An Asset Investment Decision Framework to Prioritise Shutdown Maintenance Tasks

by

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December 2015

Declaration

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Abstract

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Thesis: MScEng (EngMan)

December 2015

The 2007-2008 Global Financial Crisis and subsequent economic downturn have forced many asset-intensive organisations to direct their maintenance efforts towards achieving their strategic goals more efficiently and effectively. Hence, these organisations can ill-afford to perform non-critical maintenance before or instead of critical maintenance. This is especially true for their shutdowns, which are typically short and expensive maintenance driven projects characterised by strict time and budget constraints.

In this study, a new framework is developed to prioritise the maintenance tasks proposed for an upcoming shutdown on a critical asset. Limited maintenance resources, such as time and budget, are considered in the prioritisation process, in addition to the value delivered by each maintenance task. Value is measured in terms of return on investment, which is the reduction in risk cost achieved by performing a combination of maintenance tasks on the asset relative to the costs incurred. The developed framework selects the combination of maintenance tasks that delivers the greatest return, whilst adhering to the aforestated constraints.

The developed framework is a modification of an existing generic maintenance prioritisation framework found in literature. This generic framework is modified through the incorporation of an Imperfect Maintenance age reduction factor which quantifies the value delivered by each maintenance task performed. Moreover, four well established Multiple Criteria Decision Analysis models, namely the additive and multiplicative value functions as well as the ELECTRE II and PROMETHEE II methods, are incorporated to effectively prioritise the combinations of maintenance tasks.

A case study conducted at a South African thermal coal mine was used to validate the developed framework. Through a comprehensive case study scenario analysis, different possible shutdown scenarios were evaluated in order to help the thermal coal mine remain flexible in its decision making during the months leading up to the shutdown of one of its most critical assets. The results indicate that the developed framework is a useful tool to assist the selection of shutdown maintenance tasks that best suit the needs and objectives of the asset and organisation respectively.

KEYWORDS: Shutdowns, Asset Management, Maintenance Prioritisation, Imperfect Maintenance, Multiple Criteria Decision Analysis

Uittreksel

'n Bate-Beleggingsbesluitnemingsraamwerk om die Afsluiting vir Onderhoudsbestuurstake te Prioritiseer

"An Asset Investment Decision Framework to Prioritise Shutdown Maintenance Tasks"

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Tesis: MScIng (IngBes)

Desember 2015

Die 2007-2008 Globale Finansiële Krisis en gevolglike ekonomiese afname het baie bate-intensiewe organisasies forseer om hulle onderhoudsbestuurspogings daarop te fokus om strategiese doelwitte meer effektief te bereik. Hierdie organisasies kan dit dus nie bekostig om nie-kritiese onderhoudsbestuur voor of in plaas van kritiese onderhoudsbestuur toe te pas nie. Dit is veral van toepassing vir afsluitings wat kenmerkend kort en duur onderhoudsbestuurgedrewe projekte is, maar streng tyds- en begrotingsbeperkings het.

In hierdie studie is 'n nuwe raamwerk ontwikkel met die doel om onderhoudsbestuurstake te prioritiseer vir die naderende afsluiting van 'n kritiese bate. Beperkte onderhoudsbestuursbronne, soos tyd en begroting, word tesame met die waarde wat deur elke onderhoudsbestuurstaak gelewer word, tydens die prioritiseringsproses in ag geneem. Waarde word bepaal in terme van opbrengs op belegging, wat verwys na die afname in risiko-koste, wat behaal word deur 'n kombinasie van onderhoudsbestuurstake op die bate uit te voer, met betrekking tot die kostes aangegaan. Die ontwikkelde raamwerk selekteer die kombinasie van onderhoudsbestuurstake wat die grootste opbrengs lewer, terwyl dit steeds getrou bly aan die bogenoemde beperkings.

Die ontwikkelde raamwerk is 'n aanpassing van 'n bestaande generiese onderhoudsbestuur-prioritiseringsraamwerk wat in literatuur gevind word. Hierdie generiese raamwerk is aangepas deur die integrasie van 'n Onvolmaakte-Onderhoudsbestuur-ouderdomsverminderingsfaktor, wat die waarde-gelewer van elke onderhoudsbestuurstaak meet. Verder word vier goed gevestigde Multikriteria Besluitnemingsanalise-modelle gebruik, naamlik die *additive* en *multiplicative value functions*. Die ELECTRE II en PROMETHEE II metodes word ook geïnkorporeer vir die effektiewe priortisering van die kombinasie van onderhoudsbestuurstake.

'n Gevallestudie wat by 'n Suid-Afrikaanse termiese steenkoolmyn uitgevoer is, is gebruik om die ontwikkelde raamwerk te valideer. Verskeie moontlike afsluitingsscenarios is geëvalueer met behulp van 'n omvattende gevallestudie-scenario-analise, om die termiese steenkoolmyn te help om buigsame besluite te neem tydens die maande voor die afsluiting van een die mees kritiese bates. Die resultate toon dat die ontwikkelde raamwerk van wwarde is tydens die selektering van die mees gepaste afsluitings-onderhoudsbestuurstake vir die behoeftes en doelwitte van die bate en organisasie onderskeidelik.

SLEUTELWOORDE: Afsluitings, Bate Bestuur, Onderhoud Prioritisering, Onvolmaakte Onderhoud, Multikriteria Besluitnemingsanalise

Dedications

This thesis is dedicated to:

Marsia *and* ***Hester Swart*** *for your unwavering support, trust and unconditional love, as well as to the memory of* ***Marius Swart****,* ***Lukas*** *and* ***Hester Pretorius*** *and* ***Jo-Marie Botha****, you are sorely missed, may you forever rest in peace.*

Acknowledgements

Among the many people and organisations that contributed to the work that culminates in this thesis, special gratitude is reserved for the following:

- My family and especially Paul Swart, for their love, understanding, support and encouragement throughout this period of my studies.
- My thesis supervisor, Professor P.J. Vlok, for his invaluable guidance, wisdom and patience.
- My friends, especially Kyle, Jared, Berno, Louis and Mauritz for their motivation, endless banter and cooperation during and after 'Penthouse' office hours.
- Anglo American, for funding the research in this thesis and accommodating the case study.
- Grant Mitchell, Andreas Pfeffer, Françoise du Preez, Carl Stensby, Cecile de Jager, Niro Ramcharither and Sibongile Kgasane for the important role their assistance played in the completion of this thesis.
- Dr. John Morrison and Ilise Morrison for editing this thesis and Mizan van Wyk for translating the abstract to Afrikaans.

The Author
December, 2015

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Acronyms and Abbreviations

ACSA	Anglo Coal South Africa
AM	Asset Management
AMS	Asset Management System
AST	Available Shutdown Time
BF	Budget Factor
BI	Budget Index
CM	Corrective Maintenance
OP Mine	Open-pit Mine
ConMon	Condition Monitoring
DL-A	Dragline-A
DL-B	Dragline-B
DL-C	Dragline-C
DT	Downtime
ELECTRE	Elimination and Et Choice Translating Reality
FMECA	Failure Modes Effects and Criticality Analysis
GAMOF	Generic Asset Maintenance Optimisation Framework
ISO	International Organisation for Standardisation
ISO 55000	International Organisation for Standardisation 55000
MCDA	Multiple Criteria Decision Analysis

MCDM	Multiple Criteria Decision Making
MII	Maintenance Investment Index
MP	Maintenance Package
MPDT	Maintenance Package Downtime
MRL	Mean Residual Life
NOT	Non-operating Time
ODC	Output Dimension Cost
PAS 55	Publicly Available Specification 55
PdM	Predictive Maintenance
PL	Production Loss
PM	Preventive Maintenance
PROMETHEE	Preference Ranking Organisation Method for Enrichment of Evaluations
RDC	Risk Dimension Cost
ReDC	Resources Dimension Cost
SB	Shutdown Budget
SMPF	Shutdown Maintenance Prioritisation Framework
TF	Time Factor
TI	Time Index
TPMPF	Tam and Price Maintenance Prioritisation Framework

Notation

Notation for Multiple Criteria Decision Analysis

m	Number of alternatives
n	Number of criteria
A_i	i^{th} alternative of m number of alternatives
C_j	j^{th} criterion of n number of criteria
w_j	Weighting of j^{th} criterion

Notation for Imperfect Maintenance

ij	Component ij is the j^{th} parallel-connected component in the i^{th} independent series-connected subsystem of a series-parallel system
A_{ij}	Effective age before maintenance for ij
t_{ij}	Effective age after maintenance for ij
$m(A_{ij})$	Characteristic constant of ij at A_{ij}
C_{ij}^{R}	Replacement cost of ij
C_{ij}^{MR}	Minimal repair cost of ij
I_{ij}	Discrete level of maintenance performed on ij
$C_{ij}(I_{ij})$	Maintenance cost of ij as function of I_{ij}
b_{ij}	Age reduction factor of ij
Y_{ij}	Component state (fail/functioning) of ij

Notation for Shutdown Maintenance Prioritisation Framework

β	Weibull distribution shape parameter
η	Weibull distribution scale parameter
x	Continuous time
X_i	Inter-arrival time between the $(i-1)^{th}$ and the i^{th} failure
$f(x)$	Weibull probability density function
$F(x)$	Weibull cumulative probability function
$R(x)$	Weibull reliability function
$h(x)$	Weibull instantaneous failure (hazard) rate
C_{conseq}	Consequences cost
C_f	Fixed maintenance cost (e.g. spare parts)
C_v	Variable maintenance cost per unit time (e.g labour)

Chapter 1

Introduction

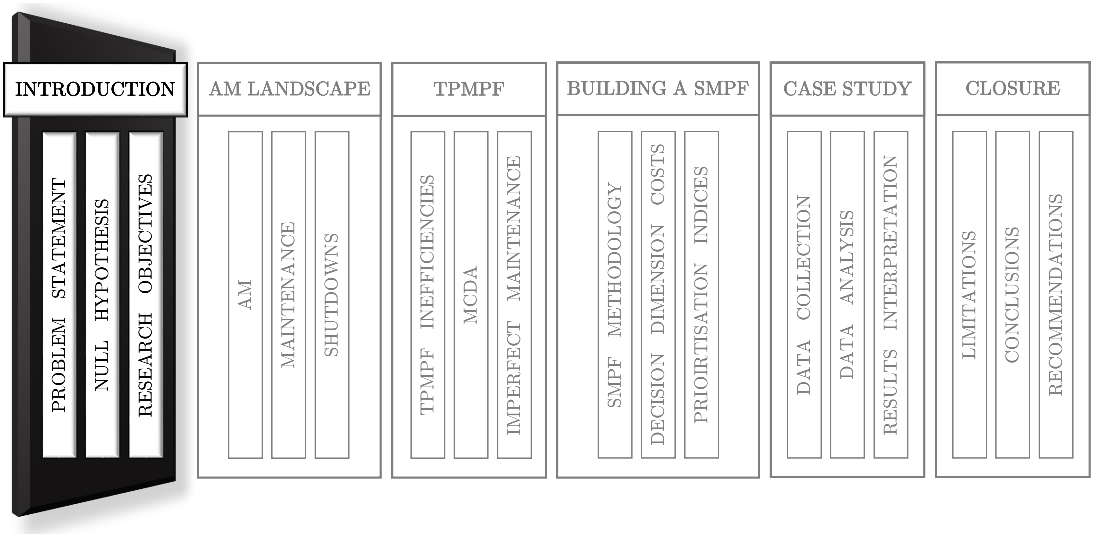


Figure 1.1: Thesis roadmap

Chapter Aims:

Chapter 1 introduces the reader to the research undertaken in this thesis. It provides background and presents the fundamental topics necessary in understanding the study conducted. The problem statement describes the identified problem and is translated into a null hypothesis and achievable research objectives. Next, the thesis scope is demarcated along with the methodology followed to address the identified problem. Finally, the chapter concludes with the outline or roadmap of the study.

Chapter Outcomes:

⇒ Demarcation of research domain and delineation of research problem.

⇒ Presentation of research design and methodology overview.

⇒ Development of thesis roadmap (Figure 1.1).

1.1 Theoretical Background

Today, many organisations are still reeling from the dramatic events of the 2007-2008 Global Financial Crisis. It is considered by top economists as the worst financial crisis since the Great Depression of the 1930s (Business Wire News, 2009). The 2008-2012 global recession that ensued, forced many businesses to close-down permanently or downsize their operations in order to cut costs and survive. Since the recession, events such as the Eurozone crisis involving Cyprus, Greece, Ireland, Portugal and Spain have added to the lingering uncertainty of an economic recovery.

This uncertain economic climate has impacted how many organisations, especially asset-intensive industries, conduct their business post 2008. A study by the Aberdeen Group in 2009 revealed that 70% of the 139 surveyed asset-intensive organisations had either frozen their capital and operational budgets or decreased them by as much as 20%, compared to the year before (Shah and Littlefield, 2009). Hence, to remain competitive in the current economic climate, Ismail (2011) points out that these asset-intensive organisations are seeking new ways to improve the ways in which they:

- utilise their assets i.e. “deliver more with less”;
- ensure their assets remain functional and operational; and
- plan for the unexpected failures of their critical assets.

According to Mardiasmo *et al.* (2008), asset-intensive organisations such as utilities, mining and transport are dependent on the performance of their *physical assets* in order to generate revenue. This means that the short term as well as the long term futures of these organisations rely on the performance of their physical assets. Hastings (2010) therefore stresses how important it is for asset-intensive organisations to *appropriately manage* their physical assets throughout each asset’s individual life cycle.

1.1.1 Asset Management

People have been managing physical assets for many years, yet the discipline of Asset Management (AM) is still relatively new (Davis, 2007). Despite its infancy, Tywoniak *et al.* (2008) state that AM is recognised in various fields such as engineering, information technology, financial services and human resources. It was born out of the realisation that organisations needed to manage their assets more efficiently and effectively, in order to respond to the pressures that were hampering the achievement of their strategic goals.

The current economic climate, described in Section 1.1, has put further emphasis on AM and it is presently the subject of intense research and discussion for both industry and academia. A study by the Aberdeen Group in 2012 surveyed 134 asset-intensive organisations in order to identify the top pressures which were driving them to focus on AM (Ismail and Paquin, 2012). The results of this study are presented in Figure 1.2, with the need to reduce operating and capital budgets as well as to maximise the return on assets featuring prominently.

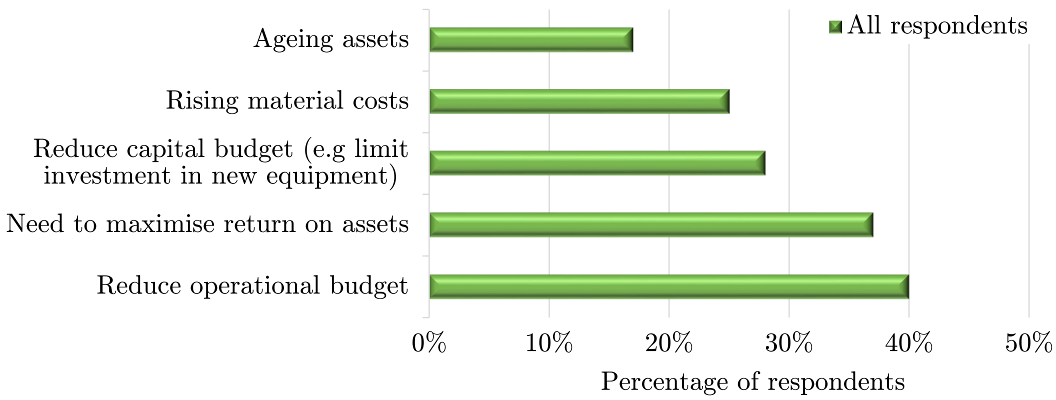


Figure 1.2: Top pressures driving organisations to focus on AM

Adapted from Ismail and Paquin (2012)

According to Mitchell (2007), the main objective of AM is to increase the value and return on the physical assets which are responsible for revenue generation in asset-intensive organisations. Furthermore, it is stated by Koronios *et al.* (2007) that AM entails:

> *preserving the value function of an asset during its life cycle and maintaining it to as designed or near original condition through maintenance, upgrade and renewal until sustainable retirement of the asset due to end of need or technology refresh.*

It is important to note here the emphasis placed on the holistic approach that AM undertakes. It considers all the assets' life cycle stages and not just maintenance when managing the asset. A common, yet dissipating, misconception is that AM is the equivalent of maintenance management. This is not the case and Hastings (2010) identifies AM as the "grey area" below senior management and above maintenance management. Nevertheless, maintenance remains a critical function of AM and will be discussed in the following subsection.

This so-called grey area has gained further credibility with the recent development of the AM standard Publicly Available Specification 55 (PAS 55) in 2004. PAS 55 was seen as the one of the first steps toward bridging the organisational gaps between higher and lower level management in the field that used to be known as maintenance. Its enormous success lead to the development of the International Organisation for Standardisation 55000 (ISO 55000) family of AM standards which were released in early 2014. ISO 55000 has since superseded PAS 55 and is the current authority on AM standards.

Chapter 2 is dedicated to exploring the landscape of AM. An in-depth discussion of AM, its evolution and definition as well as supporting standards (PAS 55 and ISO 55000) are detailed in Sections 2.1 to 2.5.

1.1.2 Maintenance

It was mentioned in the previous subsection that maintenance is a critical function of AM. This assertion makes intuitive sense considering that maintenance is responsible for maintaining the desired or required health of the revenue generating physical assets. Numerous definitions of maintenance exists, however as good as any is Márquez (2007) who defines maintenance as:

> *the combination of all the technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function.*

It is noted by Blischke and Murthy (2000) that the approach to maintenance has changed considerably in the last century. According to Moubray (1997), since the 1930s the evolution of maintenance can be categorised into three broad generations as illustrated in Figure 1.3.

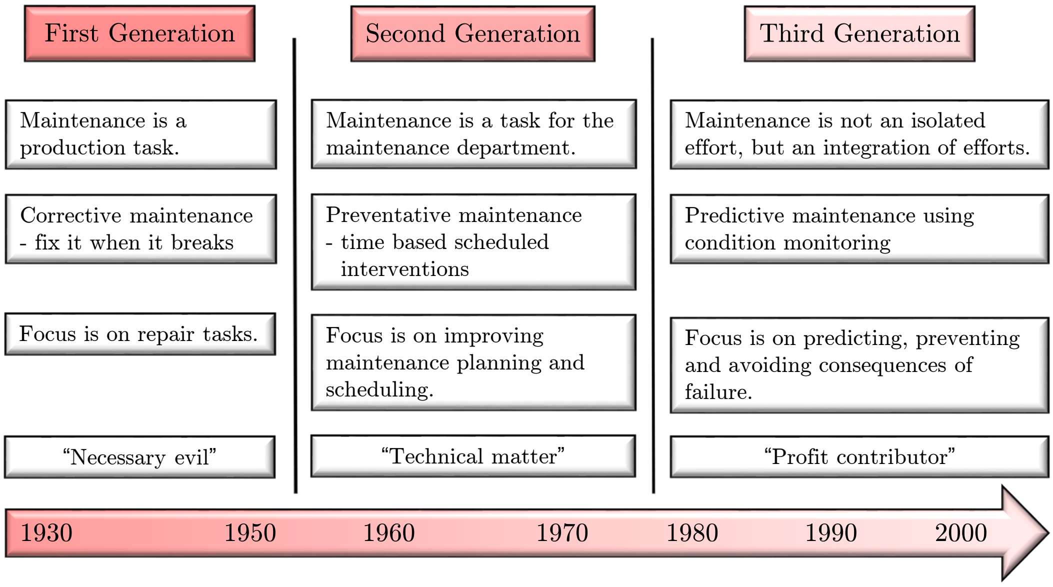


Figure 1.3: Evolution of maintenance approaches since the 1930s

Adapted from Moubray (1997), Deshpande and Modak (2002) and Waeyenbergh and Pintelon (2002)

The first generation saw maintenance as a necessary evil of production and only performed maintenance *after* failure i.e. Corrective Maintenance (CM). This approach resulted in exorbitant maintenance costs and excessive downtime, which is why the following two generations focused on performing maintenance *before* failure. The second generation performed Preventive Maintenance (PM) based on the asset's age, whereas the third generation performed Predictive Maintenance (PdM) based on the asset's condition through a process called Condition Monitoring (ConMon). These maintenance approaches are explained in greater detail in Section 2.6.

The third generation in Figure 1.3 indicates that maintenance is now seen as a profit contributor. Ben-Daya and Duffuaa (1995) states that maintenance is no longer viewed as necessary evil, but rather a value-adding activity whose importance to profitability has recently been recognised. Moreover, Sharma *et al.* (2011) reports that contemporary organisations are adopting maintenance as a *profit generating business element*. Hence, the goal of maintenance is to increase an organisation's profitability (Swart and Vlok, 2015) and facilitate the achievement of its strategic goals.

Deterrents for adopting a value-based maintenance approach centred around the difficulty in quantifying the benefits or the value of maintenance. For example, Dekker (1996) notes "whether maintenance output is produced both effectively, in terms of contribution to company profits, . . . , is very difficult to answer" and Mechefske and Wang (2003) states that "the output of maintenance is hard to measure and quantify". Hence, the simpler cost-based approach of trying to minimise or manage the easily quantifiable direct maintenance costs proved difficult to discard.

The asset maintenance and management industry is littered with inefficiencies that provide scope for improvement opportunities. Mobley (2002) states that surveys on maintenance management effectiveness indicated that 33% of all maintenance costs were wasted on unnecessary or improperly carried out maintenance. Penrose (2008) adds that the size of the reliability and maintenance industry in the United States of America in 2005 was US$1.2 trillion, of which US$500 to US$750 billion was attributed to the cost of poor physical asset maintenance and management.

This unnecessary expenditure on maintenance can have a significant effect on an organisation's profits. Ben-Daya *et al.* (2009) claim that a reduction of $1 million in maintenance expenditure in large organisations contributes as much to profits as increasing its sales by $3 million. These aforementioned inefficiencies suggest that asset maintenance and management improvements may be the "quick wins" or "low hanging fruit" for asset-intensive organisations in the current uncertain economic climate.

1.1.3 Shutdowns

The subsection before disclosed the enormity of the costs involved in the asset maintenance and management industry. Within this industry, one major expense and therefore consumer of maintenance budgets in asset-intensive organisation is *shutdowns*. Sahoo (2013) reveals that the costs of shutdowns in process plants normally exceed 30% of the annual maintenance budget. The author further adds that a delay in the plant start-up can cause a loss of operating profit greater than the total cost of the shutdown.

Ben-Daya *et al.* (2009) and Emiris (2014) define shutdowns as:

> *periodic maintenance in which plants are shut down to allow for inspections, repairs, replacements and overhauls that can be carried out only when the assets (plant facilities) are out of service.*

The definition emphasises the point that plants are non-operational during the shutdown period. This means in addition to the maintenance costs, organisations incur a loss in production for the duration of the shutdown. Ashok *et al.* (2011) therefore advocates completing the shutdown work in as short a times as possible. As a result, shutdowns are generally characterised as short in duration, yet high in intensity (Kister and Hawkins, 2006).

IAM (2012) describes shutdowns as expensive to execute, intensive on skilled labour resources, undesirable from an operational point of view and often *unavoidable*. On top of being unavoidable, Section 2.7 provides logistic and economic justifications for the implementation of shutdowns. For example, economically it makes more sense to conduct a total plant shutdown as it is far less expensive than conducting more frequent shutdowns in separate areas of the plant.

According to Duffuaa and Ben Daya (2004), shutdowns consists of four phases, namely *initiation*, *preparation*, *execution* and *termination*. The first two phases deal with the shutdown planning process and Duffuaa and Ben Daya (2004) insist that the "successful execution of a shutdown hinges on good preparation". Ghazali *et al.* (2009) concur and point out that substantial time and effort should be allocated for the planning and work scheduling of a shutdown. Hence, a successful shutdown starts with proper planning, i.e., proper identification, *prioritisation* and scheduling of the shutdown maintenance work.

With so much attention on the cost, duration and planning of a shutdown, it is unsurprising to see how the success of shutdowns are measured. Obiajunwa (2012) explains that shutdown success is traditionally assessed using measures such as "meeting schedule" and "staying within budget". Moreover, it is argued by Pokharel and Jiao (2008) that an important criterion for shutdown success is the proper planning of the shutdown's maintenance activities.

Section 2.7 discusses the concept of shutdowns in greater detail. Important characteristics of shutdowns, the motivation for shutdowns and the importance of shutdown planning are covered extensively in this section.

1.1.4 Tam and Price Maintenance Prioritisation Framework

As the name suggests, the Tam and Price Maintenance Prioritisation Framework (TPMPF) was developed by Tam and Price (2008*b*). The TPMPF provides a new approach to *prioritise asset maintenance work by maximising the return on maintenance investment under the constraints of budget and time.*

Tam and Price (2008*b*) view maintenance as a business function, no different to any other in an organisation, and therefore it has to prioritise its activities in terms of return on investment. Moreover, the authors acknowledge that the maintenance function, in particular, has to contend with the limited time and budget available to it. That is why these two constraints are incorporated into the TPMPF's decision making process. These distinguishing features of the TPMPF make it particularly applicable to organisations in the current uncertain economic climate that have adopted the present view of maintenance as a profit contributor.

Section 1.1 mentioned that asset-intensive organisations are tightening their capital and operating budgets. This means many ageing pieces of equipment cannot be easily replaced and the final stages of their useful lives need to be extended. However, keeping ageing equipment operational with dwindling maintenance funds will be a daunting challenge. To complicate matters, asset-intensive organisations are seeking to deliver even more from their assets in order to remain competitive. This all emphasises how important it is for current asset-intensive organisations to consider limited maintenance resources in their decision making process. The TPMPF and numerous other maintenance models can assist organisations in taking into account their limited maintenance resources.

