consistency and repeatability in the asset replacement process, and (4) enables management to make defensible decisions by considering the evolution of asset performance and business risks on a medium to long-term basis. The proposed framework is therefore validated and the research proposition is evaluated and it is confirmed that such a framework was developed to incorporate business risks in asset replacement decisions.

**Table 5.1:** Research question of thesis

| |
|---|
| Can a quantitative decision-making framework can not be developed to incorporate business risks in physical asset replacement decisions in capital-intensive industries. |

## 5.4 Limitations

Bryman and Bell (2014) state that any research study is subjected to certain limitations. Research limitations are conditions or influences that restrict certain aspects of a study or influence the results obtained. This section acknowledges and discloses these limitations in order to help the reader gain a thorough understanding of the development and implementation of the framework incorporating business risks into physical asset replacement decisions in capital-intensive industries. The development and application of framework exposed the following limitations:

- The availability and quality of the data used is an inherent feature of the framework incorporating business risks in the asset replacement process and this is reflected in the results obtained. Results are dependent on accurate data such as system transition probabilities and immediate rewards associated with an action and system state. Moreover, transition probabilities of business risk information is subjective in nature and could have an influence on the final replacement policy obtained. Assumptions therefore have to be made for unavailable data and poor quality data may results in less than optimal results.

- The framework consider the engineering availability profile and OM costs of a business-critical physical asset in its entirety. Organizations in industry often use indicators for subsystems or individual components in the decision-making process when replacing assets. In addition, a single asset is considered in this framework thus excluding the possibility of analyzing the effects of business risks on asset replacement decision on a fleet of assets.

- Tying in with the previous limitations, the results generated by the framework is dependent on the system resolution. The MDP modeling technique is prone to an exponential increase in computational effort when expanding the size of a system. However, certain programming techniques such as vectorization and precalculations can be used to dampen this effect.

- The framework incorporating business risks into physical asset replacement decisions is not a once-off implementation process and should be updated for every decision-epoch to obtain the most reliable results. This will ensure that the forecasted results obtained for a finite period of time into the future are accurate and reflect current conditions.

- The application of the framework requires knowledge of the main concepts involved in the analysis such as the AM landscape, asset replacement, business risks, and the MDP modeling technique in order to interpret and analyze the results that are obtained.

- The framework is validated by applying it to a case study in the capital-intensive industry. Therefore, the framework will not necessarily prove to be valid for other types of industries.

Equipped with the research limitations associated with this study, the thesis closes with a discussion on certain recommendations for future research in the following section as identified throughout the research process.

## 5.5 Recommendations for Future Research

The research process highlighted several considerations that may prove beneficial to investigate in future research. Tying in with the limitations of this study and renewed insights into the field of asset replacement and business risks, the following considerations may be worth further investigation:

- The framework in this thesis considers the replacement of a single asset in its entirety. It would, therefore, be beneficial to integrate the possibility of incorporating business risks into multiple-asset replacement decisions. In addition, the engineering availability of subsystems or components can also be incorporated as well as lead-time on replacement assets to increase the accuracy of replacement policies. This would involve other topical areas in the AM domain such as fleet replacement and spare parts management.

- The framework in this research focused on including business risks into physical asset replacement decisions in capital-intensive industries. Future research could investigate the application of incorporating business risks into certain strategic decision-making processes in industries other than capital-intensive industries.

- The MDP modeling technique is prone to an exponential increase in computational effort when expanding the size of problem. Future research could investigate another modeling technique or a hybrid combination of suitable modeling techniques to prevent expensive computation and data collection for large systems.

- The structured process of the framework in this thesis guides the decision-making process. As a result, the framework requires a large amount of manual intervention in identifying the applicable business risks and asset-related factors to include in the asset replacement process since it depends on various industry and organizational conditions. Future research could investigate the use of Artificial Intelligence (AI) methods for the development of a tool to assist the identification of influential business risks and asset-related factors in an automated manner to ease certain laborious aspects of the framework.

The aforementioned recommendations offer interesting opportunities for future research to be conducted in the domain of incorporating business risks in physical asset replacement decisions as studied in this thesis.