Extensive literature exists on optimal maintenance models that appropriately allocate available maintenance resources, such as time and budget, in order to make them drivers of competitiveness. In each of these models, an objective function is postulated and maximised/minimised subject to certain constraints. Take for example Cassady *et al.* (2001*b*), who developed three maintenance models, each with a specific aim:

- *Model 1* maximises system reliability subject to time and cost constraints;
- *Model 2* minimises system repair cost subject to the time constraint and a minimum required reliability level; and
- *Model 3* minimises system repair time subject to the cost constraint and a minimum required reliability level.

These three models, in addition to those found in literature, often deal with the cost of maintenance in their objective function or constraints. On the other hand, Marais and Saleh (2009) complain that few of these models consider the *value* of maintenance and seldom in an analytical or quantitative way.

Subsection 1.1.2 revealed that maintenance is now viewed as a value-adding activity or a profit contributor for organisations. This is where the TPMPF comes into its own. Marttonen *et al.* (2013) mention that the TPMPF is one of a few studies that has linked the AM perspective to enterprise-level goals and profitability. In addition to taking time and budgets constraints into account, the TPMPF considers the value of maintenance and quantifies it in terms of return on investment. For the reasons just described, it is made abundantly clear that *only* the TPMPF and no other maintenance model nor framework is considered in this thesis.

According to Bharadwaj *et al.* (2012), every maintenance action has an associated cost, which can be considered an investment, and when this cost is incurred a certain return on the investment is expected. In the TPMPF, return is measured as the reduction in risk cost achieved by the maintenance performed. With organisations tightening their budgets, a number of different maintenance actions can be expected to compete for investment. It is therefore necessary to determine, given the constraints (time and budget) that apply, which maintenance action(s) would give an organisation the greatest return.

Chapter 3 discusses maintenance prioritisation and examines the various elements in the TPMPF. What is more, inefficiencies in the framework are identified and possible solutions are posited to address these inefficiencies.

1.2 Problem Statement

The development of PAS 55 and the ISO 55000 family of standards gave renewed impetus and creditability to the field of AM. Within industry and academia, the research focus has shifted towards AM, however maintenance is still viewed as a critical function in the management of physical assets. Despite often being undervalued, it plays a crucial role in an organisation's ability to compete in the market (Pinjala *et al.*, 2006).

Today, the perception of maintenance is changing. It is considered an integral part of the business process and perceived as a value-creating or value-adding activity (Liyanage and Kumar, 2003). The notion that "maintenance has no intrinsic value" (Keeney, 1996) is contested in newer literature. In order to start using maintenance as a value driver, Rezvani *et al.* (2010) stress that organisations must move away from cost-based thinking towards value-based thinking. An example of a recent value-based approach is the TPMPF, introduced in Subsection 1.1.4, which prioritises maintenance work in terms of return on investment in addition to considering the constraints of time and budget.

It is estimated that $15 - 40\%$ of production costs can be attributed to maintenance costs (Maggard and Rhyne, 1992; Mobley, 2002) and it is further estimated that $18-30\%$ of this is wasted (Mulcahy, 1999; Bever, 2000). Hence, the importance of maintenance planning is obvious. It becomes even more obvious when the challenges of planning the maintenance work for a shutdown are considered. Raoufi and Fayek (2014) describe shutdowns as unique maintenance projects with a high probability of *scope change*, *time delay* and *cost overrun*. Subsection 1.1.3 showed how important planning, meeting schedule and staying within budget is to completing a successful shutdown. According to Oliver (2002), "organisations that complete shutdowns on time, on budget and without surprises invariably have a defined work process and adhere to it". Thus, it is imperative for organisations to have an established process for shutdown planning and management.

The motivation for conducting the research in this thesis stems from the revelation made by Obiajunwa (2012) concerning shutdowns:

> *Again there is no comment in the* [shutdown] *literatures of how to measure the benefits to the organisation of the entire* [shutdown] *project itself.*

To put it in another way, the literature on shutdowns is devoid of value-based approaches such as the TPMPF. What is needed is an approach that quantifies the benefit or value of performing shutdown maintenance. Importantly, this approach should be proactive and aid the decision making process at the critical planning phase of a shutdown already. That way the shutdown's benefit can be maximised. What is more, this approach should consider the maintenance resource constraints that apply to shutdowns i.e time and budget. This research therefore builds on the critical idea by Wang (2002) that cost along with the value resulting from improved reliability should be considered when making maintenance decisions.

Leading from the discussion in this section, the central research question for this thesis is formulated as:

> *Can the Tam and Price Maintenance Prioritisation Framework be modified and leveraged for the shutdown environment in order to prioritise the shutdown maintenance work of a critical system?*

From the central research question, this thesis will aim to reject the null hypothesis defined in Table 1.1.

Table 1.1: Null hypothesis (H_0) of thesis

H_0:	*The Tam and Price Maintenance Prioritisation Framework cannot be modified and leveraged for the shutdown environment in order to prioritise the shutdown maintenance work of a critical system.*

1.3 Research Objectives

The overall objective of this thesis is to answer the research question put forth in the previous section. In order to comprehensively answer the research question, the overall objective is broken up into a series of manageable research objectives. A summary of the research objectives is given in Table 1.2.

Table 1.2: Summary of thesis research objectives

#	Research objective	Chapter
1.	Establish the fundamentals of AM, maintenance and shutdowns.	2
2.	Single out the importance of shutdown maintenance planning.	
3.	Provide a sound understanding of TPMPF.	3
4.	Identify inefficiencies in the TPMPF.	
5.	Propose possible solutions to the identified inefficiencies.	
6.	Develop the shutdown maintenance prioritisation application methodology.	4
7.	Implement the developed application methodology with a case study.	5
8.	Prioritise the shutdown maintenance tasks of a critical asset.	
9.	Validate the application methodology and results analysis.	
10.	Draw conclusions from the results analysis and either accept or reject the null hypothesis.	6

The first research objective is to establish the fundamentals or key concepts that form the basis of the research in this thesis. Chapter 2 achieves this by providing an exhaustive literature review on the landscape of AM. Important functions within this landscape, such as maintenance and shutdowns, are explored in order to comprehensively understand their interconnections with AM. The second objective is to single out the importance of proper maintenance planning in successfully completing a shutdown.

Chapter 3 pursues three objectives. Through a thorough overview, the first objective examines the TPMPF as a possible solution to the problem described in Section 1.2. The second and third objectives involve the identification of inefficiencies in the TPMPF and the proposal of possible solutions to the identified inefficiencies.

The objective covered in Chapter 4 is to develop the application methodology that prioritises the maintenance work of a critical asset to perform during its shutdown. The application methodology builds on the findings of Chapters 2 and 3. What is more, Chapter 4 provides an overview of the application methodology and presents the procedural steps for its implementation.

Chapter 5 involves three objectives starting with the implementation of the application methodology in the form of a case study at a South African thermal coal mine. The second objective is to prioritises the shutdown maintenance tasks of a critical asset at the mine for an impending shutdown. Finally, the third objective is to validate the results obtained during the case study.

The thesis concludes with Chapter 6 and the final research objective is to draw conclusions from the case study. The applicability of the application methodology developed in Chapter 4 is analysed based on the results obtained in the case study and on whether the research question is answered. The problem statement's null hypothesis is subsequently either accepted or rejected.

1.4 Delimitations

In addition to what this thesis aims to achieve, its important to clarify upfront what this thesis does not aim to achieve. Stating what is not going to be done is called the delimitations, notes Leedy and Ormrod (2005). The delimitations help to establish the boundaries or the scope of the thesis in order to keep the reader's focus on the intended purpose of the study.

- The thesis is bound to the field of shutdowns. This means the application methodology is intended to prioritise the maintenance work of a critical asset only when the said asset or the entire plant is shut down i.e. non-operational or taken out of service.
- The thesis focuses solely of the prioritisation step of the shutdown planning phase and the shutdown maintenance work is only prioritised in terms of return on investment, time and budget constraints. Other factors such as those affecting the scheduling of the shutdown maintenance work, for example the lead times of spares and the availability of contractors, are not considered.
- The thesis focuses on a single critical physical asset that directly affects production and where unscheduled downtime incurs irrecoverable production losses for the organisation.
- The thesis only explores the TPMPF as a possible solution to the stated problem for the reasons outlined in Subsection 1.1.4.

With the research objectives and delimitations formalised, the following section describes the research design and methodology employed in this thesis.

1.5 Research Design and Methodology Overview

The research design is the blueprint of the plans and procedures for the intended study. Creswell (2009) illustrates in Figure 1.4 that the research design is the intersection of the selected philosophical world-view assumption, strategy of inquiry and specific research method.

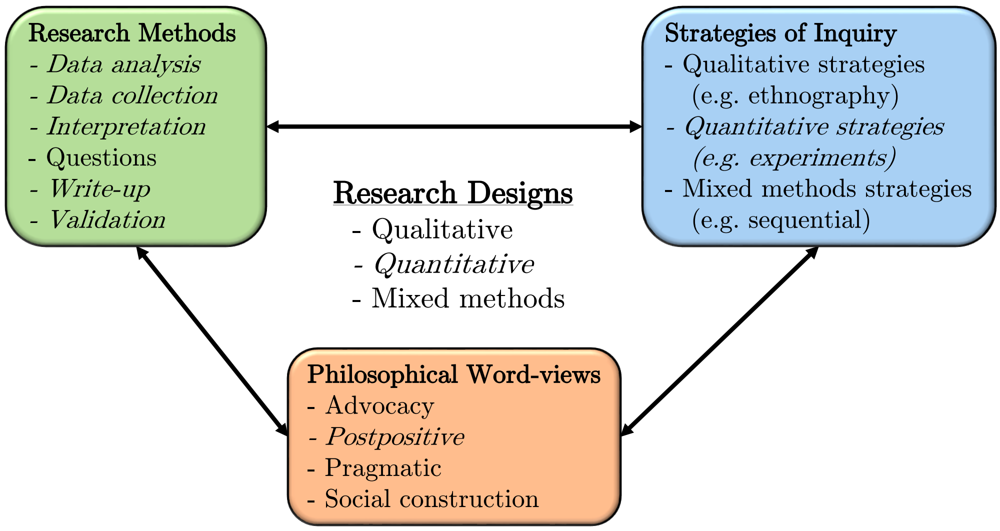


Figure 1.4: Research design framework

Adapted from Creswell (2009)

According to Mouton (2001) and Edmonds and Kennedy (2012), there are three classifications of research design, namely, *qualitative*, *quantitative* and *mixed methods*. Often studies cannot easily be grouped as either qualitative or quantitative and are better described as tending to be more qualitative than quantitative, or vice versa. Conversely, mixed methods resides in middle of the aforestated approaches.

Welman *et al.* (2005) explain that quantitative research deals with *objective data* consisting of numbers, whereas qualitative research evaluates *subjective data* produced by the minds of respondents or interviewees. The latter is framed in words rather than numbers. The research in this thesis clearly tends towards quantitative research with its use of parameters such as return on investment, time and budget. As such, this thesis closely mimics the structure of a final written report for quantitative research suggested by Creswell (2008): introduction, literature and theory, methods, results and discussion.

The philosophical world-view that best describes the research conducted in this thesis is Postpositivist. Creswell (2009) states that the Postpositivist world-view starts with a theory, then data which either supports or refutes the theory is collected, after that necessary revisions are made before additional tests are performed. The research method and strategy of enquiry for this thesis are rather straightforward and are italicised in Figure 1.4 along with the philosophical world-view. Table 1.3 provides a summary of the research design of this thesis.

Table 1.3: Summary of thesis research design

Research design	Quantitative approach
Philosophical world-view	Postpostivism knowledge claims
Strategy of inquiry	Experimental research including a case study
Research methods	Predetermined approach, instrument based questions and on site performance data collection
Practices of research	Tests or verify theories or explanations, identify variables to study, observe and measure information numerically

Adapted from Creswell (2009)

1.6 Thesis Outline

This section provides a summary of the thesis content as well as the structural layout in which the content is presented. The thesis structure is aligned to follow the sequence of research objectives outlined in Section 1.3 (see Table 1.2) and corresponds to the stated research design and methodology. As a result, the reader is able to follow the flow of the study in alignment with the progressive achievement of each research objective. This thesis is structured as follows:

Chapter 1: Introduction serves to introduce the research undertaken in this study. First, the theoretical background and fundamental concepts of the study are explained. Next, the problem statement is formulated and translated into research objectives, delimitations and the overall research design and methodology. This chapter concludes by outlining the thesis structure.

Chapter 2: Asset Management Landscape establishes the fundamentals of AM, maintenance and shutdowns. The interconnections between these fields are examined and special attention is afforded to the importance of maintenance planning in the shutdown environment. This chapter contextualises the problem formulated in Chapter 1.

Chapter 3: Tam and Price Maintenance Prioritisation Framework introduces an important component of maintenance planning — *prioritisation*, and presents an overview of the TPMPF. Inefficiencies in the TPMPF are identified and other fields such as Multiple Criteria Decision Analysis (MCDA) and Imperfect Maintenance are explored as possible solutions for these inefficiencies. This chapter paves the way for the development of the application methodology in the subsequent chapter.

Chapter 4: Building a Shutdown Maintenance Prioritisation Framework proposes the application methodology, called the Shutdown Maintenance Prioritisation Framework (SMPF), to the problem presented in Chapter 1. The SMPF is discussed in detail and tailored to the findings of both Chapters 2 and 3. This chapter is used as template for the case study conducted in the chapter that follows.

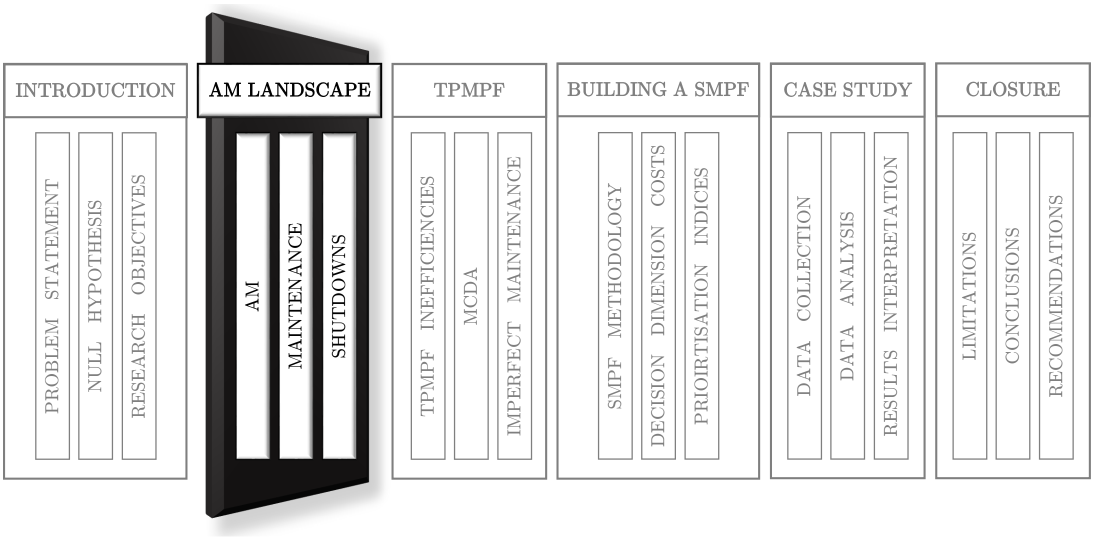
Chapter 5: Case Study applies the SMPF to a real life problem in the South African coal mining industry. The implementation of the SMPF and the interpretation of the results are presented and reviewed in order to validate the research.

Chapter 6: Closure reflects on the research conducted in this thesis and discusses the limitations of the study. Final conclusions are drawn and linked back to the research question and null hypothesis of the problem statement in Chapter 1. The null hypothesis is subsequently either accepted or rejected and the thesis concludes with the recommendations for future research.

The thesis outline described in this section is graphically depicted at the beginning of this chapter in Figure 1.1. It acts as a roadmap to indicate where the reader is along the research process and is updated at the beginning of each chapter to show the progress made.

Chapter 2

Asset Management Landscape



Chapter Aims:

Chapter 2 endeavours to contextualise the identified problem of Chapter 1 within literature. Fundamental concepts such as Asset Management, maintenance and shutdowns are established in order to provide the reader with sound background for the remainder of the thesis. Particular focus is placed on the changing face of maintenance and the importance of maintenance planning to shutdown success. This chapter serves as theoretical foundation for the chapters that follow.

Chapter Outcomes:

⇒ Comprehension of Asset Management, maintenance and shutdowns.

⇒ Delineation of the changing view of maintenance to a value-adding activity.

⇒ Understanding of the importance of shutdown maintenance planning.

2.1 Introduction to Asset Management

The term Asset Management (AM) is shrouded in obscurity owing to its widely practised synonymical use across various industries. Woodhouse (2003) and Mitchell (2007) reveal six distinctly different common uses of the term, of which the *latter* applies to this thesis:

- In the financial services sector, AM describes the management of securities (e.g bonds, mutual funds, stocks, etc.) or investment portfolios.
- Company board directors use AM in relation to the buying, selling or reorganisation of companies (i.e. mergers and acquisitions).
- Equipment maintainers assumed the term AM in order to raise corporate agenda awareness in an attempt to ascertain greater creditability and therefore support for their maintenance activities.
- Akin to equipment maintainers, software vendors relabelled their Computerised Maintenance Management Systems (e.g. asset registers) and started selling them as Enterprise Asset Management Systems.
- Within the information systems world, AM refers to the bar-coding of computers and the tracking of their locations and statuses.
- Infrastructure or plant owners and operators adopted AM to describe the appropriate and optimal life cycle management of their physical assets. This includes the combination of investing, exploiting, maintaining and decommissioning of their plants, infrastructures and any associated facilities.

As described by the closing bullet, AM in the context of this thesis refers to the holistic management of *physical assets* (e.g plant, machinery, property, buildings and vehicles) from their acquisition, through their life cycle until they are decommissioned and ultimately discarded. Having introduced the term AM, the following sections will elaborate on how it has evolved, what is meant by the term asset, and which definition of AM is adopted by this thesis.

2.2 Evolution of Asset Management

According to IAM (2012), AM is not new and people have been managing assets for thousands of years. However, the term AM (as concluded in Section 2.1) has only been adopted recently.

The North Sea Oil and Gas industry headed the initial movement towards AM following the crises of the late 1980s, these included the Piper Alpha disaster, oil price crash, Lord Cullen's report on corporate risk/safety management and market globalisation (Woodhouse, 2003). Large companies were forced to re-evaluate their underlying business models if they wanted to survive. A pivotal finding was that while they held a number of strategic advantages and economies of scales, they lacked the integrated thinking approach and operational efficiency of smaller organisations (IAM, 2012). In response, these larger businesses formed small, dynamic, multi-disciplined teams to manage the life cycles of their oil platforms which soon translated into massive improvements in performance, safety and productivity.

Hastings (2010) states that historically, AM has not been a well defined activity. This is mainly due to educational and professional specialisations that result in the functional isolation of various disciplines that surround the management of physical assets. Amadi-Echendu (2006) and Woodhouse (2006) coincide that this *silo effect* as well as *short term thinking*, which concentrates on immediate profit instead of asset longevity, are major threats to AM.

Since the 1990s, academics and industry professionals have argued for an interdisciplinary approach for AM (Amadi-Echendu *et al.*, 2010). The contention is to ensure a sufficient mix of skills are available to address and resolve vexing AM issues. Cross functional learning and the sharing of knowledge helps break down the barriers of the silo effect which, in the opinion of IAM (2012), is good AM.

Adding to this interdisciplinary approach is Schuman and Brent (2005) who implore the adoption of a holistic view of AM. McGlynn and Knowlton (2011) support a broadened scope of AM that focuses on whole life cycle management of assets rather than just the maintenance aspects. This is what Amadi-Echendu (2004) refers to when the author states that AM is a "paradigm shift from the conventional cost doctrine typical to maintenance". Adopting this holistic view of AM combats the threat of short term thinking and ensures the value profile of the asset is enhanced sustainably throughout its lifetime.

The concept of AM has recently become acknowledged in various industries and is rapidly growing worldwide (Frolov *et al.*, 2010). Examples of AM publications in other industries include: the built environment (Newton and Christian, 2004; Amadi-Echendu, 2004), chemical engineering (Chopey and Fisher-Rosemount, 1999), construction (Vanier, 2001), electricity (Morton, 1999; Hoskins *et al.*, 1999), irrigation (Malano *et al.*, 1999) and even transport (McElroy, 1999; OECD, 2001).

An upsurge in publishing activity around the year 2000 (Amadi-Echendu *et al.*, 2007) resulted in disjointed AM principles, structures and even definitions which inhibited the implementation of AM in practise (Campher, 2012). Then in 2002, a number of organisations began realising that greater clarity and guidance was needed to resolve these AM integration and optimisation challenges (Woodhouse, 2006). Clearly, what was needed was an industry standard that can be used as a model or framework for various organisations specialising in a variety of assets types.

In response to demand from industry, Publicly Available Specification 55 (PAS 55) was developed and published in 2004. It was the first industry standard for the integrated, optimised and sustainable management of physical assets. Its widespread adoption and acceptance served as basis for developing the International Organisation for Standardisation 55000 (ISO 55000) family of standards. This family of standards was released in early 2014 and is the current authority on AM. PAS 55 and ISO 55000 are extensively covered in Subsections 2.5.1 and 2.5.2 respectively.

The purpose of this section was to explore the relevant literature surrounding AM. Since AM is the cornerstone of this thesis, it is vitally important that the reader is presented with the subject's body of knowledge. The following section aims to solidify the reader's understanding of core concepts such as asset, asset types and asset life cycle. Comprehension of these concepts are necessary to define the term AM in Section 2.4.

2.3 Asset, Asset Types and Asset Life Cycle

Depending on the context, the term *asset* can be interpreted in a number of distinctly different ways. Nonaka *et al.* (2000) provide a general definition that envelopes all the assets of an organisation without bias towards any particular asset type. They define assets as:

> *firm-specific resources that are indispensable to create values for the firm.*

A firm's balance sheet classifies assets as either *current* or *non-current* (Firer *et al.*, 2012). Current assets have high turnover rates and will usually be converted into cash within twelve months, e.g. cash, inventory and accounts receivable. Conversely, non-current assets generally have life spans exceeding a year, e.g. machinery, vehicles, land and buildings. Snitkin (2003) adds a third classification with *intangible* assets, which can be patents, trademarks, licensing agreements, etc. Intangible and human assets are becoming increasingly important in the value creation process and should therefore not be underestimated (Ananthram *et al.*, 2013; Chareonsuk and Chansa-ngavej, 2010).

The AM standard PAS 55 advocates the holistic management of different asset types. It recognises five categories of assets that should be managed integrally in order to achieve the organisational strategic plan, they are: *human assets*, *information assets*, *intangible assets*, *financial assets* and *physical assets*. The latter is heavily emphasised in PAS 55's scope (see Figure 2.1) and its definition of an asset. PAS 55 defines assets as (BSI, 2008*a*):

> *plant, machinery, property, buildings, vehicles and other items that have a distinct value to the organisation.*

ISO 55000, the successor to PAS 55, and the current authority on defining assets in the context of AM, provides a general definition that considers all asset types. It defines an asset as (ISO, 2014*a*):

> *an item, thing or entity that has potential or actual value to an organisation.*

The definition is qualified by three notes:

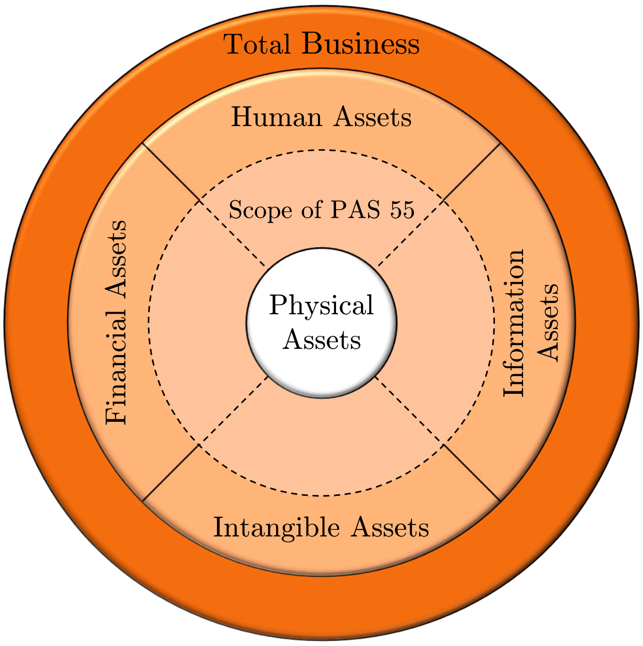


Figure 2.1: PAS 55 scope amongst five broad asset type categories

Adapted from BSI (2008a)

1. Value can be tangible or intangible, financial or non-financial, and includes considerations of risk and liabilities. It can be positive and negative at different stages of the asset life.

2. Physical assets usually refer to equipment, inventory and properties owned by the organisation. Physical assets are the opposite of intangible assets, which are non-physical assets such as leases, brands, digital assets, use rights, licences, intellectual property rights, reputation or agreements.

3. A grouping of assets, referred to as an asset system, could also be considered as an asset.

Pioneers in the field of AM (see Section 2.2) emphasised the importance of adopting a whole life cycle approach to the management of physical assets. Hence, understanding the asset life cycle is paramount in comprehending the complex concept of AM. ISO 55000 simply refers to asset life cycle as the "stages involved in the management of an asset" (ISO, 2014*a*). More rounded definitions are given by authors such as Hastings (2010) and McGlynn and Knowlton (2011).

The life cycle of a typical asset consist of several independent stages (Snitkin, 2003). PAS 55 condenses it into four principle stages, namely, *create/acquire*, *utilise*, *maintain*, and *renew/dispose* (BSI, 2008*a*). During the initial stage, the need for an asset is identified and a business case along with financial, technological and exploitation ideas are initiated and formalised (Amadi-Echendu, 2004). The utilisation and maintenance stage is the longest, as during this stage the asset creates value for the firm and needs care in order to maintain its performance (Jooste, 2014). In the final stage the asset is decommissioned at the end of its useful life and often requires safety and environmental considerations during the asset's disposal (Hastings, 2010).

At lower levels of asset granularity, such as physical equipment components, the concept of asset life cycle is easy to understand. However, as mentioned in the final qualifying note in ISO 55000's definition of an asset, asset systems can also be considered assets. Therefore, as the asset system complexity increases, it becomes more difficult to identify its various life cycle stages. Herein lies the challenge to determine optimal maintenance strategies, replacements, modifications, changing of function demands and recycling options throughout the lifetime of the asset (IAM, 2012). Figure 2.2 shows the typical life cycle stages of an asset along with possible variations.

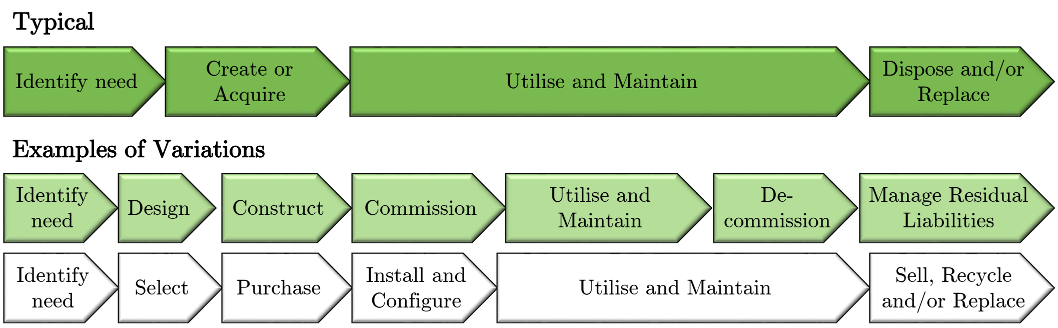


Figure 2.2: Typical asset life cycle stages and examples of variations

Adapted from IAM (2012)

This section elucidated the concepts of asset, asset types and asset life cycle. They are important for the comprehension of AM and with these concepts thoroughly discussed, the term *Asset Management* can be defined within the context of this thesis.

2.4 Definition of Asset Management

As the field of Asset Management (AM) emerged, scholars attempted to differentiate between different asset types by adding qualifying adjectives to AM. Authors such as Mitchell (2007), Amadi-Echendu (2004) and Hastings (2010) used the term "Physical Asset Management". Lin *et al.* (2006), Van der Lei *et al.* (2012) and Amadi-Echendu *et al.* (2007) preferred "Engineering Asset Management". Less prominently was Snitkin (2003) and Waeyenbergh and Pintelon (2002) who referred to "Capital Asset Management".

IAM (2012) believes these qualifying objectives are unnecessary and add no value as they attempt to make a special case for something that is inherently consistent. Regardless of the asset type, scratching beneath the surface reveals a clear set of generic requirements which should be managed appropriately. This view is shared by the communities of experts who developed both PAS 55 and ISO 55000 as they converged on the simplest term possible — *Asset Management*.

According to Amadi-Echendu *et al.* (2007), until quite recently the definitions of AM focused on two distinctly different yet important aspects relating to the management of physical assets. The first concentrates on the communication and information technologies necessary to manage the data relating to the assets, whereas the second focuses on systems integration and management needed to facilitate informed decision-making about the assets.

More recently, however, the definition of AM underwent a paradigm shift towards a broader view with a stronger focus on organisational integration. In the early 2000s, definitions of AM started acknowledging this wider perspective in addition to AM being an integral function of an organisation (Brown and Humphrey, 2005). Literature is populated with different definitions of AM[1]. PAS 55 defines AM as (BSI, 2008*a*):

[1]See Mitchell and Carlson (2001), Vanier (2001), Woodhouse (2001), Hastings (2003), Stewart *et al.* (2003), Smith (2005), Schneider *et al.* (2006), Davis (2007) and Tywoniak *et al.* (2008)

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

ISO 55000, on the other hand, provides a more general definition for AM in that it is the (ISO, 2014*a*):

> *coordinated activity of an organisation to realise value from assets.*

The definition is qualified with three notes:

1. Realisation of value will normally involve a balancing of costs, risks, opportunities and performance.
2. Activity can also refer to the application of the elements of the asset management system.
3. The term activity has a broad meaning and can include, for example, the approach, the planning, the plans and their implementation.

ISO 55000's definition appears general, which according to IAM (2012) is intentional, as "the thinking is common to the use of assets in whatever form they take. It is up to the organisation to choose *how* to manage those assets to derive best value…". For the purpose of this thesis, the unadorned term of *Asset Management* and the ISO 55000 definition of AM are adopted.

2.5 Asset Management Standards

Up until early 2014, PAS 55 was the authoritative standard in the field of AM. Its widespread adoption and acceptance lead to the development of the ISO 55000 series of international standards for AM. ISO 55000 has since superseded PAS 55 as the current authority on AM, but the importance of understanding the former has not declined. Especially given that, at the time of writing, organisations are transitioning from PAS 55 to ISO 55000 and an understanding of their structures, similarities, differences as well as subsequent additions and omissions cannot be overemphasised.

2.5.1 Publicly Available Specification 55

Publicly Available Specification 55 (PAS 55) was developed by the Institute of Asset Management, British Standards Institute and a number of collaborating parties. It was first published in 2004 and substantially revised in 2008. According to Campbell *et al.* (2011), PAS 55 first gained traction in the United Kingdom's utilities sector in 2006, but has since been applied to various other business sectors and geographies.

PAS 55 is published in two parts. The first part, *PAS 55-1: Specification for the optimised management of physical assets*, provides recommendations for establishing, documenting, implementing, maintaining and continually improving an Asset Management System (AMS), see BSI (2008*a*). The second part, *PAS 55-2: Guidelines for the application of PAS 55-1* comprises of guidance for the implementation of PAS 55-1, see BSI (2008*b*). Hereinafter, these two parts are consistently referred to as PAS 55, rather than the two separate publications.

The scope of PAS 55 is primarily fixated on the management of physical assets, but does recognise other types of asset (as discussed in Section 2.3 and Figure 2.1). However, these other asset types are only considered if they directly impact the management of an organisation's physical assets. According to BSI (2008*a*), PAS 55 is applicable to three main categories of organisations detailed in Table 2.1.

Table 2.1: Organisational field of application for PAS 55

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

According to BSI (2008a)

Amongst other things, Hastings (2010) states that the adopting of PAS 55 can provide organisations with the following:

- a structured view and understanding of AM;
- effective relationships between top management, AM, operations and maintenance;
- improvements in asset financial returns;
- insurance, health and safety, regulatory benefits;
- improvements in AM organisation;
- company recognition/marketing; and
- improvements in training and development.

Van den Honert *et al.* (2013) reports that since its creation, PAS 55 has proven to be a success, however, it is guilty of lacking detail. Industry and professional bodies around the world attempted to address this issue in 2009 already, by putting forward PAS 55 to the International Organisation for Standardisation (ISO) as the basis for a new ISO standard for AM. This request was subsequently approved and the following subsection discusses the ISO 55000 series of standards.

2.5.2 International Organisation for Standardisation 55000

The ISO 55000 series of international standards was officially released in early 2014. It was developed by the ISO Committee PC251 with the participation of 31 countries. PAS 55 was used as basis for creating the ISO 55000 series, which consists of the following three documents:

- *ISO 55000: Asset management - Overview, principles and terminology*, see ISO (2014*a*).
- *ISO 55001: Asset management - Management systems - Requirements*, see ISO (2014*b*).
- *ISO 55002: Asset management - Management systems - Guidelines for the application of ISO 55001*, see ISO (2014*c*).

ISO 55000 provides a critical overview of what an Asset Management System (AMS) consists of and contains the terminology used throughout the three documents. The minimum requirements to establish, implement, maintain and improve an AMS is specified in ISO 55001. Lastly, ISO 55002 offers interpretation and guidance on the implementation of an AMS in accordance to the ISO 55001 requirements. Henceforth, these three documents are consistently referred to as ISO 55000, rather than the three separate publications.

The structure of an AMS in the context of the organisation's strategic plans, objectives and its stakeholders is shown in Figure 2.3. In line with ISO 55000, an AMS is defined as:

> *a set of interrelated and interacting elements of an organisation, whose function is to establish the asset management policy and asset management objectives, and the processes, needed to achieve those objectives. In this context, the elements of the asset management system should be viewed as a set of tools, including policies, plans, business processes and information systems, which are integrated to give assurance that the asset management activities will be delivered.*

According to Ma *et al.* (2014), the most significant change between PAS 55 and ISO 55000 is the target scope of application. PAS 55 is overtly focused on physical assets, whereas ISO 55000 is designed to apply to any asset type. However, ISO 55000 recognises its particular applicability to physical assets. This change has meant a generalisation of language throughout the documents, so they can be understood and interpreted within different asset management contexts.

Woodhouse (2013) points to key themes, which contributed to the popularity and success of PAS 55, that are retained in ISO 55000. These include:

- Alignment (line of sight) of organisational objectives feeding clearly into asset management strategies, objectives, plans and day-to-day activities.
- Whole life cycle asset management planning and cross-disciplinary collaboration to achieve the best value combined outcome.
- Risk management and risk-based decision-making.

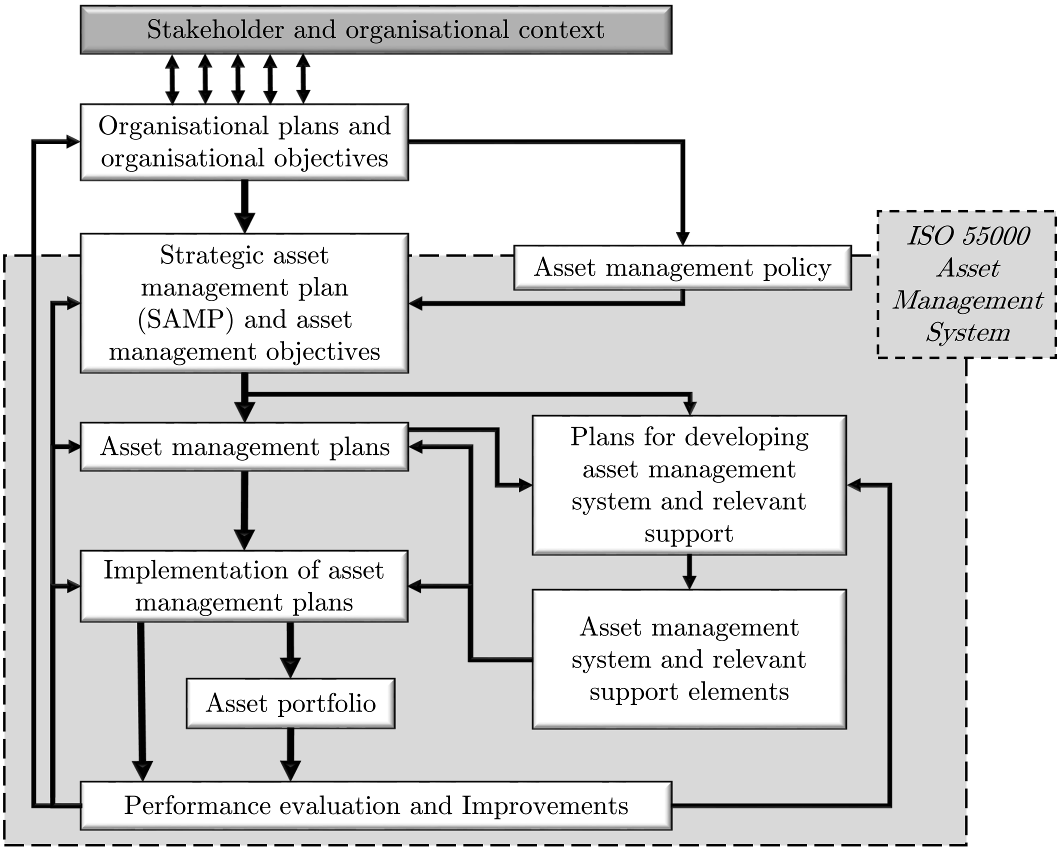


Figure 2.3: Asset management system according to ISO 55000

Adapted from ISO (2014a)

- The enablers for integration and sustainability; particularly leadership, consultation, communication, competency development and information management.

The issuance of ISO 55000 brought further creditability and momentum to the field of AM as well as PAS 55. Woodhouse (2013) states that owing to the generic nature of ISO 55000, PAS 55 will continue to remain popular as expanded knowledge on the management of physical assets.

2.6 Maintenance

In today's cut-throat global marketplace, it is imperative that organisations identify and exploit any competitive advantage available to them. With external factors such as revolutionary technological advances few and far between, organisations are diverting some of their attention in-house and seeking to operate as efficiently and as effectively as possible.

Asset intensive organisations can strive to be more efficient and effective by maximising their assets' operational time (Syafar *et al.*, 2015) and optimising their operational costs (Moore and Starr, 2006). In other words, to be more profitable organisations must ensure their assets remain operable by appropriately maintaining them in the most cost effective way possible. This, however, is no easy feat with maintenance expenditure continually on the rise due to the changing organisational role of maintenance, non-performance of systems becoming less acceptable, increasing functional requirements and greater complexity of manufacturing technologies (Moore and Starr, 2006; Parida and Kumar, 2006),

Koronios *et al.* (2007) reports that operational and maintenance costs constitute up to 70% of an asset's total cost of ownership. In fact, within most organisations, maintenance represents the largest single variable operating cost when considering physical plant value, maintenance labour, material and overheads (Li *et al.*, 2006). In manufacturing organisations, for example, maintenance related costs are estimated to be 25% of the overall operating cost (Komonen, 2002). While in other industries such as petrochemical, electrical power and mining, maintenance related costs might even surpass the operational costs (Raouf, 1993; De Groote, 1995; Eti *et al.*, 2005).

With no asset intensive organisation being exempt from having to maintain their equipment, performing maintenance optimally can generate a competitive advantage for an organisation. Hence, the maintenance function is no longer perceived as a "necessary evil", but a crucial "value adding" contributing activity that promotes an organisation's competitiveness (Van Horenbeek and Pintelon, 2014). Companies have realised that maintenance contributes "more than ever" to the achievement of business objectives (Waeyenbergh and Pintelon, 2002) and are subsequently adopting maintenance as a profit generating business element (Sharma *et al.*, 2011).

A wide range of varying maintenance definitions are found in literature. For example, Mitchell (2007) defines maintenance as "the act of causing to continue" whereas Organ *et al.* (1997) choose to adopt the dictionary definition of maintenance which is "to keep in existence". Gulati (2012) provides a broader definition for maintenance:

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

This definition implies the term maintenance includes activities performed to circumvent failures as well as tasks to restore assets to their original condition. Pintelon and Waeyenbergh (1999) agrees and defines the concept of maintenance as a set of various preventative, corrective and condition based maintenance interventions. Inspections, functional testing, condition monitoring, repair, refurbishment, life extension and replacement of individual assets are examples of maintenance interventions, notes BSI (2008*a*).

In general, literature broadly classifies maintenance into two main types: *corrective* and *preventive* (Duffuaa *et al.*, 2001; Waeyenbergh and Pintelon, 2004; Yao and Ralescu, 2013). The difference between Corrective Maintenance (CM) and Preventive Maintenance (PM) is that they are performed *after* and *before* system failure respectively (Wang, 2002). Figure 2.4 shows a breakdown of both these maintenance types according to EN 13306:2001 (2001).

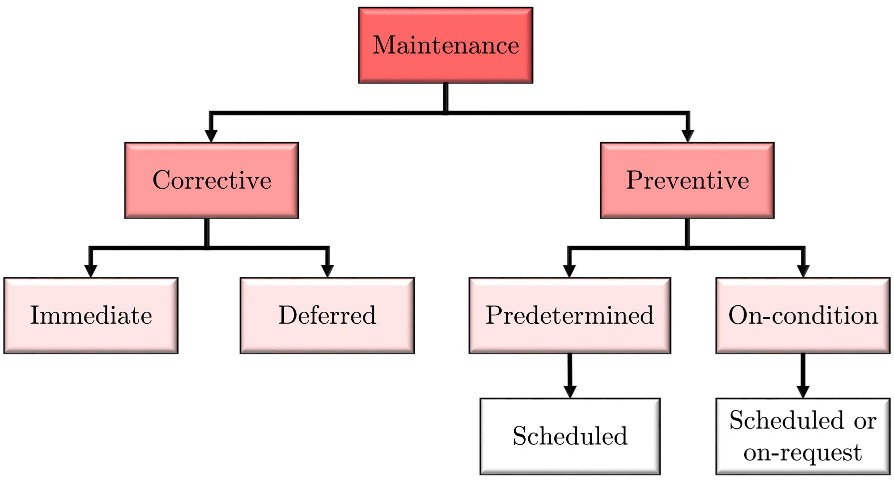


Figure 2.4: Breakdown of maintenance types

Adapted from EN 13306:2001 (2001)

The earliest maintenance strategy is CM, which lead to high levels of machine downtime (production losses) and maintenance (repair and replacement) costs due to sudden and unplanned failures (Tsang, 1995). An alternative to

CM is the PM strategy which contributes to minimising failure costs and machine downtime in addition to increasing product quality (Usher *et al.*, 1998).

Initially, PM (also known as time-based, used-based or periodic-based maintenance) decisions, such as preventive repair times/intervals, were based solely on the failure time data or used-based data of a physical asset (Lee *et al.*, 2006) and paid no attention to the asset's health status. This meant healthy assets were unnecessarily maintained or replaced at costs that were needless and avoidable. Clearly, a more efficient PM approach based on the asset's condition was needed and later developed with Predictive Maintenance (PdM). PdM, also known as condition-based maintenance, recommends maintenance actions (decisions) based on the information collected through a Condition Monitoring (ConMon) process (Ahmad and Kamaruddin, 2012). An asset's health is monitored through its operating condition, which can be measured using various monitoring parameters such as vibration, temperature, lubricating oil, contaminants, and noise levels. PdM is currently the most modern and popular maintenance technique discussed in literature (Dieulle *et al.*, 2001; Han and Song, 2003; Moya, 2004).

Wang *et al.* (2007) warns that CM actions cannot be completely avoided when maintenance strategies such as PM (time-based/used-based) and PdM are applied. This can be attributed to the stochastic nature of equipment failure. The risk of failure can be reduced by correctly selecting and implementing PM and PdM strategies, however the risk cannot be negated completely.

Chelsom *et al.* (2005) state that maintenance is self-evident in most engineering firms as its absence would curtail the survival of plant equipment. According to IAM (2012), the overall objective of maintenance is to ensure that assets remain safe and operational to meet their service duty and performance requirements. To put it in another way, the maintenance function aims to safely maximise the availability of equipment in order to achieve the desired output quantity and quality. Pintelon and Gelders (1992) adds that the maintenance objective must be realised in a cost effective way as well as conform to environmental and safety regulations.

Achieving the overall maintenance objective requires a multidisciplinary approach where maintenance is viewed strategically from the overall business perspective. Murthy *et al.* (2002) highlights the important features of this multidisciplinary approach as:

- the integration of technical and commercial issues;
- a quantitative approaches involving mathematical models;
- the use of all relevant information; and
- continuous improvement in maintenance management.

The maintenance function serves to support an organisation's larger ambitions. For this to be a fruitful endeavour, both these entities need to work in unison. That is, the objectives and goals of the maintenance function needs to be aligned with those of the whole organisation. Through a systems view, Visser (1998) puts maintenance in perspective with the whole organisation (see Figure 2.5). In Visser's input-output model, to achieve high levels of maintenance system maintainability requires the deployment of resources such as labour, spares, tools, information, materials, money and external services (contractors). The quality of maintenance performed will influence the availability, safe operation, output volume and quality of the production system. These factors in turn will ultimately determine the profitability of the enterprise.

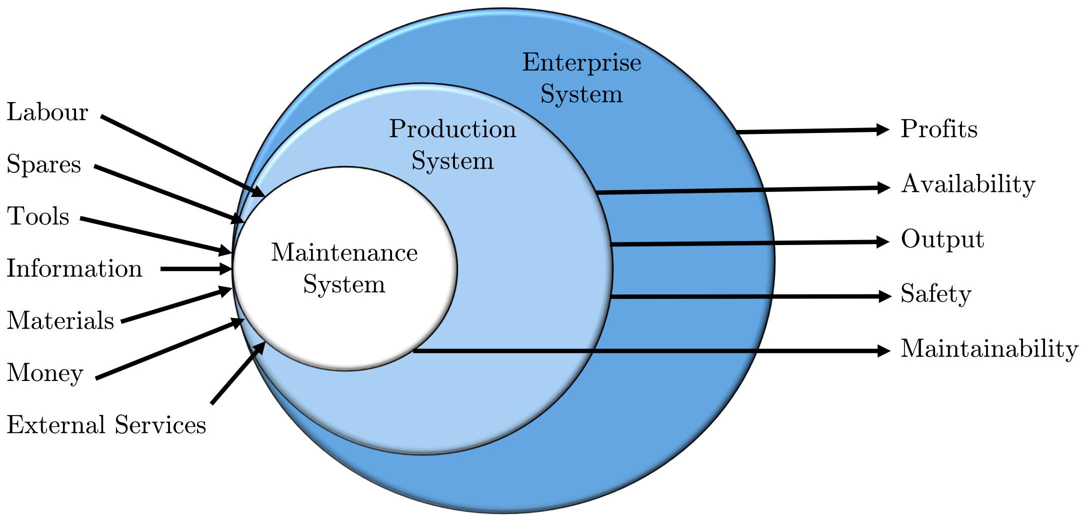


Figure 2.5: System perspective of maintenance in organisational context

Adapted from Tsang (2002) and Al-Turki (2009)

Leading from the aforementioned systems view, maintenance is put forward at the heart of an enterprise (Al-Turki, 2009). With the importance of maintenance now established, the following subsections provide an in-depth discussion of the different maintenance strategies available to organisations that can help them achieve their enterprise objectives.

2.6.1 Corrective Maintenance

Corrective Maintenance (CM) may be described as the fire-fighting approach to maintenance and is exemplified by popular phrases such as "run-to-failure" and "fix it when it brakes". It is the oldest maintenance strategy in industry (Mechefske and Wang, 2003) and was used exclusively up to and during the 1950s (Garg and Deshmukh, 2006).

McKenna and Oliverson (1997) define CM as:

> *all actions performed as a result of failure to restore an item to a specified condition.*

Leading from this definition, CM can be described as event driven. In other words, equipment is allowed to run until failure and only then will it be maintained (repaired or replaced). According to Dhillon (2002), CM is an unscheduled maintenance action comprising of unpredictable maintenance needs that cannot be preplanned. These actions, amongst others, include the repairing, salvaging, rebuilding or overhauling of equipment (Al-Turki *et al.*, 2014). Furthermore, Uday *et al.* (2009) stress that CM can be either immediate of deferred (also shown in Figure 2.4):

- *Immediate maintenance* is carried out without delay after a fault has been detected to avoid unacceptable consequence.
- *Deferred maintenance* is not immediately carried out after a fault detection, but is delayed according to given maintenance rules.

Mobley (2002) declares that CM is the *most expensive* maintenance strategy. This claim is backed by Mitchell (2007) who suggests CM costs are typically two to four times greater than failure avoidance approaches (PM and PdM). Other disadvantages include fluctuations in production capacity, higher downtimes, greater overall maintenance costs to repair catastrophic failures and an increase in the scrap and rework rate (Bateman, 1995; Swanson, 2001; Sharma *et al.*, 2005). Moreover, CM often causes serious damage to related facilities, personnel and the environment (Wang *et al.*, 2007).

CM makes no attempt to anticipate failure and is by its very nature a reactive approach. For this reason, Lind and Muyingo (2012) believe the problem with CM is that faults happen in unexpected ways and at inconvenient times which leads to higher than expected costs. Wang *et al.* (2014) stresses that no approach can completely eliminate failures, which is why CM is still widely adopted in engineering practise. An advantage of CM is that it allows a plant to minimise the amount of maintenance manpower on hand and money spent to keep the equipment running (Vanzile and Otis, 1992). Actually there are other instances in which CM makes economic sense and becomes a feasible option.

According to Nakagawa (2005), CM is adopted in situations where units can be repaired and their failures do not have any detrimental effects on the entire system function. Al-Turki *et al.* (2014) support this view, but warn that CM should only be utilised on non-critical assets where capital costs are small, failure identification is quick, and rapid repair is possible. What is more, it is argued by Sharma *et al.* (2005) that CM is a viable approach in situations where customer demand exceeds supply and profit margins are large, because its objective is to keep the process running in order to maximise equipment availability.

The reality, however, is that global competition is increasing and profit margins are getting smaller. This has forced maintenance managers to apply more effective and reliable maintenance strategies (Wang *et al.*, 2007). Mechefske and Wang (2003) recommends moving from CM to PM in order to obtain improvements in equipment breakdowns, downtime durations, lost revenue and unsafe working conditions.