# Appendices

# Appendix A

# Markov Decision Process Model Code

See next page.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%This function implements backward induction to determine the optimal action
for each time period. Moreover, this function uses the following function
(optimality) to determine the optimal action and its associated TEDR.
function [V, policy] = execute_finite(P, R, D_F, N, T_R)

    V_size = size(P,1);     %Size of the matrix P = "Number of states" and is
                            %used to ensure matrix consistency with regards
                            %to matrix dimensions throughout the model.
    V = zeros(V_size,N+1); %Initialize value matrix for revenue function.
                            %zeros matrix with the dimensions of the sys
      if nargin == 5;       %Assign terminal rewards position in TEDR matrix.
        V(:,N+1) = T_R;
    end;

    R_value = R;            %Combined rewards matrix for both actions
                            %(keep and replace).
    for n = 0: N-1          %Determines and store the optimal value for each
                            decision epoch.
        [K,L] = optimality(P,R_value, D_F,V(:,N-n+1));
        V(:,N-n) = K;          %Optimal output for objective function and the
                               %action chosen at a specific state.
        policy(:,N-n) = L;     %Optimal output for action policy at a certain
                               %time period and system state.
    end

end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%This function determines the value of the objective function that are used
to determine the optimal policy and values associated with it. The primary
objective is to compare the TEDR for the two available action and to select
the optimal action.
function [V, policy] = optimality(P, R_value, D_F, Vprev)

        Number_actions = size(P,3);   %Number of actions available are the
number of dimensions in the array of P (transition probability matrix).

%Equation to calculate value of objective function for each action (keep or
replace) using the Bellman equation.
        for a=1:Number_actions
            Q(:,a) = R_value(:,a) + (P(:,:,a)*Vprev)/(1+ D_F)
        end
    [V, policy] = max(Q,[],2);    %Store the maximum value and its associated
policy in the array max(A,[],2) is a column vector containing the maximum
value of each row.
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%This function generates the system transition probability matrix for the
action of keeping the CAT 793C haul truck. A similar function is implemented
for the action of replacing the haul truck. Extensive use of probability
theory is used throughout this function.

SLTO = [0.8 0.17 0.03;              %Transition probabilities for business
        0.45 0.5 0.05;              %risk Social License to Operate (SLTO)
        0.05 0.5 0.45];

Asset = [0.5 0.25 0.15 0.08 0.02;   %Transition probabilities for the
         0.3 0.4 0.2 0.07 0.03;     %haul truck based on engineering
```

```
         0.1 0.35 0.4 0.1 0.05;     %availability
         0.03 0.07 0.25 0.5 0.15;
         0.02 0.03 0.15 0.3 0.5];

Labour = [0.7 0.27 0.03;        %Transition probabilities for the business
          0.5 0.45 0.05;        risk labour relations
          0.1 0.6 0.3];

Exchange = [0.84 0.12 0.04;     %Transition probabilities for the business
            0.45 0.45 0.1;      risk global economic circumstances that
            0.05 0.35 0.6];     includes the exchange rate fluctuations.

Productivity = [0.8 0.18 0.02;  %Transition probabilities for the business
                0.25 0.65 0.1;  risk overall productivity
                0.05 0.45 0.5];

Reliance = [0.85 0.1 0.05;      %Transition probabilities for the business
            0.25 0.55 0.2;      risk Reliance on third party infrastructure
            0.1 0.35 0.55];

states = 1215;              %Number of system states
Rows = 1215;                %Number of rows in output matrices
Ptotal = zeros(1,states);   %Initialize system transition probability matrix
Answer1 = zeros(Rows,states);   %Optimal answers are stores in this matrix
for the time period under investigation.
c = 1;                          %Initialize counter for this action.