2.6.2 Preventive Maintenance

Preventive Maintenance (PM) differs from CM in that it does not wait for equipment to fail. This means maintenance is performed *prior* to failure. It is usually based on the condition (health) or the aged related failure history of the equipment (Kumar and Maiti, 2012), which respectively makes PM either *predictive* or *periodic* (Nielsen and Sørensen, 2011; Zaim *et al.*, 2012).

Predictive (condition-based) maintenance takes action such as repair, replacement and overhaul based on an assessment of the asset's condition. The health of the asset is assessed through diagnostic measurements such as lubricant analysis, vibration analysis, thermography, radiography and ultrasound. (Carnero, 2005). This type of PM has evolved to the extent that it is now accepted in literature as a maintenance strategy on its own. For this reason it is covered separately under its own heading in Subsection 2.6.3.

The current subsection deals exclusively with the latter PM type. Other terms in literature for periodic maintenance include "time-based maintenance", "used-based maintenance", "planned maintenance", "predetermined maintenance" and "scheduled maintenance". After the establishment of predictive maintenance, literature started putting all these terms under one umbrella simply termed — PM. This thesis chooses to do the same as Vlok (2013) reveals that PM actions are based on the asset's age as measured in time, miles, tons processed, or any other convenient process parameter. Hence, PM encompasses all the aforestated names since it can be based on time or how much the asset has been used (in times, tons, etc.), and because it is performed before failure; by its very nature it is planned/scheduled.

Smith and Hinchcliffe (2004) define PM as:

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

Adding to this definition, Swanson (2001) reports that PM work may include equipment inspection and lubrication, parts replacement, cleaning and adjustments. What is more, PM programs can vary greatly between being considered *extremely limited* to being considered *comprehensive*, depending on the PM work selected for implementation (Mobley, 2002). It is the applicability of the maintenance work rather than its volume that will ultimately determine whether a PM programs is comprehensive or not.

Dhillon (2002) does, however, point out that in an maintenance organisation, PM usually accounts for a major portion of the maintenance effort. A major reason for this, according to Sarker and Haque (2000), is the general assumption that it costs more to repair and replace operating components after failure than it is to do the same at some predetermined time.

Niebel (1994) highlights some characteristics of a plant that would benefit from a good PM program:

- low equipment use due to failures;
- large volume of scrap or rejects due to unreliable equipment;
- rise in equipment repair costs due to negligence in lubrication, inspection and replacement of worn components;
- high idle operator times due to equipment failure; and
- reduction in capital equipment expected productive life due to unsatisfactory maintenance.

The main objective of carrying out PM is to improve long term system reliability (Li *et al.*, 2006) by reducing frequent and sporadic equipment failure (Sharma *et al.*, 2005). Other objectives include minimising total inspection and repair costs (Mirghani, 2009), better planning and scheduling of necessary maintenance work, minimising equipment downtime and therefore production losses (Niebel, 1994). Through proper implementation, these objectives can be translated into subsequent PM benefits. Additional advantages of PM include extending equipment life (Swanson, 2001) and promoting the general health as well as safety of the equipment user and maintenance personnel (Raymond and Joan, 1991).

Despite its numerous advantages, PM is not devoid of criticism. Saranga (2002) complains that it may, at times, create problems that were non-existed before. This is due to the invasive nature of PM in that it interrupts production at scheduled times in order to perform the work. These scheduled interruptions and their intervals are determined without consideration of the asset's condition. Mechefske and Wang (2003) warns that this practice often leads to unnecessary maintenance and therefore significant losses of remaining useful equipment life. A lack of sufficient historical data has been identified as a culprit for the inability to define effective PM intervals (Mann *et al.*, 1995).

Without careful justification of PM intervals, both Sherwin (2000) and Pun *et al.* (2002) agree that many PM programs motivate the indiscriminate use of preventive overhauls and replacements. Nevertheless, Kumar and Maiti (2012) concede that PM is effective in many capital intensive processes, but in some cases the rate of deterioration depends on various other factors like operational and environmental conditions in addition to the amount of time elapsed. Hence, these cases require a more sophisticated maintenance strategy than PM.

An alternative is to use PdM, which holds several advantages over PM. According to Yang (2003), it can be a better and more cost-effective maintenance strategy. Moreover, Kumar and Maiti (2012) state that a PdM policy is preferred to PM due to its superior risk reduction capability. The following subsection discusses PdM in greater detail.

2.6.3 Predictive Maintenance

Predictive Maintenance (PdM), also known as condition-based maintenance, was introduced in 1975 in order to maximise the effectiveness of PM decision making (Ahmad and Kamaruddin, 2012). PM had become a major expense in industrial companies and PdM was seen as a more efficient maintenance approach (Jardine *et al.*, 2006). The popularity of PdM has only grown since its introduction and according to Sharma *et al.* (2005) it is especially popular in process industries such as paper mills, oil refineries, sugar mills and thermal power plants.

Butcher (2000) defines PdM as:

> *a set of maintenance actions based on real-time or near real-time assessment of equipment condition obtained from embedded sensors and/or external tests and measurements using portable equipment.*

This definition highlights the central feature of a PdM program. That is, PdM programs use the actual operating condition of plant equipment and systems to posit maintenance repair and replacement decisions (Raheja *et al.*, 2006). Lee *et al.* (2004) state that, in principle, the PdM maintenance decision-making process consists of the following three steps:

1. The *data acquisition step* collects and stores the data relevant to equipment or system health.

2. The *data processing step* handles and analyses the data or signals collected in Step 1 for better understanding and interpretation of the data.

3. The *maintenance decision-making step* makes decisions to recommend efficient maintenance policies.

Firstly, asset data is gathered by continuously monitoring signals using special instruments such as sensor systems (Wang *et al.*, 2007). Next, the asset condition is monitored using techniques such as vibration monitoring, lubrication analysis and ultrasonic testing (Niu *et al.*, 2010). Finally, the asset condition results indicate whether the asset is operating normally or not (Pariazar *et al.*, 2008) and maintenance decisions can subsequently be made. This process is the heart of PdM and is referred to as Condition Monitoring (ConMon). In summary, Campos (2009) mentions that ConMon includes all activities from asset data acquisition, processing, analysis and interpretation in order to extract meaningful information about the condition or health of that asset.

As with PM, the main objective of PdM is to reduce the probability of equipment breakdown. However, PdM also aims to minimise the total cost of inspection and repair by reducing unnecessary maintenance work. It achieves this by continuously or intermittently collecting and interpreting asset operating condition data, thus performing a real-time or near real-time assessment of equipment condition, in order to make maintenance decisions (Knapp and Wang, 1992; Gupta and Lawsirirat, 2006).

Compared to CM, for example, there are numerous advantages associated with PdM. Some of these benefits include a reduction in equipment breakdown (Swanson, 2001), easy identification of faulty components, greater safety, reduction in maintenance costs (Heng, 2009), improved productivity, product quality and overall effectiveness of manufacturing and production plants (Mobley, 2002). Moreover, Mechefske and Wang (2003) points out that PdM identifies the symptoms of failure which establishes a lead time that allows the scheduling of maintenance work just before complete failure. Hence, the remaining equipment useful life is utilised as much as possible as maintenance is only performed when the need is imminent.

In spite of all these benefits PdM may not always be the best maintenance method to implement. A major issue according to Yang (2003) and Ellis (2008) is whether a PdM program is necessary from a cost effectiveness perspective. The cost of implementing a PdM program needs to be justified by its implementation on critical assets that pose major financial and operational risks in the event of failure. In addition to cost effectiveness, Al-Najjar and Alsyouf (2003) are concerned about the effectiveness and accuracy of a PdM program where data is deficient, limited or of poor quality.

A PdM program recognises symptoms of failure and allows proper maintenance actions to be taken ahead of failure and with minimal loss of residual asset life. However, such a program needs to be cost effective in order to justify its introduction. What is more, it should not be constrained by deficient or limited asset condition data.

2.6.4 Selective Maintenance

All three the maintenance types (CM, PM and PdM) made reference to how important it is for an organisation to chooses the method that is most cost effective. In today's competitive environment, asset managers are tasked with doing more with less. Available resources such the maintenance budget and time allocated for maintenance are limited and in some cases even diminishing. This has meant that not all maintenance activities can be performed, but only the most critical few. Performing maintenance under limited resources is known in literature as selective maintenance.

Cassady *et al.* (2001*a*) defines selective maintenance as:

> *the process of identifying a subset among sets of desirable maintenance actions. This implies deciding which system components to maintain, and whether to repair or replace a system component to optimise a system performance parameter, for example reliability under operational constraints such as time and cost.*

This definition indicates how the landscape of maintenance has changed from doing the best maintenance possible to doing the best maintenance that the limited resources available is able to support. Until recently, the majority of maintenance research has ignored the potential of limitations on the resources required to perform maintenance actions (Maillart *et al.*, 2009).

2.7 Shutdowns

To be profitable, organisations need to ensure their plants are safe, reliable and run as efficiently as possible. Industrial settings such as chemical manufacturing, refining and power plants, to name a few, conduct large-scale maintenance activities during total plant shutdowns to achieve these goals (Megow *et al.*, 2011). Shutdowns provide an opportunity to help restore equipment and machinery that deteriorated during operation due to a number of factors such as ageing, wear, corrosion, erosion and fatigue (Hameed and Khan, 2014).

The majority of PM activities are performed when the manufacturing plant is in operation (Kister and Hawkins, 2006). However, some maintenance work such as major equipment overhaul or replacement may not be possible unless entire equipment systems (production lines) are shut down. While it may be possible to only shut down the portion of the plant needing attention, many major plants cannot isolate their equipment during normal operation (Hadidi and Khater, 2015). Another issue is that the labour in charge of performing daily maintenance work in the operating section of the plant may be left short staffed or even depleted (Bevilacqua *et al.*, 2012). Therefore, organisations most often opt for a *total plant shutdown.* In addition to being less disruptive, Kister and Hawkins (2006) point out that a total plant shutdown makes more economic sense as it is far less expensive to conduct in comparison to more frequent shutdowns in separate areas of the plant.

2.7.1 Definition of Shutdowns

There is inconsistent use of vocabulary pertaining to the shutting down of an entire facility to perform maintenance work. Terms such as "Plant Maintenance Shutdowns", "Plant Shutdowns", "Shutdowns", "Maintenance Outages", "Outages", "Turnaround Maintenance" and "Turnarounds" coexist throughout literature. This thesis chooses to adopt the simple and unadorned term — *Shutdowns*. This is in line with the influential publications *Asset Management - an anatomy* (IAM, 2012) and *The Asset Management Landscape* (GFMAM, 2014). All subsequent definitions have been harmonised with this decision.

Lenahan (2011) defines a shutdown as:

> *an engineering event during which new plant is installed, existing plant overhauled and redundant plant removed.*

A more descriptive definition is provided by Duffuaa and Ben Daya (2004) who define shutdowns as:

> *periodic maintenance in which plants are shutdown to allow for inspections, repairs, replacements and overhauls that can be carried out only when the assets (plant facilities) are taken out of service.*

It is noted from these definitions that a shutdown constitutes a major endeavour consisting of an array of diverse yet inter-related maintenance activities. These activities may include any or all of the different maintenance types (CM, PM and PdM) described in Section 2.6. The following subsections builds on these definitions and aims to provides greater clarity on the complex concept of shutdowns.

2.7.2 Characteristics of Shutdowns

With a term as broad as shutdowns it is difficult to underpin the essential elements needed to fully comprehend the concept. However, there are certain characteristics that the majority of shutdowns share. According to Levitt (2004), shutdown can have a variety of different sizes and characteristics (see Table 2.2), but they generally consists of five phases, namely *planning*, *initiating*, *executing*, *completion* and *closeout*.

Table 2.2: Shutdown sizes and characteristics

Shutdown size	Labour and parts cost ($\$\times10^3$)	Shutdown duration	Lead time	Contractor use	Shutdown team composition
Small	Less than 250	Hours	Weeks	Low percentage	Existing staff
Small to moderate	250 to 1,500	Short days	Months	Moderate percentage	Usually existing staff
Moderate to large	1,500 to 10,000	Days	Months to years	High percentage	Usually separate shutdown staff
Large	More than 10,000	Weeks	Years	Very high percentage	Separate shutdown staff needed

Adapted from Levitt (2004)

Utne *et al.* (2012) reports that shutdowns can generally be classified as *planned* or *unforeseen* (see Figure 2.6). As the name suggests, planned shutdowns are prearranged and scheduled ahead of time in order to prepare for the impending shutdown. The opposite is true for unforeseen shutdowns as they are usually forced upon management by an unexpected event. Should the event come with some lead time, e.g. a pipe with a propagating crack rather than a break, management can still venture to plan and mobilise the manpower and resources necessary to execute a shutdown before the lead time runs out. This situation represents a *plannable* shutdown. Whereas, if there where no lead time, it would be grouped as an *unplannable* shutdown.

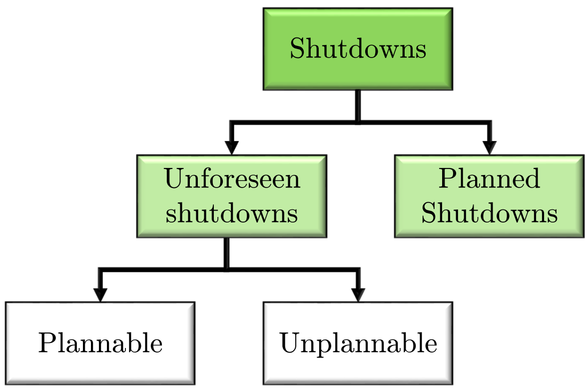


Figure 2.6: Main categories of shutdowns

Adapted from Utne et al. *(2012)*

Plant shutdowns are normally planned and consist of maintenance activities such as inspection, overhaul, modification and the installation of new parts or equipments (Ghazali *et al.*, 2009). What distinguishes these activities from normal everyday maintenance work is that they cannot be performed unless the plant is in a non-operational state (Hameed and Khan, 2014). As mentioned, shutdowns may constitute a multitude of different types of maintenance work, but according to Duffuaa and Ben Daya (2004) the work can be divided into the following categories:

- projects;
- major maintenance tasks such as the overhaul of a large machine;
- small maintenance tasks; and
- bulk work such as the overhaul of a large number of small items.

Even though any type of maintenance work can be scheduled during a shutdown, it does not mean it should be scheduled. Lenahan (2011) reveals the golden rule of shutdowns as "the only tasks allowed on to the shutdown work list are those which cannot be done at any other time, unless there is an overriding reason (e.g. maintainability, hazard, etc.)". Hence, only tasks that cannot be performed when the plant is in operation or tasks with adequate justification should be scheduled during a shutdown.

2.7.3 Motivation for Shutdowns

As mentioned in the beginning of Section 2.7, a total plant shutdown as opposed to more frequent shutdowns in separate areas of the plant is preferred, because it is less disruptive and far less expensive. Shutting down the entire facility supports plant improvement programs and major maintenance work, increases plant output, helps with the implementation of new statutory requirements and the adoption of new technologies, etc. (Levitt, 2004). What is more, entire production units can be disassembled, comprehensively inspected and renewed (Megow *et al.*, 2011). Duffuaa and Ben Daya (2004) mention that the following types of maintenance work are performed during a total plant shutdown:

- work on equipment which cannot be done unless the whole plant is shut down;

- work which can be done while equipment is in operation but requires a lengthy period of maintenance work and a large number of maintenance personnel; and
- defects that are pointed out during operation, but could not be repaired, are maintained during the shutdown period.

It is unsurprising that an endeavour as big and complex as a total plant shutdown has numerous advantages and disadvantages. Organisation should weight up the pros and cons of shutdowns as well as its applicability to the particular organisation before deciding whether to implement a shutdown or not. Next follows an elaboration of some benefits and drawbacks of shutdowns that organisations should consider in their decision making processes.

Benefits of Shutdowns

It has been established that a shutdown is by its very nature both disruptive and costly, which begs the question why organisations still have shutdowns. Intuitively the advantages should outweigh the disadvantages, otherwise shutdowns would be rendered as nothing more than an incubator of inefficiencies.

In an ideal world organisations will avoid total plant shutdowns. However, as mentioned previously, partial plant shutdowns are hindered by logistical and cost issues. Therefore, until these issues are resolved, shutdowns will not go away for asset intensive organisations and every effort should be made to optimise the process and deriving maximum value from it.

McQuillan *et al.* (2003) report that the benefits of optimising the work done during a shutdown include:

- reducing the probability of breakdowns between shutdowns;
- protecting future process performance at design throughput/energy efficiency;
- increasing the interval between shutdowns; and
- reducing the duration of each shutdown.

Pokharel and Jiao (2008) concur with Kister and Hawkins (2006) in arguing that shutdowns are not only necessary to reduce the risk of unscheduled breakdowns and the resulting unplanned outages, but are essential to maintaining consistent productivity and increasing equipment asset reliability. According to Obiajunwa (2007), shutdowns expectations include:

- bringing the plant to its original health;
- making the plant safe to operate till the next shutdown;
- improving efficiency and throughput of the plant;
- reducing routine maintenance costs; and
- increasing the reliability and availability of equipment during operation.

Obiajunwa (2007) continues that these expectations should be met on time, within budget and satisfy all quality and safety requirements to the shutdown to be considered successful.

Drawback of Shutdowns

Shutting down a plant or factory always has a negative financial impact. Shutdowns are extremely expensive endeavours even though their durations are inherently short. This is mainly due to the number of exorbitant costs involved in the short shutdown period.

A plant has limited or no output for the duration of a shutdown. This means the organisation will experience a loss in production (sales) revenue for the shutdown period (Amaran *et al.*, 2015). This monetary loss can be huge depending on the size of the organisation, the duration of the shutdown and whether the planned shutdown period is exceeded.

In addition to the sales losses are the actual costs of performing maintenance during a shutdown. Since shutdowns consist of major maintenance work and a variety of activities (e.g inspection, modification, overhaul and equipment installation), vast amounts of resources are consumed. The cost of these resources include the purchasing of equipment, tools and spare parts, holding costs for spares, as well as direct labour costs (Vaughan, 2005). Maintenance personnel, technicians, craftsmen, and skilled and specialised contractors contribute to the direct labour costs (Ghazali *et al.*, 2009). Owing to the volume of work scheduled for shutdowns, contractors are becoming increasingly important to the process. As Pinjala *et al.* (2006) points out, shutdown maintenance requires more manpower, which is why many maintenance jobs may have to be outsourced.

One of the biggest pitfalls of shutdowns is trying to force as much work as possible into a short shutdown period. This puts the entire process under pressure (Kister and Hawkins, 2006) and increases deferred maintenance tasks.

2.7.4 Shutdown Intervals and Duration

With the motivation for shutdowns established in the previous subsection, the next question for organisations becomes *when*, and for *how long*, to have a shutdown? As shown in Table 2.2, shutdowns can vary significantly in terms of size and duration.

According to Ghazali *et al.* (2009), the frequency of a shutdown is largely determined by variables such as plant technology, the required level of plant reliability and the legal requirements associated with the operation. This suggests that the intervals between shutdowns are flexible and based on the condition of the equipment and therefore the plant. The unfortunate reality, however, is that the opposite of this is true.

IAM (2012) states that historically, shutdown intervals have been established with no real strategic thought process. The author continues that in many cases the reason for the current shutdown interval is either not known or has become redundant. Or as Muganyi and Mbohwa (2013) observe, shutdowns are scheduled on a fixed-interval basis of "we always have our shutdown during this time".

This fixed-interval way of scheduling shutdowns incurs large inefficiencies as maintenance is not based on the condition of the equipment. Similar to PM in Subsection 2.6.2, maintenance can be performed too soon at the expense of asset residual life or too late, which increases the risk of larger costs sustained due to unplanned failure. What is evident is that these fixed-interval maintenance policies do not necessarily extend the life of the components as much as possible (Endrenyi *et al.*, 2001).

The importance of determining the optimal interval and duration of shutdowns are noted in this thesis, but falls outside the scope. An example of work done in this field is Ghosh and Roy (2009) who proposed optimising the maintenance intervals by maximising a reliability based cost/benefit ratio.

2.7.5 Importance of Shutdown Planning

According to Williams (2004) and Cui *et al.* (2013), planning has been identified as being absolutely critical to the success of shutdown maintenance. This is not surprising considering the expensive nature of shutdowns, hence proper shutdown management is critical to minimising the impact on the organisation's bottom line.

Kister and Hawkins (2006) make the case for why planning is such a vital cog to a successful shutdown:

> *No single strategy is more important, or more often neglected or overlooked, than planning. Planning for and managing a maintenance outage in the manufacturing plant environment are difficult and demanding operations. If not properly planned, managed and controlled, companies run the risk of serious budget overrun and costly schedule delays. The Planning and Scheduling operations are central to completing an outage within budget and on schedule.*

Utne *et al.* (2012) add to this by stating that "it is hardly possible to undertake maintenance, and specifically maintenance work requiring shutdown, if the organisation is not well prepared and the work requiring shutdown is not sufficiently planned".

Planning is especially important for shutdowns as its work scope is subject to change. This is a common feature of shutdowns (Lenahan, 1999; Oliver, 2002) where during a shutdown hidden failures or potential risks are discovered. These discoveries may need attention and can affect the planned work. It is imperative that the planners are able to prioritise these discoveries and mobilise the resources necessary to deal with them. Pokharel and Jiao (2008) mention that proper planning of maintenance activities is an important criterion for the success of a shutdown.

2.8 Chapter 2 Concluding Remarks

The aim of this chapter was to contextualise the problem statement in Section 1.2. The chapter started with a thorough discussion on AM, which laid the foundation of this thesis and demarcated the research domain. This discussion covered amongst other things the evolution of AM over the last four decades, its relevance in industry today as well as the recently developed AM standards PAS 55 and ISO 55000.

The second part of this chapter focused on a critical aspect of AM, namely the maintenance function. It explained how maintenance approaches have become less reactive and more proactive in recent years. Moreover, it described how the way in which maintenance is viewed has changed. Maintenance is no longer only viewed as a cost-centre. Instead, it is seen as a value-adding activity, profit contributor, and driver of competitiveness for organisations.

The final part of this chapter focused on the maintenance function to discuss shutdowns. It provided an overview of shutdowns that included the definition, characteristics and motivation for conducting a shutdown. This chapter concluded by emphasising the importance of maintenance planning in successfully completing a shutdown on time and within budget. It is this emphasis on maintenance planning that leads to the following chapter. Chapter 3 examines maintenance planning, more specifically maintenance prioritisation, and provides an overview of a promising maintenance prioritisation framework.

Chapter 3

Tam and Price Maintenance Prioritisation Framework

Chapter Aims:

Chapter 3 focuses on the role that prioritisation plays in maintenance. It builds on the concerns of the problem statement in Chapter 1 along with the necessary contextualisation gained from Chapter 2. The Tam and Price Maintenance Prioritisation Framework (TPMPF) is presented and inherent inefficiencies within the framework are identified and possible solutions are put forward. This chapter paves the way to the development of the application methodology in Chapter 4.

Chapter Outcomes:

⇒ Thorough overview of the TPMPF.

⇒ Understanding of the TPMPF's inefficiencies and the proposed solutions.

3.1 Introduction to Maintenance Prioritisation

The maintenance of a system is both a technical and a managerial challenge, claim Warrington *et al.* (2002). Technical challenges centre around fault diagnosis such as fault visibility and fault isolation. On the other hand, managerial challenges include the scheduling of resources, forward planning and the *prioritisation* of individual tasks. The focus of this section and the remainder of this thesis will be on the managerial challenge of maintenance prioritisation.

In today's competitive environment, the need to prioritise and perform *appropriate* (or *critical*) maintenance is becoming increasingly apparent. Manufacturing industries are moving towards just-in-time systems which means even small breakdowns are now capable of causing a total plant shutdown (Moubray, 1994). Furthermore, maintenance expenditure is continually on the rise while maintenance budgets are in decline (see Section 2.6). This has led to increased pressure on maintenance managers to direct their maintenance efforts towards achieving the organisation's strategic goals more efficiently and effectively (Al-syouf, 2007; Al-Najjar, 2007). In short, organisations can no longer afford to perform non-critical maintenance before or instead of critical maintenance.

Maintenance prioritisation involves the balancing of multiple objectives, where some may even be in conflict with others. Labib (1998) gives an example of conflicting maintenance objectives as the maximisation of production throughput, equipment availability and product quality whilst minimising the available spares and manpower. According to Da Silveira and Slack (2001), conflicting objectives do not have equal importance in terms of the organisation's performance and should therefore be traded-off against each other. In the same way, maintenance prioritisation is a trade-off among different objectives with the ultimate goal of achieving the organisation's strategic goals.

To challenge in today's market, Pascual *et al.* (2009) calls for organisations to continuously enhance their capability of adding value and improving the cost-effectiveness of their decision making processes. Liao *et al.* (2009) state that most maintenance policies in literature are cost-centred. In other words, they are developed to minimise maintenance cost. Liu *et al.* (2014) contend that maintenance actions are meant to generate profit for companies and it is therefore more reasonable to view maintenance as a value-generating action.

As discussed in Section 1.2 and corroborated by Rosqvist *et al.* (2009), most maintenance studies have yet to address the problem of a value-based maintenance policy. Popular maintenance prioritisation approaches such as the Pareto analysis and Failure Modes Effects and Criticality Analysis (FMECA) are also deficient in this regard, in addition to other weaknesses. The Pareto analysis, for example, prioritises maintenance according to one criterion only. See Knights (2001) and Fotopoulos *et al.* (2011) for additional deficiencies. As for the FMECA, it fails to integrate with financial considerations (Achermann, 2008), and is time consuming and prone to error due to its inherent subjectivity (Kovacova and Janco, 2008). What is more, neither approach considers the possibility that the resources (e.g. time and budget) needed to perform the maintenance may be limited.

The following section reviews the Tam and Price Maintenance Prioritisation Framework (TPMPF). It is a value-based maintenance prioritisation approach that considers multiple criteria as well as limited maintenance resources. These qualities make it a promising framework with which to address the research problem put forth in Section 1.2. However, the TPMPF has inherent inefficiencies and the sections succeeding the review will undertake to resolve each of the identified inefficiencies.

3.2 Overview of the TPMPF

This section provides an overview on the promising framework developed by Tam and Price (2008*b*) in their research paper titled "*A maintenance prioritisation approach to maximise the return on investment subject to time and budget constraints*". The framework has no designated name and for the purposes of this thesis is referred to as the Tam and Price Maintenance Prioritisation Framework (TPMPF).

Compared to most other maintenance models, the TPMPF is unique in that it prioritises asset maintenance work in terms of maximising the return on maintenance investment, under the constraints of both time and budget. It was not a singular development, but rather an expansion on the existing Generic Asset Maintenance Optimisation Framework (GAMOF) by Tam and

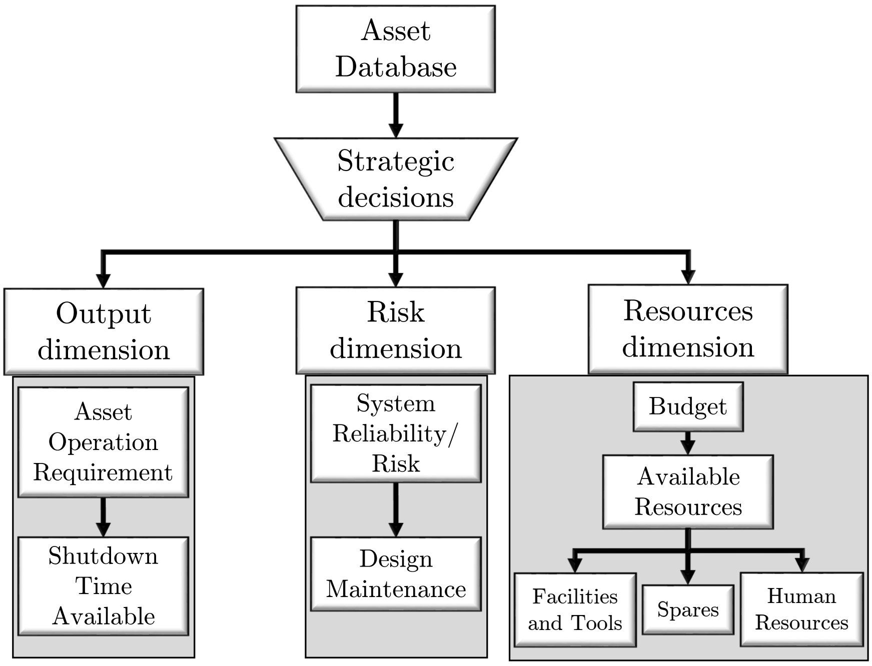


Figure 3.1: Generic asset maintenance optimisation framework

*Adapted from Tam and Price (2008*a*)*

Price (2008*a*). For this reason, important elements in the GAMOF that were incorporated into the TPMPF are also discussed in the subsections that follow.

3.2.1 Decision Dimensions

The GAMOF, shown in Figure 3.1, is the foundation upon which the TPMPF is built. In the same way, the cornerstone of the GAMOF is its three business decision dimensions, namely the *Output dimension*, *Risk dimension*, and *Resources dimension*. Inspiration for these dimensions comes from the work done by Tsang *et al.* (2000), which categorises businesses into three main operational scenarios that impact the maintenance strategies used by an organisation.

- *Cost constrained* businesses can sell more products or services if their prices are lowered. To increase sales these businesses should focus on controlling costs i.e. labour, materials and overheads.

- *Capacity constrained* businesses can sell everything they produce. For maximum profits, these businesses should focus on maximising production output by ensuring high levels of asset availability, reliability and maintainability.

- *Compliance constrained* businesses must adhere to the regulations enforced by government authorities or the quality standards of customers.

Tam and Price (2008*a*) contest this assertion that businesses should be characterised as one of the aforestated operational scenarios. Their counter argument is that all businesses engaged in AM are constrained by cost, capacity and compliance to some extent. In other words, the importance of each constraint may vary from system to system, but by no means are these constraints isolated from one another.

Take for example the nuclear industry. Based on the definitions of business operational scenarios by Tsang *et al.* (2000), nuclear industries can be categorised as compliance constrained. The dangers associated with nuclear power means these industries need to comply with numerous regulatory and safety requirements. Compliance may be their primary concern, but operational (capacity) and economic (cost) aspects are also important when making decisions. Operational aspects are concerned with whether the industry has sufficient capacity to meet its commitments e.g. power demand during peak hours. Furthermore, economic aspects focus on minimising support costs, such as maintenance and inventory holding costs, in order to remain competitive and therefore profitable. As with the said nuclear industry example, Tam and Price (2006) illustrate using examples how cost-constrained or capacity-constrained businesses are not solely constrained by cost or capacity respectively.

Categorising businesses as cost, capacity or compliance constrained shifts the maintenance decision-making focus towards a particular scenario and therefore overlooks the other scenarios. For this reason, Tam and Price (2008*a*) insist maintenance optimisation must occur in an integrated fashion that considers all three these business operational scenarios *simultaneously*. To account for these three scenarios, the authors developed and proposed the GAMOF.

According to Sinkkonen *et al.* (2013), the GAMOF is a maintenance investment model that aims to concurrently minimise the sum of three cost categories, namely, the costs of planned downtime, the costs of quantified risks and the costs of maintenance resources. These three cost categories are simply the output, risk and resources decision dimensions quantified to monetary cost values.

Output Dimension

The output dimension deals with the cost incurred when production is disrupted to perform *planned maintenance* work. This loss in production is the result of not having sufficient time available to perform the planned maintenance and therefore production time has to be sacrificed in order to complete the work. The time made available for maintenance, called the Non-operating Time (NOT), is influenced by the strategic business decisions made by an organisation's top management. They determines the required asset output rate that meets the organisation's production and service delivery targets. It is then up to the engineering team to asses the asset's deterioration rate and perform maintenance that helps the asset achieve the required output rate without exceeding the NOT available and breaching any regulatory, safety and company quality standards.

Risk Dimension

The risk dimension differs from the previous decision dimension in that it is concerned with the cost of *unplanned failures* and *unexpected incidents*. During operation assets deteriorate and becomes less reliable, which in turn increases the risk of failure. The breakdown cost (cost of unreliability) and risk cost (product of consequence and frequency) are the two measures of the risk dimension. Breakdown cost refers to the costs involved in repairing the asset to a functional state. On the other hand, risk cost designates other costs in the event of failure for example production losses. Both these costs can be minimised and controlled by performing the appropriate asset maintenance.

Resources Dimension

The resources dimension is concerned with the cost of maintenance resources, e.g. maintenance personnel, spares, facilities and tools. These resources support the maintenance function by lowering the risks of failure and achieving the desired output rate from the assets. Its support is limited by the allocated budget, which is set by top management or financial department often without much consideration of the engineering aspects (Tam and Price, 2008*a*).

Dimensional Relationship

The three decision dimensions are essentially in conflict with one another (Tam *et al.*, 2007). The resources dimension is a controllable variable. It is up to the engineering department to decide how to best utilise their available budget in terms of the maintenance to be performed. Their choices will ultimately be reflected in the other two dimensions. The output dimension is partially controllable as even maximum utilisation of the maintenance budget cannot guarantee the production target will be met. As for the risk dimension, it is the dependable variable reliant on the other two dimensions. Increasing the production rate will cause equipment to deteriorate at an accelerated rate, which increases risk. Similarly, decreasing the maintenance resources will inhibit the ability to repair and replace ailing equipment, hence the risk of failure will become greater.

3.2.2 Prioritisation Indices

Awan (2014) states that the TPMPF in Figure 3.2 prioritises maintenance work with respect to three dimensions:

1. meeting production targets and satisfying regulatory requirements;
2. minimising financial and non-financial losses due to failures; and
3. controlling maintenance logistics costs.

These three dimensions refer to the output, risk and resources dimensions described in the previous subsection. As mentioned in Section 3.2, the TPMPF is an expansion on the GAMOF. This extension refers to the introduction of three prioritisation indices, namely the Maintenance Investment Index (MII), Time Index (TI) and Budget Index (BI). Figure 3.2 shows how the MII, TI and BI corresponds to the risk, output and resources dimensions respectively.

Maintenance Investment Index

The MII is a measure of how much *return* maintenance generates relative to the costs incurred to support the maintenance work. Return is defined as a reduction in asset risk for a given period of time. In other words, it quantifies the difference between the cost determined in the risk dimension before and after maintenance is performed. The costs incurred to support the maintenance

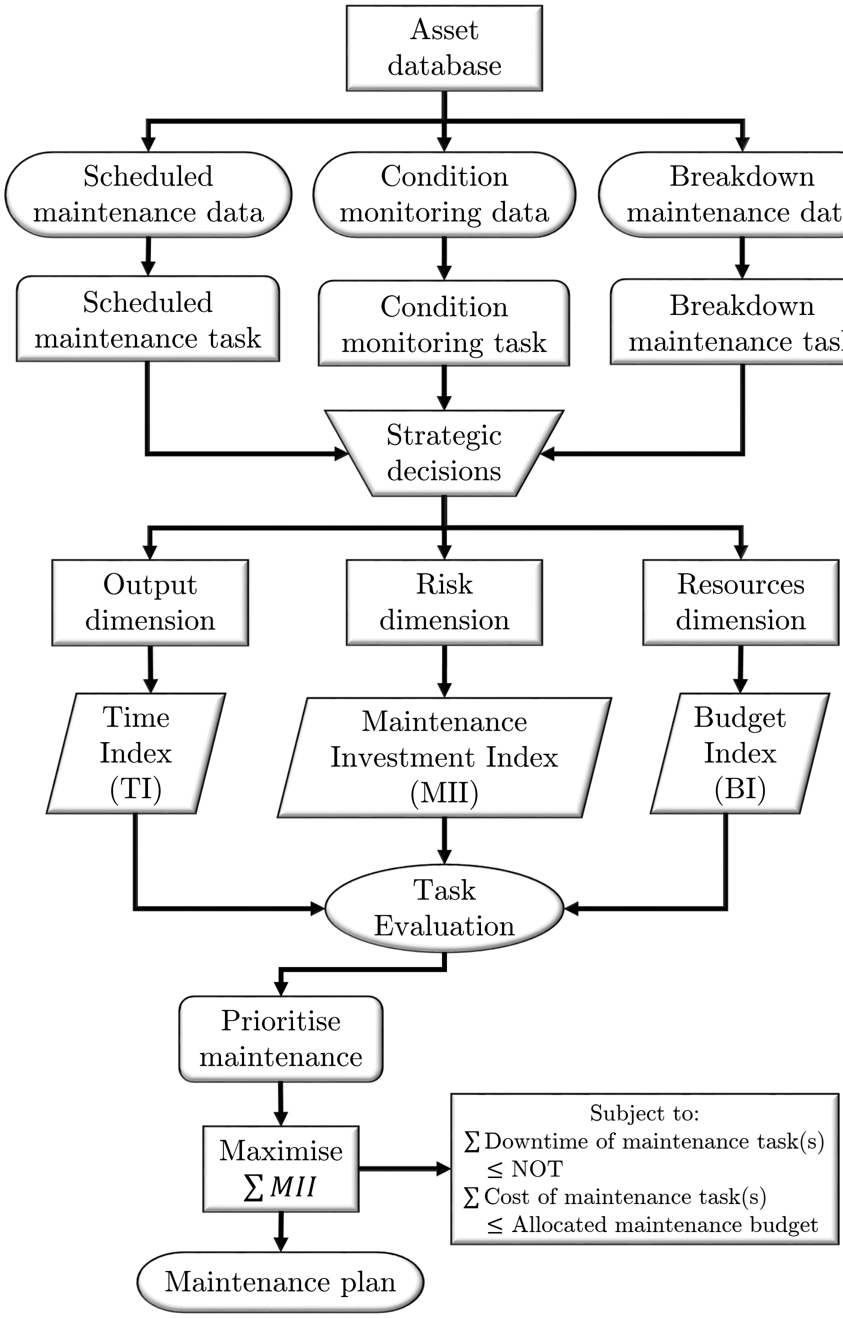


Figure 3.2: Tam and Price maintenance prioritisation framework

Adapted from Tam and Price (2008b)

work is the cost of the resources to support the maintenance work as well as production losses incurred to perform maintenance. The MII is defined as:

$$\text{MII} = \frac{\text{Maintenance Return}}{\text{Production Losses} + \text{Maintenance Expenditure}} \tag{3.1}$$

Analogous to investing in securities, MII can be interpreted as follows:

MII < 0	Negative return on maintenance investment
MII $= 0$	No return on maintenance investment
MII > 0	Positive return on maintenance investment

Ideally, a MII greater that zero is sought in order to validate the maintenance investment in the first place. The greater the MII, the more financially effective the maintenance work.

Time Index

Any maintenance effort constitutes one or a number of different maintenance tasks all requiring various durations to complete. The TI is a ratio of the duration of one task (or the summation of numerous task times) relative to the amount of NOT available to complete maintenance tasks without infringing on production time.

$$\text{TI} = \frac{\sum \text{Downtime of Maintenance Task(s)}}{\text{Non-operating Time}} \tag{3.2}$$

The TI can be interpreted as follows:

TI $= 0$	No maintenance task(s) selected
TI < 1	Maintenance task(s) are within NOT
TI > 1	Maintenance task(s) exceed NOT

A TI less than unity is preferred as it means the time needed to perform the maintenance work does not exceed the NOT and no production losses will be incurred in the process.

Budget Index

The BI indicates how much money is needed to execute the maintenance work with respect to the allocated budget for maintenance. Therefore, the BI is a measure of the portion of funds consumed by the maintenance tasks.

$$\text{BI} = \frac{\sum \text{Cost of Maintenance Task(s)}}{\text{Allocated Maintenance Budget}} \tag{3.3}$$

The BI can be interpreted in the same way as the TI. It is preferable to have a BI less than unity as that means the cost of the maintenance task(s) can be supported by the allocated budget and no additional funds need to be requested and procured.

3.2.3 Asset Database and Strategic Decisions

Two other important elements of the TPMPF and the GAMOF are the asset database and strategic decisions. Both frameworks starts with the asset database and move on to the strategic decisions before reaching the previously discussed decision dimensions and subsequently the prioritisation indices.

The asset database accumulates all the pertinent asset information from various sources such as scheduled PM data, condition monitoring (PdM) data and breakdown maintenance (CM) data. From the asset database, the proposed maintenance tasks to prevent or restore failures are identified. What is more, the asset database provides a basic reference of the asset's performance during the time that data was captured.

The strategic decisions are made with reference to the asset's performance data. This information along with other important factors such as enterprise financial performance, strategic output and risk tolerance targets are considered and analysed. From here top management makes the decisions that will influence the determination of the maintenance budget and the available outage time (NOT) for the planned maintenance for a given period.

It would be beneficial for top management to consult asset and maintenance managers when making these strategic decisions, but this is not always the case. Sometimes asset and maintenance managers are just given enterprise targets that must be transformed into strategic AM policies that facilitates the achievement of those enterprise targets. It is then up to the engineering department to consider all three decision dimensions and prioritise maintenance work in such a way that these strategic enterprise targets are achieved.

3.3 Inefficiencies of the TPMPF

The TPMPF proposes a new approach to prioritise and rank order maintenance tasks by simultaneously emphasising maintenance return on investment and constraints such as time and budget. Regrettably, it is accompanied by certain inefficiencies that taint its results and invites scrutiny. The identified inefficiencies include its *semi-quantitative ranking procedure* and its *quantification of maintenance effectiveness*. These inefficiencies are discussed in greater detail in the ensuing subsections.

3.3.1 Semi-quantitative Ranking Procedure

A major inefficiency of the TPMPF is its semi-quantitative ranking procedure shown in Table 3.1. This procedure has the following flaws:

1. Evaluating three prioritisation indices that are not put in a numerically comparable form (i.e. comparing "apples with oranges").

2. Using the arithmetic mean of the individual prioritisation index scores to determine the "average rank score" and consequently rank the maintenance plans.

3. Ranking the maintenance plans on an ordinal scale (1^{st}, 2^{nd}, 3^{rd}, etc.) that does not allow for relative degrees of difference between the plans.

Before proceeding to examine these identified flaws, it is first necessary to explain the semi-quantitative ranking procedure. The procedure starts by identifying all the maintenance tasks to be performed on the asset. This information is extracted from the asset database and each task is assigned to a Maintenance Package (MP), which relates to a specific component of the asset.

Once all the maintenance tasks are formulated into MPs, and the MII, TI and BI are calculated for each MP. Next, each index is ranked relative to the same index for all the other MPs as given by the "MII Rank", "TI Rank" and "BI Rank" columns. The MII is ranked from highest to lowest whereas the TI and BI are ranked from lowest to highest. A higher MII indicates a more cost-effective MP. A lower TI or BI specifies that the MP consumes less time or costs less respectively. From the rankings it becomes clear that a MP with a high MII value and low values for TI and BI are preferred.

The next step is to take the arithmetic average of the MII Rank, TI Rank and BI Rank columns for each MP. Identical weightings are assigned to the three indices as they are considered to be equally important. This gives rise

Table 3.1: Example of the TPMPF semi-quantitative ranking procedure

Maintenance Packages	MII	BI	TI	Rank MII	Rank BI	Rank TI	Average rank score	Maintenance plan ranking
MP1	0.91	0.55	0.45	6	4	5	5.00	3
MP2	0.91	0.35	0.28	7	1	1	3.00	2
MP3	0.07	0.65	0.40	30	5	4	13.00	12
MP4	0.22	0.43	0.34	25	2	3	10.00	9
MP5	1.20	0.50	0.28	1	3	1	1.67	1
MP12	0.99	0.90	0.74	5	8	11	8.00	5
MP13	0.47	1.20	0.85	16	15	15	15.33	16
MP14	0.63	0.98	0.80	11	10	14	11.67	10
MP15	1.12	1.05	0.74	3	12	11	8.67	7
MP23	0.38	1.00	0.68	19	11	9	13.00	12
MP24	0.56	0.78	0.63	14	6	7	9.00	8
MP25	1.17	0.85	0.57	2	7	6	5.00	3
MP34	0.13	1.08	0.74	29	13	11	17.67	18
MP35	0.60	1.15	0.68	12	14	9	11.67	10
MP45	0.81	0.93	0.63	9	9	7	8.33	6
MP123	0.35	1.55	1.14	21	23	22	22.00	24
MP124	0.50	1.33	1.19	15	17	24	18.67	20
MP125	1.00	1.40	1.02	4	18	18	13.33	14
MP134	0.05	1.63	1.19	31	25	24	26.67	27
MP135	0.41	1.50	1.14	18	21	22	20.33	23
MP145	0.60	1.48	1.08	13	20	21	18.00	19
MP234	0.30	1.43	1.02	22	19	18	19.67	21
MP235	0.71	1.50	0.91	10	21	16	15.67	17
MP245	0.88	1.28	0.91	8	16	16	13.33	14
MP345	0.45	1.58	1.02	17	24	18	19.67	21
MP1234	0.18	1.98	1.48	28	28	29	28.33	29
MP1235	0.29	2.05	1.42	23	29	28	26.67	27
MP1345	0.22	2.13	1.48	26	30	29	28.33	29
MP2345	0.26	1.93	1.31	24	27	26	25.67	26
MP1245	0.35	1.83	1.36	20	26	27	24.33	25
MP12345	0.20	2.48	1.76	27	31	31	29.67	31

to the "Average rank score" column. From here, the average rank scores are ranked from lowest to highest. A lower average rank score indicates a MP that performed better, *on average*, in terms of the three prioritisation indices. The maintenance plan is to perform the MP that has the lowest average rank score and should scores be equal, the score with the highest MII is preferred.

The first flaw of the semi-quantitative ranking procedure is the direct comparison of the three prioritisation indices that are not put in a numerically comparable form. Hwang and Yoon (1981) states that "a high value for one attribute must receive approximately the same numerical values as high values for other attributes". This is for the case where higher values for all three attributes are preferred. For attributes MII, TI and BI, it is preferable to have a higher value for the former and lower values for the rest. Hence, the attributes must be made numerically comparable in such a way to incorporate that a higher value for MII is preferred in the same way lower values are preferred for TI and BI.

The second identified flaw is the use of the arithmetic average. It is simple to calculate and understand, but this is also the reason why often misused. The arithmetic average is sensitive to extreme values (typically found in dispersed or volatile data sets). Take for example MP4, with respective rankings of 25, 2 and 3 for MII, BI and TI, it achieved an average rank score of 10 and is rated as the 9$^{\text{th}}$ best maintenance plan. The average value of 10 is not a good measure of its individual numbers and is clearly sensitive to the extreme value, which in this case is 25. Table 3.1 may only have 31 MPs, but the arithmetic average will only become more sensitive to extreme values as the number of MPs increases, which can be expected in industry and especially during a plant shutdown.

The final flaw is the ranking of MPs on an ordinal scale. Take the cases of MP5 and MP2, they are rated as the best and second best MP respectively. However, Table 3.1 provides no further information with regards to what relative degree of difference MP5 should be preferred to MP2. Is MP5 twice as good as MP2, or perhaps 10% better? A decision maker cannot answer these questions from the information provided in the table. The decision maker can simply say MP5 should be preferred to MP2, but not by how much or to what degree.

This subsection identified and described three flaws pertaining to the semi-quantitative ranking procedure of the TPMPF. Section 3.4 will address these three flaws and propose different approaches that are devoid of the aforementioned flaws or at least offer an improvement on the current semi-quantitative ranking procedure.

3.3.2 Quantification of Maintenance Effectiveness

Tam and Price (2008*b*) acknowledge that a major challenge for the TPMPF is quantifying the return on investment for a specific maintenance task. Maintenance return in Equation 3.1 was defined as a reduction in risk for a given period of time.

Risk can be reduced in a number of ways, of which maintenance is one. By performing appropriate maintenance the risk associated with equipment breakdown (i.e. failure frequency) can be lowered. However, the question is by *how much* is a maintenance action able to restore life to the system? In other words, how effective is the quality of the maintenance.

The TPMPF categorises maintenance actions into three types, namely:

1. Replacement or repair (perfect or near-perfect maintenance)

2. Service (imperfect maintenance)

3. Inspection (nil maintenance)

Perfect maintenance returns a component's condition to as good as new. Only replacement and good repair fall in this category. Near-perfect maintenance refers to when mistakes can be made and the process cannot be considered as perfect maintenance. Imperfect maintenance returns the condition of the component to somewhere in between as good as new and as bad as old. Finally, nil maintenance means no maintenance is performed as the component's condition remains as bad as old. Table 3.2 shows the effect different types of maintenance have on system life.

The TPMPF highlights the importance of quantifying maintenance effectiveness. Moreover, it gives broad guidelines (see Table 3.2) as to how much the condition of equipment will improve with each type of maintenance. However, the TPMPF does not provide any means of quantifying and therefore calculating the effectiveness of maintenance. What is more, MPs might consist of

Table 3.2: Types of maintenance and their effect on asset life

Maintenance action type	Action	Effect on system life
Replacement or repair	Regardless of condition, component is replaced with a new one.	Returns component life to as good as new.
Service	Cleaning, lubrication, replacing filters, etc.	Partially restore component life till next service interval.
Inspection	The use of human senses or apparatus to examine or measure the condition of the component.	No change. The component's condition is determined to be adequate to continue operating till next service interval when its condition will be re-evaluated.

According to Tam and Price (2008b)

more than one type of maintenance action for a component e.g. replacing small parts and then lubricating the component. The TPMPF provides no guidance on what to do in such an case.

Section 3.5 will look to address and resolve the issue brought to hand in this subsection. The concept of imperfect maintenance will be explored to ascertain a method of quantifying maintenance effectiveness for actions that improve the condition of an component.

3.4 Multiple Criteria Decision Analysis

Leading from Subsection 3.3.1, which describes the TPMPF's inefficient semi-quantitative ranking procedure, this section looks at alternative ranking approaches within the field of Multiple Criteria Decision Analysis (MCDA). These established approaches can be used instead to prioritise the MPs given in Table 3.1.

MCDA, also sometimes called Multiple Criteria Decision Making (MCDM), is a sub-discipline of operation research that helps decision makers who are faced with problems that are conflicting in nature. Botti and Peypoch (2013) define MCDA as:

> *a general term for methods providing a quantitative approach to support decision making in problems involving several criteria and choices (alternatives or actions).*

Wang and Triantaphyllou (2008) continue that MCDA models improve the quality of decisions by making the decision process more explicit, rational and efficient. Moreover, Belton and Stewart (2002) state that these models can be classified into three broad categories:

1. *Value measurement models* construct numerical scores to showcase the degree to which one decision option (alternative) is preferred to another.

2. *Goal, aspiration or reference level models* have desired or satisfactory levels of achievement established for each of the criteria. The process seeks to discover decision options that achieve, or comes closest to achieving, these goals or aspirations.

3. *Outranking models* compare decision options in a pairwise manner in order to establish the strength of evidence in terms of criterion comparisons to favour the selection of one alternative over another.