for count = 1:Rows          %The following piece of code is a part of the
  Sample1 = [1,1,1,1,1];    code used to generate the system transition
  Sample2 = [2,2,2,2,2];    probability matrix.
  Sample3 = [3,3,3,3,3];    %Row vectors are created to act as counters
    A1 = Sample1;           for each business risk in the implementation
    A2 = Sample2;           of the equation to calculate system transition
    A3 = Sample3;           probability for each system state.
    for count1 = 1:8
        A1 = [A1,Sample1];
        A2 = [A2,Sample2];
        A3 = [A3,Sample3];
    end
    Sample = [A1,A2,A3];
    L1 = Sample;
.
.
.
        while c <2         %Implements probability theory to calculate the
            for slto=1:3   system probability matrix one row at a time.
                for g=1:3
                    for a = 1:3
                        for p=1:3
                            for s=1:3
                                for b = 1:5
Ptotal=Reliance(S1(1,count),s)*Productivity(P1(1,count),p)*Labour(L1(1,coun
t),a)*Asset(A1(1,count),b)*Exchange(E1(1,count),g)*SLTO(SL1(1,count),slto);
                                    Final1(:,c) = Ptotal;
                                    c = c + 1;
                                end
                                Final1;
                            end
                        end
                    end
                end
```

```
            end
         end
       c=1;
     Answer1(count,:)= Final1;
     P(:,:,1) = Answer1;    %Store the system transition probability matrix
for keeping the haul truck in the transition probability array.
End

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
The main aim of this function is to generate the system reward matrix and to
execute the entire program by using the execute_finite function to obtain
the results. Only the calculations of the system rewards for the action to
keep the CAT 793C haul truck is illustrated here.

R_asset1 = [200.43 206.76 213.06 219.387 225.7]; %Rewards associated with
the different engineering availability levels, discritized from the profile
of the haul truck.

R_SLTO1 = [-0.3 -0.15 -0.1];     %Rewards associated with the business risk
Social License to Operate (SLTO) for its three levels Bad, Average, and Good.

R_labour1 = [-23 -2.3 2.3];      %Rewards associated with the business risk
labour Relations for its three levels Bad, Average, and Good.

R_Exchange1 = [-3 -1 3];        %Rewards associated with the business risk
global economic circumstances for its three levels Bad, Average, and Good.

R_Productivity1 = [-23 -4.6 11.5];   %Rewards associated with the business
risk overall productivity for its three levels Bad, Average, and Good.

R_Reliance1 = [-0.3 -0.1 0.05];    %Rewards associated with the business
reliance on third party infrastructure for its three levels Bad, Average,
and Good.

R_out1 = zeros(1215,1);  %Initialize system rewards matrix.
R_states = 1;             %Initialize counter for the following for-loop.
while R_states < 1215     %Condition to exit for loop for system size.
  for f = 1:3             %For-loops for every variable are used to generate
    for h = 1:3        the system rewards matrix. The same consistent system
        for t = 1:3        convention is used as for the probability matrix.
            for p1 = 1:3
                for synth = 1:3
                    for p = 1:5
Rtotal=R_SLTO1(f)+R_asset1(p)+R_labour1(t)+R_Exchange1(h)+R_Productivity1(p
1)+R_Reliance1(synth);
                        R_out1(R_states,1) = Rtotal;
                        R_states = R_states + 1;
                    end
                end
            end
        end
    end
  end
end
R(:,1) = R_out1;     %System rewards matrix for action 1 is stored in the
overall rewards array.
D_F = 0.05;          %Discount factor for system.
[V, policy] = execute_finite(P, R, D_F, 5, T_R) %Executes entire program and
stores the final results in the V (TEDR) and policy (optimal actions)
matrices.
```

# Appendix B

# Expert Interview: Physical Asset Management in the Mining Industry

See next page.

# Interview with Mr. Smith

| **Interview details** | |
|---|---|
| Name: | Mr. Smith |
| (The interviewee's name is arbitrary to ensure confidentiality.) | |
| Occupation: | Lead Asset Manager |
| Company | Large mining organization in Southern Africa |
| Date | 15-01-2016 |
| Time | 12:00 - 14:00 |
| Place | Centurion, Gauteng |

**Author (A) and Mr. Smith (S) exchange pleasantries. Interview begins with the author providing a brief overview of the research and how it is applicable to Physical Asset Management in the mining industry.**

**A: The latest definition provided by ISO 55000 for the broad field of Asset Management states that "Asset Management is the balancing of costs, opportunities and risks against the desired performance of assets, to achieve the organizational objectives. Asset management enables an organization to examine the need for, and performance of, assets and asset systems at different levels." Do you agree with this definition and would you change or add something to it especially from an industry point of view maybe referring to labour relations or other external factors?**

S: "Yes, I agree with this definition. I would not add anything to the definition if the risk aspect is inclusive. Risk should therefore include aspects such as risk to the environment, risk to employees health and safety, and risk to business longevity."

**A: What factors are included and focused on in the asset replacement process within your organization? For example do you focus on operating hours, failure statistics, or any other aspects?**

S: "At this point in time we have a rather simplified approach. We consider equipment condition and equipment life cycle. I think there has been a lot of work done in the mining industry with regards to the optimal replacement of pieces of equipment. In general, all organizations stick to those tried and tested methods. I think there is a lack of better quantification of the terms *equipment condition* and *equipment life cycle*. What I mean by that is that sometimes we abuse pieces of equipment and you change the equipment condition. - [refers to an example of a haul truck's main frame when cracks begin to surface at 50 000 operating hours due to bad operating conditions when replacement is only due at 100 000 operating hours. Equipment condition has therefore changed significantly]. Then you really need to consider what is the best option in the greater scheme of things. I think the aspects you focus on in your research therefore really needs to be considered in the asset replacement process such as equipment condition, cost, risk, and opportunity costs and it has to be tracked on a continual basis. You therefore stay informed all the time to make the correct decision. Another important aspect we focus on is life cycle aspects of not only replacement of pieces of equipment, but the acquisition of pieces of equipment. For example, if you look at a shovel or haul truk, the average delivery time is close to a year. You therefore have to plan ahead into the future, sometimes predicting, taking all these factors into consideration. In conclusion, we look at where the asset is in its life cycle and what is the asset condition at that period. To a lesser extend, we focus on the forecasted production to determine the number of asst we need in production and the condition they need to be in to achieve the forecasted production."

**A: Do you rely on ground floor information (operators and artisans) when considering the replacement of assets at all or do you focus heavily on data obtained from operations?**

S: "We do not rely on it enough. If you talk to artisan and operators you do get valuable information but this does not always filter through to the people making the replacement and investment decisions. As a decision-maker you look at an overview of key statistics on physical condition and production targets but do not always focus on the information from artisans. So with regards to the physical conditions of equipment, I feel we do not rely enough on the information given by operators and artisans."