In the context of engineering, decision problems can be grouped as either design or evaluation problems (Pascual *et al.*, 2009). In design problems, decision makers seek to identify a preferred alternative from an *infinite* set of alternatives defined by a group of constraints. These problems can usually be solved using goal or aspiration models. On the other hand, in evaluation problems decision makers analyse a *finite* set of predetermined alternatives from which a preferred alternative is selected. Figueira *et al.* (2009) note that the favoured models to solve these kinds of problems are value or outranking models. Examples of value, goal and outranking models used to solve design and evaluation problems in the context of AM are given in Table 3.3.

Table 3.1, which shows the semi-quantitative ranking procedure of the TPMPF, is an example of an evaluation problem. A discrete set of alternatives, in the form of MPs, are weighed up against one another via three decision criterion, namely the MII, TI and BI. The aim is to identify a preferred alternative amongst the set, and rank order the remaining MPs with respect to how well they satisfy all the criteria. Hence, the TPMPF can essentially be described as a MCDA model. Regrettably, the evaluation process

Table 3.3: Examples of design and evaluation problems in the context of AM

Problem type	Summary of Examples
Design	Goodhart (1999) appropriates the overhaul funding of a fleet of tactical ground equipment under the constraint of a budget.
	Shohet and Perelstein (2004) allocate financial resources amongst various building projects (rehabilitation, renovation and upgrading).
	Grierson (2008) designs bridge maintenance intervention protocols by considering maintenance cost, condition and safety.
Evaluation	Chareonsuk *et al.* (1997) select optimal preventive maintenance intervals for components in a paper factory using the PROMETHEE method.
	Carnero (2006) combines elements of the Analytic Hierarchy Process, Bayesian tools and decision rules to set up predictive maintenance programs.
	Karydas and Gifun (2006) use the Analytic Hierarchy Process to prioritise maintenance in the context of facilities management.

of this model is inefficient, which restricts the credibility of its results.

The road to betterment starts by understanding the context of the problem before attempting to solve it. In the words of Belton and Stewart (2002), "this recognition of the need to match methodologies to problem context is essential to an integrated understanding of MCDA". The TPMPF is identified as an *evaluation problem* and the subsections to follow contain an example of a typical evaluation problem, core MCDA concepts and an elaboration of a few established value measurement and outranking models found in MCDA literature.

3.4.1 Typical MCDA Evaluation Problem

The field of MCDA is accompanied by a set of concepts that should be clarified upfront in order to comprehend the ensuing subsections. Amongst many, Triantaphyllou (2000) highlights the following important concepts:

- *Alternatives* signify the options, choices or actions available to the decision maker. As mentioned previously, evaluation problems have a finite set of alternatives from which to select a preferred alternative.
- *Multiple attributes* (also called characteristics, decision criteria, objec-

tives or goals) refer to the different dimensions in which the decision maker can view or assess an alternative.

- *Decision weights* denote the relevant importance of a particular criterion. Usually, these weights are normalised to add up to one.

A MCDA problem with its alternatives, decision criteria and relevant weights can be easily expressed in a decision matrix, similar to the one provided in Table 3.4. The decision matrix, termed **A**, is a $(m \times n)$ matrix populated with a_{ij} elements. An a_{ij} element indicates the performance value of alternative A_i, when it is evaluated in terms of the decision criterion C_j, for $i = 1, 2, 3, \ldots, m$ and $j = 1, 2, 3, \ldots, n$. The relative performance of the decision criterion are represented by a weight w_j for $j = 1, 2, 3, \ldots, n$ and the weights are normalised to unity i.e. $\sum_{j=1}^{n} w_j = 1$.

Table 3.4: Structure of a typical MCDA decision matrix

$\mathbf{A} =$

Alternatives	C_1 $(w_1$	C_2 w_2	C_3 w_3	$\cdots$ $\cdots$	C_n $w_n)$
A_1	a_{11}	a_{12}	a_{13}	$\cdots$	a_{1n}
A_2	a_{21}	a_{22}	a_{23}	$\cdots$	a_{2n}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
A_m	a_{m1}	a_{m2}	a_{m3}	$\cdots$	a_{mn}

A fictitious haul truck selection problem is described next in order to illustrate a typical MCDA evaluation problem. This example highlights the core concepts already discussed and expresses the problem in a decision matrix form for further analysis.

Example of Haul Truck Selection Problem

A coal mining company is looking at purchasing a fleet of haul trucks to transport product from their mine to a power station nearby. Asset managers at the company congregate and agree that five attributes (criteria) should be considered when buying haul trucks. These are maximum speed, engine power, maximum payload, truck weight and purchasing cost. The asset managers converge on five types of haul trucks (alternatives) that deserve further consideration. The features of each truck is detailed in Table 3.5.

Table 3.5: Haul truck selection problem

Haul truck	Max speed (kph)	Engine power (hp)	Max payload (ton)	Weight (ton)	Cost ($\$ \times 10^6$)
1	68	4000	400	61	15
2	78	3500	375	55	11
3	70	4250	420	70	9
4	80	3800	390	55	13
5	75	3950	380	65	12

The asset managers realise that this is a MCDA evaluation problem and quickly set up the decision matrix shown in Table 3.6. They also assign weights to the decision criteria in order to indicate the relative importance of each decision criterion. These weights are given in Table 3.7. Now, the asset managers must rank the five haul trucks in terms of their buying preference.

Table 3.6: Decision matrix of haul truck selection problem

	C_1	C_2	C_3	C_4	C_5
Alternatives	$(w_1$	w_2	w_3	w_4	$w_5)$
A_1	68	4000	400	61	15
A_2	78	3500	375	55	11
A_3	70	4250	420	70	9
A_4	80	3800	390	55	13
A_5	75	3950	380	65	12

Table 3.7: Criterion weightings of haul truck selection problem

j	C_1	C_2	C_3	C_4	C_5
w_j	0.2	0.2	0.3	0.1	0.2

The following two subsections describe MCDA value measurement and outranking models that can assist the asset managers in ranking the haul trucks and selecting the best truck, in accordance to the attributes they agreed upon.

3.4.2 Value Measurement Approaches

The aim of value measurement models is to construct a means of associating a real number with each alternative, in order to produce a preference order of the alternatives. That is to say a real number $V(A_k)$ is associated with each alternative A_k, such that A_k is preferred to A_l (denoted $A_k \succ A_l$), if and only if $V(A_k) > V(A_l)$, taking all criteria into account. In the same way indifference between A_k and A_l is implied if and only if $V(A_k) = V(A_l)$. Belton and Stewart (2002) state that any preference order constructed implies preferences and indifferences are complete and that preferences are transitive, i.e.:

- *Preferences are complete:* For any pair of alternatives, either one is strictly preferred to the other or there is indifference between them (i.e. either $A_k \succ A_l$, or $A_l \succ A_k$, or $A_k \sim A_l$)
- *Preferences and indifferences are transitive:* For any three alternatives, say A_k, A_l and A_g, if $A_k \succ A_l$ and $A_l \succ A_g$, then $A_k \succ A_g$. Similarly for indifference, if $A_k \sim A_l$ and $A_l \sim A_g$, then $A_l \sim A_g$.

One of the first steps with a value measurement model is to construct a "marginal" or "partial" value function a_{ij} for alternative A_i in terms the criterion C_j, for $i = 1, 2, 3, \ldots, m$ and $j = 1, 2, 3, \ldots, n$. A fundamental property of the partial value function must be that alternative A_k is preferred to A_l in terms of criterion j if and only if $a_{kj} > a_{lj}$. Similarly, indifference between A_k and A_l in terms of criterion j exists if and only if $a_{kj} = a_{lj}$.

According to Belton and Stewart (2002) it is generally advised to standardise the partial value functions on a local or global scale. Take for example the criterion of the haul trucks in Table 3.5. Its columns consist of dissimilar units such as kph, hp, ton, etc. This makes it a multi-dimensional MCDA problem where one is essentially evaluating or comparing "apples with oranges". This problem can be circumvented by standardising the partial value functions either locally (being the best and worst outcomes of the available alternatives) or globally (being the best and worst outcomes conceivable in other similar contexts) for each criterion. Typically, the "worst" and "best" outcomes are designated as 0 and 1 respectively, whereas the other options lie somewhere in between.

This somewhere in between can be calculated using a linear transformation scale. In Table 3.6, the decision makers want to maximise criterion C_1 (speed), C_2 (power) and C_3 (payload) while at the same time minimise criterion C_4 (weight) and C_5 (cost). C_1, C_2 and C_3 are defined as *benefit criteria* where a larger single attribute level x_{ij} (e.g. speed, power or payload) is preferred. Conversely, C_4 and C_5 are defined as *cost criteria* where a smaller x_{ij} (e.g. weight or cost) is preferred. The cost and benefit criteria transforms each single attribute level x_{ij} into a partial value function a_{ij}.

The partial value function is computed as follows for a benefit criterion,

$$a_{ij} = \frac{x_{ij} - x_j^{\min}}{x_j^{\max} - x_j^{\min}}, \qquad j = 1, 2, 3, \ldots, n \tag{3.4}$$

and for a cost criterion,

$$a_{ij} = \frac{x_j^{\max} - x_{ij}}{x_j^{\max} - x_j^{\min}}, \qquad j = 1, 2, 3, \ldots, n \tag{3.5}$$

where, x_{ij} is the single attribute level for the i^{th} alternative in terms of the j^{th} criterion. As for $x_j^{\min}$ and $x_j^{\max}$, they denote the minimum and maximum single attribute value in the j^{th} criterion respectively.

An advantage of calculating a_{ij} with Equations 3.4 or 3.5, is that the scale of measurement varies precisely between 0 and 1 for each criterion. The worst outcome for each criterion implies $a_{ij} = 0$, while the best implies $a_{ij} = 1$. An additional benefit is that a_{ij} is now dimensionless as the units of measure have been eliminated. Instead of using actual values (x_{ij}), relative ones (a_{ij}) can now be used which allows different criteria to be evaluated or compared as "apples with apples". This will be shown with the additive and multiplicative value function discussed in the proceeding sub-subsection.

It should be noted that the hugely popular Analytical Hierarchy Process method is not considered in this thesis. This is firstly due to the rank reversal problem that may arise when the number of alternatives becomes sizeable (Pascual *et al.*, 2008). Secondly, the decision maker's subjectivity may yield uncertainties when determining the pairwise comparisons (Whaiduzzaman *et al.*, 2014).

3.4.2.1 Additive Value Function

The additive value function is arguably the simplest and most widely used method of all the value measurement approaches (Triantaphyllou, 2000). Assuming there are m alternatives and n criteria, the work by Barron and Barrett

(1996) and Winston and Goldberg (2004) shows that the best alternative is the one that maximises the following expression:

$$V(A_i) = \sum_{j=1}^{n} w_j a_{ij} \tag{3.6}$$

where $0 \leq V(A_i) \leq 1$ for alternative A_i, $i = 1, 2, \ldots, m$. The value score a_{ij} reflects the performance of alternative A_i for criterion j, $0 \leq a_{ij} \leq 1$, and w_j is the weight assigned to reflect the importance of alternative A_i for criterion j, $0 \leq w_j \leq 1$ with $\sum_{j=1}^{n} w_j = 1$.

3.4.2.2 Multiplicative Value Function

The multiplicative value function is similar to the additive model, however it differs in that it uses multiplication instead of addition. As with the additive model, for m alternatives and n criteria, the best alternative is the one that maximises the following expression (Wang *et al.*, 2009):

$$M(A_i) = \sum_{j=1}^{n} (a_{ij})^{w_j} \tag{3.7}$$

where $0 \leq M(A_i) \leq 1$.

3.4.2.3 Worked Example of Additive and Multiplicative Value Functions

Consider the haul truck selection problem in Subsection 3.4.1. Five trucks are evaluated with respect to five criterion. Using Table 3.6, decision matrix $\mathbf{X}$ with all the single attribute levels can be set up. However, to make the matrix elements comparable all the units of measure must be eliminated. This can be achieved by using the benefit criteria equation and the cost criteria equation.

$$\mathbf{X} = \begin{bmatrix} x_{11} & x_{12} & x_{13} & x_{14} & x_{15} \\ x_{21} & x_{22} & x_{23} & x_{24} & x_{25} \\ x_{31} & x_{32} & x_{33} & x_{34} & x_{35} \\ x_{41} & x_{42} & x_{43} & x_{44} & x_{45} \\ x_{51} & x_{52} & x_{53} & x_{54} & x_{55} \end{bmatrix} = \begin{bmatrix} 68 & 4000 & 400 & 61 & 15 \\ 78 & 3500 & 375 & 55 & 11 \\ 70 & 4250 & 420 & 70 & 9 \\ 80 & 3800 & 390 & 55 & 13 \\ 75 & 3950 & 380 & 65 & 12 \end{bmatrix}$$

As mention before, Columns C_1, C_2 and C_3 are benefit criteria where a greater x_{ij} is preferred. The opposite its true for C_4 and C_5, these are cost criteria where a smaller x_{ij} is preferable.

In the case of haul truck one (A_1) and the maximum payload criterion (C_3), the scaled partial value function can be obtained using Equation 3.4:

$$a_{13} = \frac{x_{13} - x_3^{\min}}{x_3^{\max} - x_3^{\min}} = \frac{400 - 375}{420 - 375} = 0.56$$

As for the second truck (A_2) and the cost criterion (C_5), the scaled partial value function can be computed with Equation 3.5:

$$a_{25} = \frac{x_5^{\max} - x_{25}}{x_5^{\max} - x_5^{\min}} = \frac{15 - 11}{15 - 9} = 0.67$$

Completing this procedure for all the elements produces a comparable decision matrix $\mathbf{A}$ where all the partial value functions are scaled between values 0 and 1.

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} \\ a_{51} & a_{52} & a_{53} & a_{54} & a_{55} \end{bmatrix} = \begin{bmatrix} 0 & 0.67 & 0.56 & 0.60 & 0 \\ 0.83 & 0 & 0 & 0 & 0.67 \\ 0.17 & 1 & 1 & 0.67 & 1 \\ 1 & 0.40 & 0.33 & 1 & 0.33 \\ 0.58 & 0.60 & 0.11 & 0.33 & 0.50 \end{bmatrix}$$

In the case of the additive model, the value function from Equation 3.6 for haul truck one (A_1) is given by:

$$\begin{aligned} V(A_1) &= 0 \times 0.2 + 0.67 \times 0.2 + 0.56 \times 0.3 + 0.6 \times 0.1 + 0 \times 0.2 \\ &= 0.36 \end{aligned}$$

Similarly, $V(A_2) = 0.30$, $V(A_3) = 0.80$, $V(A_4) = 0.55$ and $V(A_5) = 0.4$. The multiplicative case for the same haul truck, using Equation 3.7, is given by:

$$\begin{aligned} M(A_1) &= 0^{0.2} \times 0.67^{0.2} \times 0.56^{0.3} \times 0.6^{0.1} \times 0^{0.2} \\ &= 0 \end{aligned}$$

Finally, $M(A_2) = 0$, $M(A_3) = 0.67$, $M(A_4) = 0.48$ and $M(A_5) = 0.33$. The ranking for both cases is presented in Table 3.8 along with the overall value function values for both methods. Both methods confirm that haul truck 3 is the preferred alternative.

Table 3.8: Ranking haul trucks with additive and multiplicative value functions

A_i	$V(A_i)$	$V(A_i)$ Rank	$M(A_i)$	$M(A_i)$ Rank
1	0.36	4	0	4
2	0.30	5	0	4
3	0.80	1	0.67	1
4	0.55	2	0.48	2
5	0.40	3	0.33	3

3.4.3 Outranking Approaches

Outranking approaches differ from value measurement approaches in that there is no underlying aggregation value function (Belton and Stewart, 2002). In other words, the output of outranking methods is a ranking of alternatives without any value function to indicate the extent to which one alternative is preferred to another. According to Chatterjee *et al.* (2014), alternative A_k is said to *outrank* A_l if, taking all criteria into consideration, there is a strong argument to support that A_k is at least as good as A_l and there is no strong argument to the contrary.

In general, outranking methods consist of two steps (Hatami-Marbini and Tavana, 2011). In the first step, the alternatives are systemically compared to one another (pairwise comparison) in order to build an outranking relation. In the second step, this outranking relation is exploited to get the final ranking of the alternatives.

The two most prominent outranking approaches are the Elimination and Et Choice Translating Reality (ELECTRE) and the Preference Ranking Organisation Method for Enrichment of Evaluations (PROMETHEE) family of methods (Belton and Stewart, 2002). The ELECTRE methods were developed by Roy and associates at the University of Paris Dauphine, whereas the PROMETHEE methods were proposed by Brans from the University of Brussels. These two outranking methods are elaborated upon next.

3.4.3.1 ELECTRE II

The first method in the ELECTRE family of methods, ELECTRE I, was developed by Roy (1968). After that, mainly during the 1970s and 1980s, several other ELECTRE methods were published. These include ELECTRE II (Roy and Bertier, 1971), ELECTRE III (Roy, 1978) and ELECTRE IV (Roy and Hugonnard, 1982). These four methods differ in how they define the outranking relations between alternatives and how they exploit these relations to get the final ranking of the alternatives. Ros (2011) summarises the differences between the aforementioned ELECTRE versions as:

- *ELECTRE I* reduces the total number of alternatives to a promising set of alternatives, called a *kernel* set.
- *ELECTRE II* is theoretically more elaborated than the previous method and therefore outputs not a kernel set, but a complete arrangement (ranking) of the alternatives.
- *ELECTRE III* constructs a fuzzy outranking relationship using two-tiered thresholds for pseudo-criteria.
- *ELECTRE IV* can be used in cases where the decision maker does not want to specify the preferential weight.

Since the 1980s, this list has grown with the addition of other variations such as the ELECTRE IS (Roy and Skalka, 1987) and ELECTRE TRI (Yu, 1992) methods. For more details on the ELECTRE family of methods, see Figueira *et al.* (2005).

Returning to the ranking inefficiency of Subsection 3.3.1, ELECTRE II is identified as a possible method to rank order the MPs in Table 3.1. The ELECTRE II method is especially convenient for decision problems that involve few criteria with a large number of alternatives (Lootsma, 1990), which is the case in Table 3.1.

The basic concept of the ELECTRE II method is to deal with *outranking relations* with pairwise comparisons among alternatives under each one of the criteria separately. The outranking relationship of two alternatives A_k and A_l, denoted $A_k \rightarrow A_l$, describes that even when alternative A_k does not dominate the alternative A_l quantitatively, the decision maker accepts the risk of regarding A_k as almost surely better than A_l (Triantaphyllou, 2000). Alternatives are said to be *dominated*, if there is another alternative that excels them in one or more criteria and equals them in the remaining criteria.

The following five procedural steps describes the implementation of the ELECTRE II method in detail. These steps are the culmination of work by Hunjak (1997), Triantaphyllou (2000), Cho (2003) and Chatterjee *et al.* (2010).

Step 1: Normalise the Decision Matrix

The first step normalises the entries of each criteria in the decision matrix, thus making them dimensionless and therefore comparable. Each entry x_{ij} is normalised to a value a_{ij} using the following equation:

$$a_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}}, \qquad \text{where} \qquad x_{ij} = \begin{cases} x_{ij} & \text{for benefit criterion} \\ \frac{1}{x_{ij}} & \text{for cost criterion} \end{cases} \tag{3.8}$$

The normalised decision matrix **A** becomes:

$$\mathbf{A} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & a_{m3} & \cdots & a_{mn} \end{bmatrix} \tag{3.9}$$

where a_{ij} is the normalised value of the i^{th} alternative in terms of the j^{th} criterion, m is the number of alternatives and n is the number of criteria.

Step 2: Weighting the Normalised Decision Matrix

Each column of matrix **A** is multiplied by its associated weight w_j to give the weighted normalised decision matrix **Y** (= **AW**).

$$\mathbf{Y} = \begin{bmatrix} y_{11} & y_{12} & y_{13} & \cdots & y_{1n} \\ y_{21} & y_{22} & y_{23} & \cdots & y_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ y_{m1} & y_{m2} & y_{m3} & \cdots & y_{mn} \end{bmatrix} = \begin{bmatrix} w_1 a_{11} & w_2 a_{12} & w_3 a_{13} & \cdots & w_n a_{1n} \\ w_1 a_{21} & w_2 a_{22} & w_3 a_{23} & \cdots & w_n a_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ w_1 a_{m1} & w_1 a_{m2} & w_3 a_{m3} & \cdots & w_n a_{mn} \end{bmatrix}$$

where,

$$\mathbf{W} = \begin{bmatrix} w_1 & 0 & 0 & \cdots & 0 \\ 0 & w_2 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & w_n \end{bmatrix}, \text{ and } \sum_{j=1}^{n} w_j = 1$$

Step 3: Determine the Concordance and Discordance Sets

The concordance set C_{kl} for a pair of alternatives A_k and A_l ($k, l = 1, 2, \ldots, m$ and $k \neq l$) consist of all the criteria for which A_k is preferred to A_l. In other words:

$$C_{kl} = \{j, y_{kj} \geq y_{lj}\}, \qquad \text{for } j = 1, 2, \ldots, n \tag{3.10}$$

The complementary subset is called the discordance set D_{kl} and it is described as follows:

$$D_{kl} = \{j, y_{kj} < y_{lj}\}, \qquad \text{for } j = 1, 2, \ldots, n \tag{3.11}$$

Step 4: Calculate the Concordance and Discordance Matrices

The relative value of the elements in the concordance matrix $\mathbf{C}$ is calculated by means of the concordance index c_{kl}. This concordance index is equal to the sum of the weights associated with the criteria contained in the concordance set. Therefore, the concordance index between A_k and A_l is defined as:

$$c_{kl} = \sum_{j \in C_{kl}} w_j, \qquad \text{for } j = 1, 2, \ldots, n \tag{3.12}$$

where $0 \leq c_{kl} \leq 1$. The concordance index reflects the amount of evidence to support the conclusion that A_k outranks, or dominates, A_l. A higher value of c_{kl} indicates that A_k is preferred to A_l as far as the concordance criteria are concerned. The concordance matrix $\mathbf{C}$ of $(m \times m)$ is defined as:

$$\mathbf{C} = \begin{bmatrix} - & c_{12} & c_{13} & \cdots & c_{1m} \\ c_{21} & - & c_{23} & \cdots & c_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ c_{m1} & c_{m2} & c_{m3} & \cdots & - \end{bmatrix} \tag{3.13}$$

where the entries are not defined when $k = l$. The discordance matrix $\mathbf{D}$ indicates the degree that a certain alternative A_k is worse than a competing alternative A_l. The discordance index d_{kl} is defined as:

$$d_{kl} = \frac{\max\limits_{j \in D_{kl}} \mid y_{kj} - y_{lj} \mid}{\max\limits_{j} \mid y_{kj} - y_{lj} \mid} \tag{3.14}$$

where $0 \leq d_{kl} \leq 1$. A higher d_{kl} value implies that, for the discordance criteria, A_k is less favourable than A_l, and a lower value of d_{kl} implies A_k is more favourable than A_l. The discordance indices form the discordance matrix **D** of $(m \times m)$:

$$\mathbf{D} = \begin{bmatrix} - & d_{12} & d_{13} & \cdots & d_{1m} \\ d_{21} & - & d_{23} & \cdots & d_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ d_{m1} & d_{m2} & d_{m3} & \cdots & - \end{bmatrix} \tag{3.15}$$

as with matrix **C**, the entries of matrix **D** are not defined when $k = l$. It should be noted that matrices **C** and **D** are not symmetric.

Step 5: Calculate pure concordance and discordance indices

The pure concordance and discordance indices are calculated and two separate rankings of the alternatives based on these indices are obtained. An average ranking from the two rankings is calculated and the alternative with the best average rank is selected. The pure concordance index is defined as:

$$C_k = \sum_{i=1, i \neq k}^{n} c(k,i) - \sum_{i=1, i \neq k}^{n} c(i,k) \tag{3.16}$$

and the pure discordance index can be calculated as:

$$D_k = \sum_{i=1, i \neq k}^{n} d(k,i) - \sum_{i=1, i \neq k}^{n} d(i,k) \tag{3.17}$$

3.4.3.2 Worked Example of ELECTRE II Method

Consider the haul truck selection problem in Subsection 3.4.1. Five trucks are evaluated with respect to five criterion. The input values for decision matrix **X** can be found in Table 3.6.