**A: In you experience, what would you say is the biggest obstacles or potential problems in physical asset replacement? Is it replacing an asset too early, or the risk and consequences of replacing an asset too late which leads to downtime and a decrease in production? Or anything else?**

S:"Firstly, we are not good enough in the process of collecting data. The second obstacle we have is once we have the required data, we ignore large portions of it. The next obstacle I would say in the physical asset replacement process is the maintenance of assets. We do not give the required attention to an asset's operating conditions. For example, if you compare the operating conditions of an asset in Australia, Europe, and United States to an asset operating in Southern Africa, you get a work force with a better work ethic, more knowledge and therefore maintains the asset better in the first world countries. This is almost never incorporated, the majority of decisions are made based on operating conditions from first world countries. I think this is a big obstacle. Another obstacle in the physical asset replacement process is to quantify an asset's physical condition. I refer to an asset's life cycle stage again and its physical condition. Using a medical analogy, a person can be 30 years old and have an unhealthy lifestyle, or a person can be 70 years old with a very healthy lifestyle, yet their life expectancies can be the same. Applying this to physical assets, two different assets can be in different life cycle stages and have different physical conditions, but still have the same remaining operating life statistically. Therefore the process of determining and quantifying physical condition is another obstacle. Other obstacles include the quantification of decision-making processes. For example, requesting money to replace an expensive asset. The person requesting the money and the person granting the money have different objectives. I think models such as your model would definitely help this process for both parties to make the optimal decision."

**A: Do you, as an experienced industry expert in Asset Management, agree that this framework may assist an analyst to:**

1. **Quantify overall risk i.e. combine operational, strategic, and external risks using a holistic approach. This includes considering internal and external business risks that affects a specific organization but also focus on the mining industry as a whole;**

2. **Provide a level of certainty associated with an asset replacement deci-**

**sion;**

3. **Create consistency and repeatability in the decision-making process; and**

4. **Make defensible decisions by considering various types of business risks?**

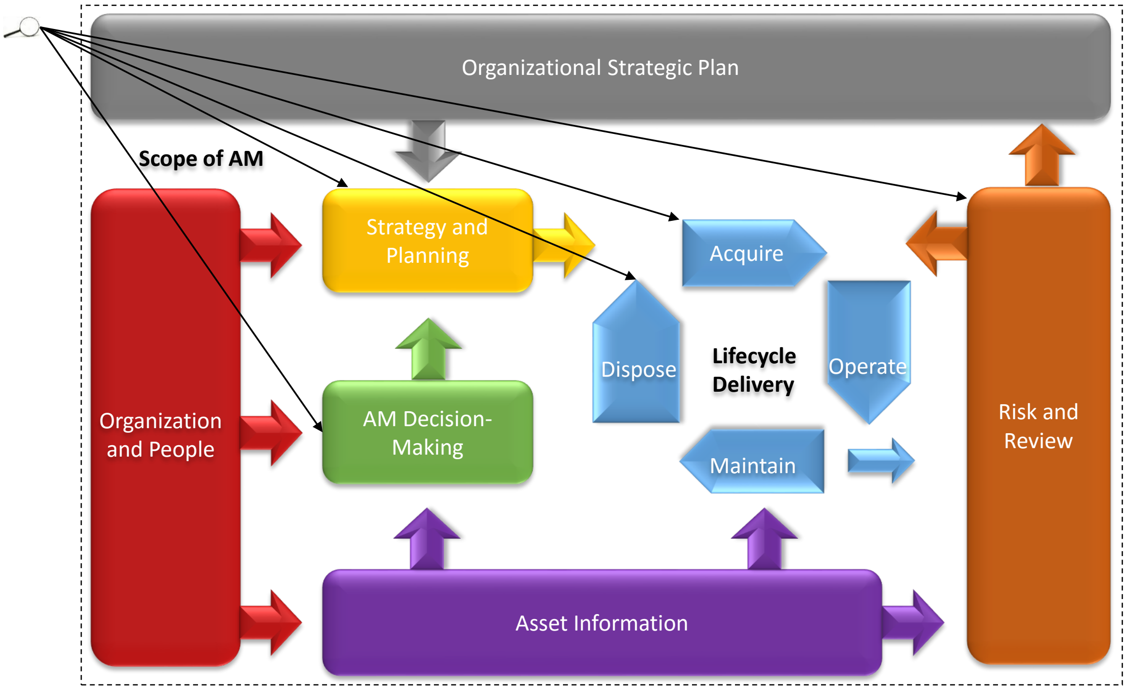
S: Absolutely. I absolutely believe in your model. I think an important aspect that we should clarify is the boundary and limits of the model. If something is not included in the model, it should be discussed and reasons given as to why it is not included, just to show comprehensiveness.

**A: For sure, this leads me to the next aspect: what changes or additions to the framework would you recommend especially from a senior management point of view?**

S: I think what I mentioned earlier, one must determine where the equipment is in its life cycle not purely based on age, but also condition. The physical condition of the asset must also be quantified. Even if you use a simplified method of quantifying the physical condition of the asset, just state that explicitly. For example, this is the scale and criteria you are using to quantify asset condition and this is how each state would impact the model.

**A: Do you agree that this framework contributes to the scope of Asset Management with reference to the figure below? In particular to the following aspects within the scope of Asset Management: (1) Risk and review processes in an organization, (2) acquisition and disposal of assets, (3) decision-making process, and (4) the Asset Management strategy and planning of an organization.**

S: Absolutely, without doubt. Like I mentioned earlier, I think we overplay the risk factor sometimes in business and underplay good business decisions in many cases. I think your model is a good balance between these two aspects. At the end of the day, why do you have assets? Because assets have the inherent ability to generate revenue and over time this changes. You have to look after that revenue by making the best business decisions throughout the life cycle of assets. In my opinion your model and the whole concept is very good.




[The interview ends with formalities; the author thanks the interviewee for his time, insight and contributions.]

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