Step 1: Normalise the Decision Matrix

The normalised decision matrix **A** is calculated by employing Equation 3.8 on the element in matrix **X**.

$$\mathbf{A} = \begin{bmatrix} 0.4091 & 0.4578 & 0.4548 & 0.4428 & 0.3424 \\ 0.4692 & 0.4005 & 0.4264 & 0.4911 & 0.4669 \\ 0.4211 & 0.4864 & 0.4775 & 0.3859 & 0.5706 \\ 0.4813 & 0.4349 & 0.4434 & 0.4911 & 0.3950 \\ 0.4512 & 0.4520 & 0.4321 & 0.4155 & 0.4280 \end{bmatrix}$$

Step 2: Weighting the Normalised Decision Matrix

Matrix **A** is weighted using the criteria weight in Table 3.7 to give the weighted normalised decision matrix **Y**.

$$\mathbf{Y} = \begin{bmatrix} 0.0818 & 0.0916 & 0.1364 & 0.0443 & 0.0685 \\ 0.0938 & 0.0801 & 0.1279 & 0.0491 & 0.0934 \\ 0.0842 & 0.0973 & 0.1433 & 0.0386 & 0.1141 \\ 0.0963 & 0.0870 & 0.1330 & 0.0491 & 0.0790 \\ 0.0902 & 0.0904 & 0.1296 & 0.0416 & 0.0856 \end{bmatrix}$$

Step 3: Determine the Concordance and Discordance Sets

The concordance C_{kl} and discordance D_{kl} sets are complementary and computed as:

$C_{12} = \{2, 3\}$ $D_{12} = \{1, 4, 5\}$
$C_{13} = \{4\}$ $D_{13} = \{1, 2, 3, 5\}$
$C_{14} = \{2, 3\}$ $D_{14} = \{1, 4, 5\}$
$C_{15} = \{2, 3, 4\}$ $D_{15} = \{1, 5\}$

$C_{23} = \{1, 4\}$ $D_{23} = \{2, 3, 5\}$
$C_{23} = \{1, 4\}$ $D_{23} = \{2, 3, 5\}$
$C_{24} = \{5\}$ $D_{24} = \{1, 2, 3, 4\}$
$C_{25} = \{1, 4, 5\}$ $D_{25} = \{2, 3\}$

$C_{31} = \{1, 2, 3, 5\}$ $D_{31} = \{4\}$
$C_{32} = \{2, 3, 5\}$ $D_{32} = \{1, 4\}$
$C_{34} = \{2, 3, 5\}$ $D_{34} = \{1, 4\}$
$C_{35} = \{2, 3, 5\}$ $D_{35} = \{1, 4\}$

$C_{41} = \{1, 4, 5\}$ $D_{41} = \{2, 3\}$
$C_{42} = \{1, 2, 3\}$ $D_{42} = \{4, 5\}$
$C_{43} = \{1, 4\}$ $D_{43} = \{2, 3, 5\}$
$C_{45} = \{1, 3, 4\}$ $D_{45} = \{2, 5\}$

$C_{51} = \{1, 5\}$ $D_{51} = \{2, 3, 4\}$
$C_{52} = \{2, 3\}$ $D_{52} = \{1, 4, 5\}$
$C_{53} = \{1, 4\}$ $D_{53} = \{2, 3, 5\}$
$C_{54} = \{2, 5\}$ $D_{54} = \{1, 3, 4\}$

Step 4: Calculate the Concordance and Discordance Matrices

The calculation of element c_{15} in the concordance matrix **C** and entire matrix itself is obtained as:

$$
\begin{aligned}
c_{15} &= \sum_{j \in C_{15}} w_j \\
&= w_2 + w_3 + w_4 \\
&= 0.2 + 0.3 + 0.1 = 0.6
\end{aligned}
\qquad
\mathbf{C} = \begin{bmatrix}
- & 0.5 & 0.1 & 0.5 & 0.6 \\
0.5 & - & 0.3 & 0.2 & 0.5 \\
0.9 & 0.7 & - & 0.7 & 0.7 \\
0.5 & 0.7 & 0.3 & - & 0.6 \\
0.4 & 0.5 & 0.3 & 0.4 & -
\end{bmatrix}
$$

The calculation of element d_{24} in the discordance matrix $\mathbf{D}$ and the entire matrix itself is obtained as:

$$
\begin{aligned}
d_{24} &= \frac{\max_{j \in D_{24}} \mid y_{2j} - y_{4j} \mid}{\max_{j} \mid y_{2j} - y_{4j} \mid} \\
&= \frac{\max\{0.0024; 0.0069; 0.0052; 0; 0\}}{\max\{0.0024; 0.0069; 0.0052; 0; 0.0144\}} \\
&= \frac{0.0069}{0.0144} = 0.48
\end{aligned}
\qquad
\mathbf{D} = \begin{bmatrix}
- & 1 & 1 & 01 & 1 \\
0.46 & - & 1 & 0.48 & 1 \\
0.12 & 0.51 & - & 0.34 & 0.21 \\
0.32 & 1 & 1 & - & 0.87 \\
0.40 & 0.76 & 1 & 1 & -
\end{bmatrix}
$$

Step 5: Calculate pure concordance and discordance indices

The ranking of the haul trucks according to the ELECTRE II method is presented in the final column of Table 3.9. This method concurs with the additive and multiplicative value functions approaches that haul truck 3 is the preferred alternative.

Table 3.9: Ranking haul trucks with ELECTRE II method

A_i	Pure concordance index	Concordance Rank	Pure discordance index	Discordance Rank	Average Rank	Final Rank
A_1	−0.6	3	2.700	5	4	5
A_2	−0.9	5	−0.325	2	3.5	3
A_3	2	1	−2.815	1	1	1
A_4	0.3	2	0.368	4	3	2
A_5	−0.8	4	0.072	3	3.5	3

3.4.3.3 PROMETHEE II

The first two members of the PROMETHEE family of methods, PROMETHEE I and II, were developed by Brans (1982). Since then, numerous developments and adaptions of these methods have been proposed and published (Brans and Mareschal, 2002). PROMETHEE III (Mareschal *et al.*, 1984), PROMETHEE IV, PROMETHEE V (Mareschal and Brans, 1992), PROMETHEE VI (Brans and Mareschal, 1995), PROMETHEE GDSS (Macharis *et al.*, 1998) and the PROMETHEE GAIA (Mareschal and Brans, 1988) method are examples of subsequent extensions.

According to Cavalcante and De Almeida (2007), the popularity of the PROMETHEE methods stems from the fact that the concepts and parameters involved in these methods are easy to understand. Albadvi *et al.* (2007) adds that these methods are rather simple compared to other MCDA ranking methods and that they are well adapted to problems where a finite number of alternatives are to be ranked considering several, often conflicting, criteria.

Owing to its simplicity and ranking proficiency, the PROMETHEE II method is identified as a possible approach to rank the MPs in Subsection 3.3.1 (see Table 3.1). Corresponding to the ELECTRE I and II methods, the respective output of PROMETHEE I and II is a partial and a complete ranking of the alternatives.

Hunjak (1997) and Bouyssou *et al.* (2006) both describe the PROMETHEE II method as a three phase procedure. In the first phase, a valued preference relation between alternatives is built for each criterion. Next, a total multi-criteria level of the preference with which one alternative dominates over the other is calculated for each pair of alternatives. In the last phase, this total multi-criteria level of the preference is exploited using the net flow procedure in order to obtain a rank order of the alternatives.

The three phase PROMETHEE II method is described in greater detail with the following six procedural steps. These steps are inspired by the work of Chareonsuk *et al.* (1997), Le Téno and Mareschal (1998), Athawale and Chakraborty (2010) and Behzadian *et al.* (2010).

Step 1: Normalise the Decision Matrix

The first step normalises the x_{ij} entries of each criterion in the decision matrix to dimensionless and therefore comparable a_{ij} values. This normalisation step is identical to the process used in Subsection 3.4.2 for the value measurement approaches. Equations 3.4 and 3.5 are employed for benefit and cost criteria respectively.

Step 2: Weighting the Normalised Decision Matrix

Each entry in the normalised decision matrix is multiplied by its associated weighted w_j, where $w_j \geq 0$ for $j = 1, 2, \ldots, n$. The weightings express the relative importance of each criterion and the sum of the weights equals one.

Step 3: Application of Preference Function

The ranking of alternatives starts with a pairwise comparison for each criterion. This comparison is measured using a predetermined preference function $P_j(k, l)$, which expresses the level of preference intensity of alternative k over alternative l for criterion j.

Vincke and Brans (1985) proposed six generalised preference functions: (1) usual criterion, (2) U-shape criterion, (3) V-shape criterion, (4) level criterion, (5) V-shape with indifference criterion and (6) Gaussian criterion. These functions, unfortunately, require the decision maker to specify parameters, such as preference and indifference thresholds, which are difficult to define. Another approach is to use the following simplified preference function:

$$P_j(k, l) = (a_{kj} - a_{lj}), \qquad \text{if} \quad a_{kj} > a_{lj} \tag{3.18}$$

$$P_j(k, l) = 0, \qquad \text{if} \quad a_{kj} \leq a_{lj} \tag{3.19}$$

Step 4: Calculate Multi-criteria Preference Index

A multi-criteria preference index $\pi(k, l)$ is calculated by summing all the weighted values of the preference function for the complete set of criteria. The value of this index, varying between zero and one, expresses the preference of alternative k over alternative l considering all criteria, and is calculated as:

$$\pi(k, l) = \sum_{i=1}^{m} w_i P_i(k, l) \tag{3.20}$$

A weak preference of alternative k over alternative l is denoted by $\pi(k, l) \approx 0$, whereas a strong global preference is denoted by $\pi(k, l) \approx 1$. That is to say, the higher $\pi(k, l)$, the more alternative k is preferred to alternative l.

Step 5: Determine the Leaving and Entering Flows

The sum of indices $\pi(k,i)$ indicates the preference of alternative k over all the other alternatives. It is termed the leaving flow $\phi^+(k)$ and defined as:

$$\phi^+(k) = \frac{1}{m-1} \sum_{i=1,\ i \neq k}^{m} \pi(k,i) \tag{3.21}$$

The sum of indices $\pi(i,k)$ shows the preference of all the other alternatives compared to alternative k. It is termed the entering flow $\phi^+(k)$ and defined as:

$$\phi^-(k) = \frac{1}{m-1} \sum_{i=1,\ i \neq k}^{m} \pi(i,k) \tag{3.22}$$

Alternative k is considered the superior alternative if its leaving flow ϕ^+ is greater than, and its entering flow ϕ^- is smaller than, the corresponding flows of alternative l.

Step 6: Calculate Net Flows

The complete ranking of the alternatives is obtained by computing the net flow $\phi(k)$ for each alternative. It is the difference in the leaving and entering flows, expressed as:

$$\phi(k) = \phi^+(k) - \phi^-(k) \tag{3.23}$$

A higher net flow indicates a superior alternative. Therefore, the best alternative is the is the one with the highest $\phi(k)$ value.

3.4.3.4 Worked Example of PROMETHEE II Method

Consider the haul truck selection problem in Subsection 3.4.1. Five trucks are evaluated with respect to five criterion. The input values for decision matrix $\mathbf{X}$ can be found in Table 3.6.

Step 1: Normalise the Decision Matrix & Step 2: Weighting the Normalised Decision Matrix

Steps one and two are identical to the corresponding steps for the value and multiplicative value functions (see Sub-subsection 3.4.2.3).

Step 3: Application of Preference Function

The preference functions for the pairs of haul trucks (alternatives) are determined to be:

Preference function pair	C_1	C_2	C_3	C_4	C_5
$P(A_1, A_2)$	0	0.1333	0.1667	0.0400	0.1333
$P(A_1, A_3)$	0	0	0	0	0.2000
$P(A_1, A_4)$	0	0.0533	0.0667	0.0400	0.0667
$P(A_1, A_5)$	0.0500	0	0	0	0
$P(A_2, A_1)$	0.1667	0	0	0	0
$P(A_2, A_3)$	0.1333	0	0	0	0.0667
$P(A_2, A_4)$	0	0	0	0	0
$P(A_2, A_5)$	0.0500	0	0	0	0
$P(A_3, A_1)$	0.0333	0.0667	0.1333	0.0600	0
$P(A_3, A_2)$	0	0.2000	0.3000	0.1000	0
$P(A_3, A_4)$	0	0.1200	0.2000	0.1000	0
$P(A_3, A_5)$	0	0.0800	0.2667	0.0333	0
$P(A_4, A_1)$	0.200	0	0	0	0
$P(A_4, A_2)$	0.0333	0.0800	0.1000	0	0.0667
$P(A_4, A_3)$	0.1667	0	0	0	0.1333
$P(A_4, A_5)$	0.0833	0	0.0667	0	0.0333
$P(A_5, A_1)$	0.1167	0	0	0.0267	0
$P(A_5, A_2)$	0	0.1200	0.0333	0.0667	0.0333
$P(A_5, A_3)$	0.0833	0	0	0	0.1000
$P(A_5, A_4)$	0	0.0400	0	0.0667	0

Step 4: Calculate Multi-criteria Preference Index

The multi-criteria preference indices for the haul trucks are computed as:

Alternative	A_1	A_2	A_3	A_4	A_5
A_1	–	0.1073	0.0400	0.0480	0.0100
A_2	0.0333	–	0.0400	0	0.0100
A_3	0.0660	0.1400	–	0.0940	0.0993
A_4	0.0400	0.0660	0.0600	–	0.0433
A_5	0.0260	0.0473	0.0367	0.0147	–

Step 5: Determine the Leaving and Entering Flows & Step 6: Calculate Net Flows

The ranking of the haul trucks according to the PROMETHEE II method is presented in the final column of Table 3.10. This method concurs with the additive and multiplicative value function approaches as well as ELECTRE II method that haul truck 3 is the preferred alternative. Furthermore, all four methods coincide that haul truck 4 is the second best alternative and all the methods, except for PROMETHEE II, agree that haul truck 5 is the third best alternative.

Table 3.10: Ranking haul trucks with PROMETHEE II method

A_i	Leaving flow	Entering flow	Net outranking flow	Rank
A_1	0.0468	0.0402	+0.0067	3
A_2	0.0258	0.0803	−0.0545	5
A_3	0.0742	0.0525	+0.0217	1
A_4	0.0557	0.0188	+0.0368	2
A_5	0.0225	0.0332	−0.0102	4

The differences in ranking results with respect to the fourth and fifth best alternatives for the haul truck selection problem are unsurprising as Kerzner (2015) reveals that:

> *often different methods may yield different results for exactly the same problem. In other words, when exactly the same problem data are used with different MCDA methods, such methods may recommend different solutions even for very simple problems (i.e., ones with very few alternatives and criteria).*

There are a number of reasons why the results of different MCDA methods can differ. Malczewski and Rinner (2010) attempt to clarify why this is the case by stating that:

> *the disagreement among MCDA methods is a source of uncertainty associated with the choice of the most suitable methods for a particular decision problem. There is no commonly accepted set of rules for selecting the 'best' MCDA model. The process of selecting an MCDA method should be concerned with with factors such as the nature of the decision problem, data requirements, consistency of results, and computational complexity.*

As mentioned at the start of this chapter, MCDA provides a more structured approach to support decision making in problems involving several alternatives and criteria (which may even be in conflicting with others). However, MCDA always involve a certain amount of subjectivity (Kerzner, 2015) as each method negotiates the subjective weightings associated each criterion in an unique manner (Al-Shalabi *et al.*, 2006). Yet, based on the general concurrence of the ranking results obtained from the four MCDA methods, it appears as if the methods selected for the haul truck selection are appropriate.

3.5 Imperfect Maintenance

This section follows on from Subsection 3.3.2, which demonstrated how the TPMPF gives insufficient guidance on how to quantify maintenance effectiveness. The work to follow explores the concept of *imperfect maintenance* in order to quantify the effectiveness of different types of maintenance actions on components at various life cycle stages.

Traditionally, it is assumed that maintenance restores the condition of a component to *as good as new* or *as bad as old* (Martorell *et al.*, 1999). The former means the age of the component is reset to zero after maintenance, whereas the component's age for the latter is the same as it was prior to the maintenance. Soro *et al.* (2010) discusses how this assumption is not realistic. A more reasonable assumption, according to Liu and Huang (2010), is to assume the component's condition is restored to somewhere in between these two extreme states. This type of maintenance is what is referred to in literature as imperfect maintenance and was first developed by Chaudhuri and Sahu (1977).

3.5.1 System Description and Levels of Maintenance

In order to explain the concept of imperfect maintenance, consider a series-parallel system consisting of s $(i = 1, 2, \ldots, s)$ independent subsystems connected in series. Each subsystem i has n_i $(j = 1, 2, \ldots, n_i)$ components connected in parallel. Figure 3.3 provides a simple illustration of such a system.

In between missions during normal operation or during a total plant shutdown, this system or some of its components can be put forward for maintenance. The condition of the components may vary, but Pham and Wang (1996) point out that imperfect maintenance literature most often deals with binary state system models. That is to say, the components are assumed to either

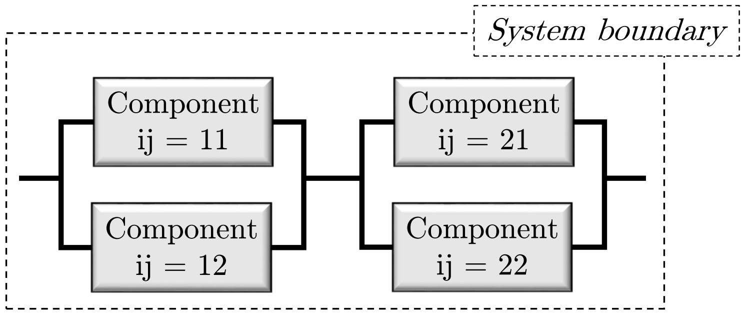


Figure 3.3: Series-parallel system example

be in a *functioning* or a *fail* state. Amongst other studies, this assumption is used by Rice *et al.* (1998), Cassady *et al.* (2001*b*), Schneider and Cassady (2004) and Maillart *et al.* (2009).

As discovered in Sections 2.6 and 2.7, maintenance constitutes a variety of different actions that can help improve equipment health. These actions can be assigned to discrete levels of maintenance I_{ij} for a component ij. This discrete nature means a total number of N_{ij} maintenance levels, i.e. $I_{ij} \in [1, 2, \ldots, N_{ij}]$, are available for every component. Take note that N_{ij} can differ for each component in the system. If $I_{ij} = 1$, it means no maintenance is performed on the component and if $I_{ij} = N_{ij}$, it indicates the component is replaced. Therefore, whenever a system or some of its components are put forward for maintenance, the following three options are available:

Maintenance Option 1:	No maintenance ($I_{ij} = 1$)
Maintenance Option 2:	Perform intermediate imperfect maintenance action ($2 \leq I_{ij} \leq N_{ij} - 1$)
Maintenance Option 3:	Replace component ($I_{ij} = N_{ij}$)

Depending on the option selected, a maintenance cost $C_{ij}(I_{ij})$ is incurred which corresponds to the specific level of maintenance performed on the component. For the first option, where $I_{ij} = 1$, no maintenance is performed and the cost equals zero. On the contrary, maintenance is performed for the second and third options ($I_{ij} > 1$) which consequently depletes a portion of the allocated budget. The incurred cost for the second option depends on the specific level of maintenance I_{ij} performed on the component. Finally, for the third option a replacement cost C_{ij}^R is incurred to replace the component.

Returning to Maintenance Option 2 and recalling that, at the time of maintenance, a component's condition can be classified as either functioning or failed. For components in the functioning state, $2 \leq I_{ij} < N_{ij}$ denotes the discrete set of maintenance levels available. They are called the intermediate levels of maintenance and improve the component's condition to somewhere between as bad as old and as good as new. Moreover, each level incurs an associated maintenance cost $C_{ij}(I_{ij})$. For components in the fail state, the intermediate levels of maintenance are denoted $3 \leq I_{ij} < N_{ij}$. Here, $I_{ij} = 2$ incurs a cost termed the minimal repair cost C_{ij}^{MR}. It is the minimum cost needed to repair a failed component to a condition as bad as old, it does not improve the component's condition any further.

3.5.2 Age Reduction Maintenance Model

Different classes of imperfect maintenance models can be found in literature, see reviews by Doyen and Gaudoin (2004), Marais and Saleh (2009) and Liu *et al.* (2012). For the problem described in Subsection 3.3.2, an age reduction model is selected. This model is more flexible than some of the other models in that it is not limited to only minimal or perfect repair. It is also more sophisticated than some of the other models in that it takes into account that repairs become less effective as the component gets older. The model assumes that maintenance reduces the age of a component by some proportion to an effective age.

As shown in Figure 3.4, during a mission (normal operation), the effective age of a component equals the chronological time. Then, after the maintenance break, assuming imperfect maintenance is performed, the condition of the component is restored to somewhere between as good as new or as bad as old. This means there is a reduction in effective age for the component from before to after maintenance is performed. The effective age of component ij after maintenance is given by:

$$t_{ij} = b_{ij} \times A_{ij} \tag{3.24}$$

where A_{ij} is the effective age of the component before maintenance and b_{ij} $(0 \leq b_{ij} \leq 1)$ is the age reduction factor representing the quality of maintenance performed.

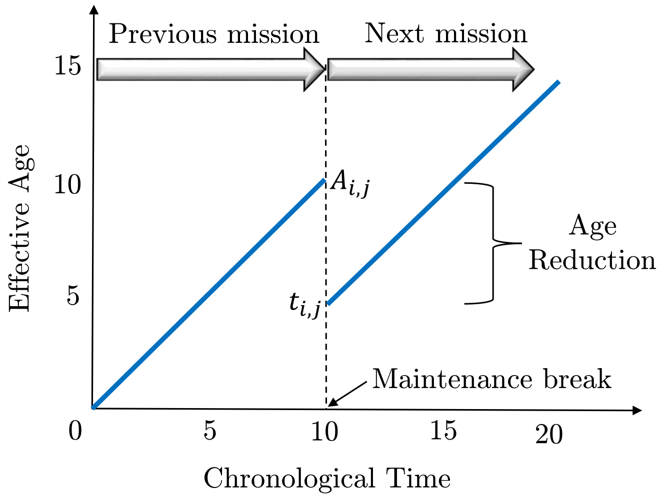


Figure 3.4: Effective age vs. chronological time for age reduction model

Adapted from Liu et al. (2012) and Pandey et al. (2012, 2013)

3.5.3 Age Reduction Factor

It is generally accepted that maintenance quality and therefore component health is directly proportional to the amount of budget allocated for the maintenance of that component (Pandey *et al.*, 2012). Lie and Chun (1986) discuss how this maintenance cost and the age of the component are the two most important factors in determining the age reduction factor b_{ij} for a component. The age reduction factor as a function of maintenance cost is defined by Liu and Huang (2010) as:

$$b(I_{ij}) = 1 - \left(\frac{C_{ij}(I_{ij})}{C_{ij}^{R}} \right)^{m} \tag{3.25}$$

where m ($m \geq 0$) is the characteristic constant that determines the exact relationship between the maintenance cost, replacement cost and the age reduction factor for component ij (see Subsection 3.5.4 for the determination of m). C_{ij} is the maintenance cost for the component, which depends on the level of maintenance I_{ij}, and C_{ij}^{R} denotes the component replacement cost. If $C_{ij}(I_{ij}) = 0$, then $b(I_{ij}) = 1$, which means no maintenance is performed and the age of the component remains unchanged. In the same way, if $C_{ij}(I_{ij}) = C_{ij}^{R}$, then $b(I_{ij}) = 0$, which means the component is replaced and the age of the component is reset to zero.

The formulation of Equation 3.25 does not consider minimal repair cost C_{ij}^{MR}. If it were included in the maintenance cost, the age reduction value would be smaller than what was actually experienced. It is important to remember that C_{ij}^{MR} does not contribute to age reduction, it simply restores a failed component back to a condition as bad as old. For this reason the minimal repair cost should not influence the determination of the age reduction factor. In order to incorporate minimal repair cost without influencing the age reduction factor, Pandey *et al.* (2012) redefines Equation 3.25 as:

$$b(I_{ij}) = \begin{cases} 1 - \left(\dfrac{C_{ij}(I_{ij}) - C_{ij}^{MR}}{C_{ij}^{R}} \right)^{m} & \text{for } Y_{ij} = 0,\ 2 \leq I_{ij} < N_{ij} \\ \\ 1 - \left(\dfrac{C_{ij}(I_{ij})}{C_{ij}^{R}} \right)^{m} & \text{for } Y_{ij} = 1,\ 2 \leq I_{ij} < N_{ij} \end{cases} \tag{3.26}$$

where Y_{ij} is the state of component ij at the time of maintenance. $Y_{ij} = 0$ denotes the component in the fail state whereas $Y_{ij} = 1$ denotes the component in a functioning state.

For the case $Y_{ij} = 0$ and $2 \leq I_{ij} < N_{ij}$, the minimal repair cost C_{ij}^{MR} does not influence the determination of the age reduction factor. If $I_{ij} = 2$ is selected for component in the fail state, then $C_{ij}(I_{ij}) - C_{ij}^{MR} = 0$ and $b(I_{ij}) = 1$. Hence, there in no component age reduction when minimal repair is performed. If any of the other intermediate maintenance levels $3 \leq I_{ij} < N_{ij}$ are selected for a failed state, the minimal repair cost will be included in the total maintenance cost. The minimal repair cost restores the component to a condition as bad as old and the remaining maintenance cost $C_{ij}(I_{ij}) - C_{ij}^{MR}$ determines the age reduction factor $b(I_{ij})$ for the component. For the case $Y_{ij} = 1$, the component is in a functioning state and any maintenance level I_{ij} improves the component's condition.

3.5.4 Characteristic Constant

The characteristic constant m is the only parameter in Equation 3.26 yet to be discussed. As pointed out in the previous subsection, m determines the exact relationship between the maintenance cost, replacement cost and the age reduction factor. According to Cheng and Chen (2003), the characteristic constant indicates whether a component is *relatively young* or *relatively old*. A smaller or larger value for m implies a component is younger or older respectively.

The rationale behind the characteristic constant is that for a given budget, more efficient maintenance is possible for a younger component compared to an older component. In other words, less money is needed to achieve similar improvements from maintenance for relatively new components as opposed to relatively older components (Wang and Pham, 2006). For example, cleaning the filter of a new component may lead to similar improvements in performance as the full service of an identical older component.

As a component ages, its effective age increase and its complementary remaining useful life decreases. Take, for example, a component that has survived up to an effective age A_{ij} and is expected to fail at time T. If $T > A_{ij}$, then the remaining useful life of the component equals $T - A_{ij}$. Banjevic (2009) calculates the expected residual life, also known as the Mean Residual Life (MRL), for a component as follows:

$$\text{MRL} = E(T - A_{ij}|T > A_{ij}) = \frac{\int_{A_{ij}}^{\infty} R(x)\mathrm{d}x}{R(A_{ij})} \tag{3.27}$$

where $R(x)$ is the component reliability as a function of time x. It is assumed the component follows a Weibull distribution with scale parameter α and shape parameter β (see Subsection 4.5.2 for a discussion on the Weibull distribution and its parameters). The reliability of the component at its effective age is denoted $R(A_{ij})$.

According to Pandey *et al.* (2013), a component's characteristic constant m is calculated as the ratio between its effective age A_{ij} and its mean residual life. If the effective age is smaller than the mean residual life, $A_{ij} <$ MRL, then $m < 1$ and the component is said to be relatively young. Conversely, if the effective age is larger than the mean residual life, $A_{ij} >$ MRL, then $m > 1$ and the component is said to be relatively old. The formulation of the characteristic constant is given as (Pandey *et al.*, 2013):

$$m(A_{ij}) = \frac{A_{ij}}{\text{MRL}} = \frac{A_{ij}}{\left[\frac{\int_{A_{ij}}^{\infty} R(x)\mathrm{d}x}{R(A_{ij})}\right]} = \frac{A_{ij} \times R(A_{ij})}{\int_{A_{ij}}^{\infty} R(x)\mathrm{d}x} \tag{3.28}$$

With the new definition of $m(A_{ij})$ formulated, the age reduction factor in Equation 3.26 can be rewritten as:

$$b(I_{ij}) = \begin{cases} 1 - \left(\dfrac{C_{ij}(I_{ij}) - C_{ij}^{MR}}{C_{ij}^{R}}\right)^{m(A_{ij})} & \text{for } Y_{ij} = 0,\ 2 \leq I_{ij} < N_{ij} \\ \\ 1 - \left(\dfrac{C_{ij}(I_{ij})}{C_{ij}^{R}}\right)^{m(A_{ij})} & \text{for } Y_{ij} = 1,\ 2 \leq I_{ij} < N_{ij} \end{cases} \tag{3.29}$$

It can be seen that a component's age reduction factor depends on its level of maintenance I_{ij} as well as its effective age A_{ij}. This means for the same maintenance cost $C_{ij}(I_{ij})$, greater age reduction is achieved for a younger ($m < 1$) component as opposed to an older ($m > 1$) component.

With the component's effective age before maintenance A_{ij} already known and the age reduction factor now determined by Equation 3.29, the component's effective age after maintenance t_{ij} can be calculated as shown in Equation 3.24.

3.6 Chapter 3 Concluding Remarks

This chapter built on the theoretical foundation of Chapter 2. It started by establishing the need for maintenance prioritisation in today's cut-throat business environment. Moreover, it mentioned the inadequacy of current maintenance prioritisation techniques such as the Pareto analysis and FMECA, especially given their inability to consider the value of maintenance.

Next, a recently developed value-based maintenance prioritisation framework in the form of the TPMPF was reviewed. This promising framework was examined as possible solution to the problem introduced in Chapter 1. Inefficiencies within the TPMPF such as its semi-quantitative ranking procedure and its quantification of maintenance effectiveness were identified and subsequently analysed.

The final part of this chapter proposed possible solutions to the aforementioned inefficiencies. Fields such as MCDA and imperfect maintenance were consulted in order to address the respective identified inefficiencies. For the semi-quantitative ranking procedure, MCDA models such as the additive and multiplicative value functions as well as the ELECTRE II and PROMETHEE II methods were presented. As for the quantification of maintenance effectiveness, an imperfect maintenance age reduction model was put forward to quantify the effectiveness of different maintenance actions.

These proposed solutions and the TPMPF are used as basis for the development of the application methodology in Chapter 4.

Chapter 4

Building a Shutdown Maintenance Prioritisation Framework

Chapter Aims:

Chapter 4 presents the proposed application methodology or Shutdown Maintenance Prioritisation Framework (SMPF), which aims to address the identified research problem in Chapter 1. The development of the SMPF draws from the theoretical foundation of Chapters 2 and 3 in order to prioritise the maintenance work of a critical asset for a forthcoming shutdown. This chapter serves as template for the case study that will be conducted in Chapter 5.

Chapter Outcomes:

⇒ Presentation of the application methodology (SMPF).

⇒ Comprehension of the SMPF implementation process.

4.1 Introduction to the SMPF Application Methodology

This chapter presents the application methodology or proposed solution which attempts to answer the central research question defined in Section 1.2. The question is repeated here for convenience:

> *Can the Tam and Price Maintenance Prioritisation Framework be modified and leveraged for the shutdown environment in order to prioritise the shutdown maintenance work of a critical system?*

The Shutdown Maintenance Prioritisation Framework (SMPF) uses the TPMPF as basis for its development. Useful features of the TPMPF are adopted and in some cases modified to make them more applicable to the shutdown environment. In addition to this, MCDA and imperfect maintenance solutions (see Sections 3.4 and 3.5) to the identified inefficiencies in the TPMPF are also incorporated into the SMPF. The end product is a framework with a more efficient ranking procedure and means of quantifying the effectiveness of different maintenance actions. Beneficial properties of the SMPF include:

- measuring the value of the shutdown maintenance to be performed;
- considering pertinent shutdown criteria such as time and budget;
- taking into account limited maintenance resources;
- making provisions, in terms of time and cost, for the discovery of hidden failures during the shutdown;
- quantifying the effectiveness of different types of maintenance actions;
- prioritising maintenance tasks using established MCDA methods; and
- performing a quantitative analysis expressed in financial terms.

Leading from the research question above, the purpose of the SMPF is to prioritise the proposed maintenance work of a critical asset for a forthcoming shutdown. It prioritises the maintenance work by maximising the return on maintenance investment subject to the time and budget constraints that apply. The seven procedural steps in the implementation process of the SMPF application methodology are illustrated in Figure 4.1. A detailed discussion of each procedural step is presented in the seven sections that follow.

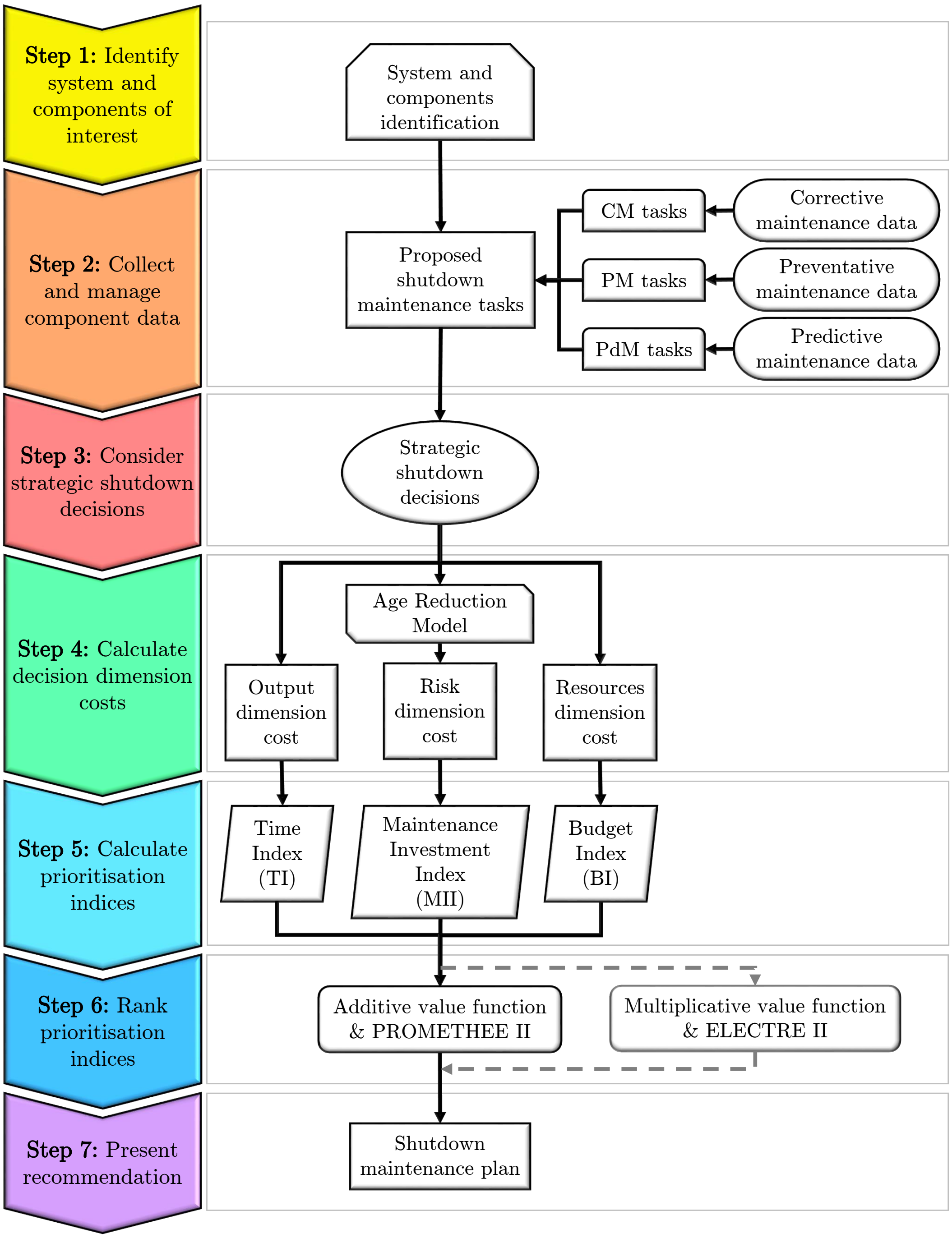


Figure 4.1: Procedural steps of the SMPF application methodology

4.2 Step 1: Identify System and Components of Interest

The implementation process of the SMPF starts by asking the following basic question: Which piece of equipment or system of interest should this framework be applied too?

A key measurement in the SMPF is the effect of planned and unplanned maintenance actions on production. For this reason, the framework should be applied to a critical system that is vital to production. In other words, a system where the organisation incurs a loss in production for any amount of system downtime. It is thus imperative to the organisation's profitability that this system remains operational and that unexpected failures as well as unplanned maintenance interruptions are kept to a minimum.

Once the critical system is identified, a boundary line can be drawn around the said system (Lipsett and Hajizadeh, 2011). This line separates the system and its components from the surroundings, as shown by the illustrative example in Figure 4.2. Everything outside the boundary line forms part of the surroundings while anything on the inside can be considered for further analysis. The latter forms the scope of the SMPF.

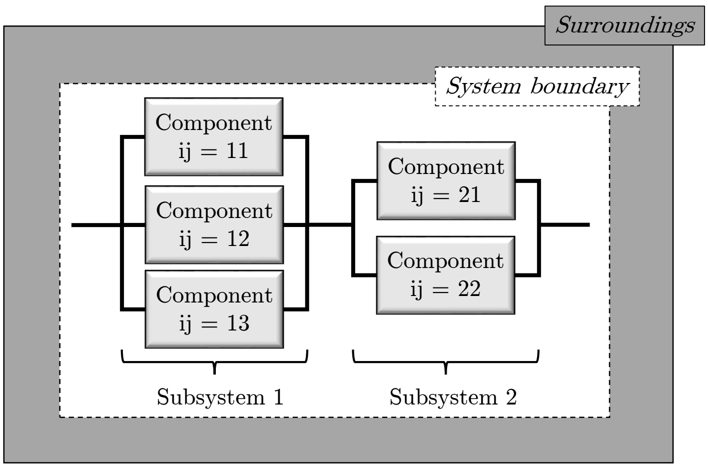


Figure 4.2: Example of a system with its boundary line and surroundings

Inside the system boundary line are the individual components of interest. The relations between these components can be depicted by a series-parallel reliability block diagram, similar to Figure 4.2, depending on the complexity of the system. However, regardless of the intricacy of the series-parallel system, each individual component can be described by ij. Here, the number of independent subsystems connected in series is denoted by s $(i = 1, 2, \ldots, s)$ and each subsystem i has n_i $(j = 1, 2, \ldots, n_i)$ components connected in parallel. It can be helpful to consult the manufacturer's manual in order to gain a better understanding of the components and their interrelations with one another inside the system.

4.3 Step 2: Collect and Manage Component Data

Once the system and the components of interest have been identified, the process of capturing and collecting data may begin. Waeyenbergh and Pintelon (2002) argue that for any scientific maintenance practice, data is one of the most important requirements and collecting it is one of the most challenging tasks. Sherwin (2004) echoes the importance of comprehensive data collection in the management of physical assets.

Al-Najjar (1996) and Al-Najjar and Alsyouf (2000, 2004) suggest storing all relevant maintenance data, from different information systems, in one centralised database. This suggestion of a common asset database is reverberated by the TPMPF, see Subsection 3.2.3. Moore and Starr (2006) acknowledge that such a database may sound like a suitable solution, but warns it is laden with the following difficulties:

- Different departments within organisations often acquire or upgrade their information systems without consulting the other departments.
- Information systems stored in different formats can be incompatible and difficult to integrate into a centralised database.
- Complex hardware and software may be needed to avoid large databases from becoming cumbersome and ineffective in their operation.
- The costs involved in setting up, maintaining and backing up a large database may not justify its introduction.

- A centralised database affects all its subsystems if it suffers a failure.

The aforementioned difficulties are not insurmountable. With the advent of new technologies and a greater understanding of these difficulties, the reality of a centralised database may be possible in the near future. However, in order to make the SMPF accessible and practical in the current AM climate, a common asset database is not a prerequisite (as is the case with the TPMPF). Nevertheless, it can easily be incorporated into the SMPF if available.

Sherwin (2006) mentions that often several sources are needed to compile a file for a particular exercise as inconsistencies in various information systems need to be resolved before useful analysis can begin. The SMPF does the same, it starts by gathering information from all the different forms of data i.e. CM, PM and PdM. Next, through data analysis, the CM, PM and PdM tasks are formulated for the components requiring maintenance work. Component tasks, from the different sources, that are identical or in conflict are analysed and amended. Finally, after the amendments are made, the tasks can be compiled into a MP which corresponds to a particular component.

Take for example a system consisting of five faulty components, it will have a MP for each component. The decision maker can choose to perform no maintenance, any one package, any combination of two packages, any combination of three packages, any combination of four packages or all five packages. This means there are in total $\sum_{n=0}^{5} \mathrm{MP}_n^5 = 32$ possible MPs to choose from. With all the possible MPs proposed, the decision maker has to select the best MP to perform during the forthcoming shutdown. The SMPF helps with selecting the best MP to perform and this selection process begins in the following section.

Table 4.1 provides a summary of all the data, at the lowest level of computational granularity, needed to implement the SMPF. What is more, the table indicates the purpose of the data, where it can typically be acquired and in which equation(s) of this chapter it is needed for computation. Some of the data such as the component minimal repair cost, Time Factor (TF) and Budget Factor (BF) are not captured, but determined by asset or maintenance managers themselves. At the end of this chapter, all the data in Table 4.1 will have been discussed in sufficient detail to understand its role in the SMPF.

Table 4.1: Data requirement for the SMPF

Data	Purpose of data in shutdown	Typical source of data capture	Used in equation(s)
Maintenance Package Downtime (MPDT)	Calculate ODC and TI.	Work orders	4.2; 4.22
Available Shutdown Time (AST)	MP constraint. Calculate ODC and TI.	Management strategy	4.2; 4.22
Production Loss (PL) per unit time	Calculate ODC and consequences cost.	Management strategy	4.2; 4.11
Historical component failure data	Evaluate component performance.	Computerised maintenance management system (CMMS)	4.6; 4.7; 4.8; 4.9; 4.10; 4.12; 4.13
Downtime (DT)	Calculate consequences cost and ReDC.	Risk analysis documentation	4.11; 4.20
Spare parts cost	Calculate consequences cost and fixed maintenance cost.	Maintenance resource planning (MRP) system	4.11; 4.20
Labour cost	Calculate consequences cost and variable maintenance cost.	Management accounting system	4.11; 4.20
Maintenance level cost	Calculate age reduction factor.	Work orders	4.14; 4.15
Component minimal repair cost	Calculate age reduction factor.	*– calculated, not captured*	4.14
Component replacement cost	Calculate age reduction factor.	Management accounting system	4.14; 4.15
Time Factor (TF)	Make provision for shutdown scope change. Calculate TI.	*– calculated, not captured*	4.22
Shutdown Budget (SB)	MP constraint. Calculate BI.	Management strategy	4.23
Budget Factor (BF)	Make provision for shutdown scope change. Calculate BI.	*– calculated, not captured*	4.23

4.4 Step 3: Consider Strategic Shutdown Decisions

In the previous section, all the possible MPs were formulated and proposed for approval by the decision maker. This section marks the beginning of the evaluation process that will ultimately determine which MP should be implemented during the forthcoming shutdown.

Subsection 3.2.3 referred to strategic decisions as board level decisions concerning the future exploitation of, and the expenditure on, the organisation's assets. In order to keep share prices high and shareholders satisfied, board members set production targets with the aim of achieving certain levels of revenue or profit. These production targets are handed down to the engineering department along with the Non-operating Time (NOT) and maintenance budget for the year. The engineering department is then tasked with achieving the production targets within the available NOT and budget.

Within an organisation's strategic decisions are the *strategic shutdown decisions* that pertain specifically to the forthcoming shutdowns. Section 2.7 revealed that shutdowns are mostly planned events with predetermined durations. Depending on the organisation, the duration of its shutdown can form part of the NOT or it can be allocated separately. In the same way, expenses incurred during a shutdown can be supported by the overall maintenance budget or by a separate shutdown budget. Kelly (2006) claims that an integral part of the planning procedure for a plant requiring a major shutdown is the need for a specific Shutdown Budget (SB).

Strategic decisions such as the production level per unit time that the production targets will aim to achieve and the strategic shutdown decisions, such as the shutdown's duration (NOT) and budget, will be discussed in the calculations of the SMPF's decision dimension costs. These costs are described in the succeeding section.

4.5 Step 4: Calculate Decision Dimension Costs

The SMPF is built on three business decision dimensions, namely output, risk and resources. Subsection 3.2.1 examined these dimensions in detail and it is suggested that this subsection be revisited in order to reacquaint the reader with each dimension. These three decision dimensions form the basis of the SMPF and their comprehension is necessary in understanding the subsequent steps of the application methodology. The following step (Section 4.6) uses these dimensions to calculate the maintenance prioritisation indices, which will then be used to rank order the proposed MPs. Hence, the business decision dimensions are fundamental to the SMPF decision making process.

According to Bharadwaj *et al.* (2012), in order for decision makers to evaluate maintenance projects, the implications of various options need to be understood in *financial* and not only engineering terms. This section quantifies the three decision dimensions in terms of costs. Not only are they expressed in financial terms, but they are quantified to the same units. Having identical units makes the decision dimensions comparable, which helps to analyse the trade-offs between the three dimensions.

Each decision dimension cost relates to the maintenance proposed for the forthcoming shutdown. Komonen and Akatemia (1998) and Komonen (2002) propose that costs associated with maintenance be grouped as follows:

- *Direct (intervention) costs* are due to maintenance operations (administrative costs, labour, materials and subcontracting).
- *Indirect (lost production) costs* are due to equipment failure.

Both groupings of maintenance costs are elaborated upon in Subsections 4.5.1, 4.5.2 and 4.5.3. This section emphasised the importance of the decision dimensions in the SMPF implementation process. The following three subsections describe how the decision dimension costs are calculated for each of the proposed MPs.

4.5.1 Output Dimension Cost

The Output Dimension Cost (ODC) is defined as the cost of lost production due to *planned* maintenance interruptions. This subsection therefore does not consider *unplanned* maintenance outages (as will be the case in Subsection 4.5.2).

According to Taylor *et al.* (2000), periods of production losses can be characterised as either planned or unplanned outages. Here, planned outages are predetermined and caused by planned maintenance programs, working hours, weekends, compliance with regulations, etc. On the other hand, unplanned outages are not prearranged, they are the result of equipment breakdowns and major incidents such as plant explosions or earthquakes.

Regardless of the outage type, nowadays, even brief outages can be expensive or detrimental to an organisation's financial future. It is therefore vital that maintenance decisions take into account the effects on production. Pascual *et al.* (2008) claim that a good estimate of equipment downtime cost can benefit maintenance decision making by:

1. measuring the impact of equipment on the efficiency of the entire system;
2. assessing the effectiveness of maintenance policies as a key performance indicator; and
3. assisting mathematical models in selecting replacement policies, maintenance strategies and the stock levels of spares.

For a power-generating plant, Krishnasamy *et al.* (2005) proposed the following formula to estimate the production lost cost:

$$\text{PLC} = \text{DT} \times \text{PL} \times \text{SP} \tag{4.1}$$

where DT is the downtime, PL is the production loss in megawatt hours and SP is the is the selling price of electricity per megawatt hour. Here, downtime includes both planned and unplanned maintenance outages.

Returning to the ODC, it only considers planned maintenance interruptions, which means there will only be a cost if the equipment downtime exceeds the time allocated for maintenance. Section 4.4 mentioned that a shutdown's duration, or the time allocated for maintenance during a shutdown, can be included in the NOT or allocated separately. To avoid any confusion, the SMPF defines the time allocated for maintenance during a shutdown as the Available Shutdown Time (AST). Furthermore, to compare the ODC for all the proposed MPs, another parameter in Maintenance Package Downtime (MPDT) is defined. The MPDT is the total amount of asset downtime associated with performing a particular MP.

Using Equation 4.1 as guideline, the ODC for each MP can be formulated. For the case, MPDT < AST, the ODC = 0. Conversely, for MPDT > AST, the ODC is calculated as:

$$\text{ODC} = (\text{MPDT - AST}) \times \text{PL} \tag{4.2}$$

where PL denotes the loss in earnings per unit time. This equates to equipment downtime costs as it is the cost of lost production to the organisation for each unit of time the system is non-operational when it is supposed to be operational.

4.5.2 Risk Dimension Cost

The Risk Dimension Cost (RDC) refers to the costs associated with *unplanned* maintenance interruptions. It includes the cost of lost production and the cost to perform emergency repair in the event of a forced outage.

Numerous definitions exist for risk. ISO 55000 defines risk as the "effect of uncertainty on objectives" (ISO, 2014*a*, pg 12) and qualifies this definition by noting the following:

> *Risk is often characterised by reference to potential events and consequences. Risk is often expressed in terms of a combination of the consequences of an event and the associated likelihood of occurrence.*

The aforestated notes are supported by numerous AM publications that preceded ISO 55000. Risk, for a particular failure scenario, is expressed numerically as the product of the probability of the failure and the consequences of the failure (API, 2002; Andrews and Moss, 2002; Jonkman *et al.*, 2003; Tan *et al.*, 2011). i.e.

$$\text{Risk} = P \times C \tag{4.3}$$

where P is the probability (or the likelihood) of component failure for a given time frame under given operating conditions and C denotes the cost of the consequences in the event of component failure.

Equation 4.3 expresses risk in terms of *expected losses.* According to Faber and Stewart (2003), this is consistent with the insurance industry where risk (or expected losses) can be presented, for example, in terms of EUROs, dollars, the number of human fatalities, etc. However, in the context of AM, risk is typically expressed as a number such as cost impact ($) per unit time (Khan and Haddara, 2003).

To calculate the RDC in the SMPF, Equation 4.3 is redefined as follows:

$$\text{RDC} = h(x) \times C_{conseq} \tag{4.4}$$

where $h(x)$ is the probability of component failure and C_{conseq} is the consequences of component failure. The determination of these two variables is explained next.

Probability of Component Failure

According to Jardine and Tsang (2006), the probability of event A occurring with the knowledge that B has occurred, is defined as *conditional probability* and may be written as $P(A|B) = h(x)\partial x$. Here, A is the event "failure occurs in interval ∂x" and B is the event "no failure has occurred up to time x". When $\partial x \to 0$, the instantaneous failure rate $h(x)$ becomes:

$$h(x) = \frac{f(x)}{1 - F(x)} \tag{4.5}$$

where $f(x)$ and $F(x)$ are the probability density function and the cumulative distribution function of the Weibull distribution respectively.

The Weibull distribution is the most popular method used to fit failure times to a distribution (Xie *et al.*, 2002; Yacout, 2010) and has been applied to various items in many different fields (Nakagawa, 2005). According to Abernethy (2002), the primary advantage of Weibull analysis, compared to other analysis techniques, is that it provides reasonably accurate failure analysis and forecasts with relatively small samples of data. Montgomery and Runger (2010) recommend using the Weibull distribution in reliability modelling owing to its flexibility. Dodson (2006) defines the probability density function for the Weibull distribution as:

$$f(x) = \frac{\beta}{\eta}\left(\frac{x}{\eta}\right)^{\beta-1} \times \exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right] \tag{4.6}$$

where $f(x)$ is the probability of component failure at instant x, continuous time is denoted by x, β is the shape parameter and η is the scale parameter of the distribution. Note that $x \geq 0$, $\beta > 0$ and $\eta > 0$.

The shape and scale parameter can be estimated analytically using estimation procedures such as Maximum Likelihood Estimation, Graphical procedure, Method of Moments and the Least Squares Method (see Nwobi and Ugomma (2014)). Each procedure has it merits, however Shin *et al.* (1996) and Vlok (2013) suggest using the Maximum Likelihood Estimation method. Both parameters can be obtained numerically by maximising the likelihood given by:

$$\ln L = \sum_{i=1}^{N}\left[\ln\frac{\beta}{\eta} + (\beta-1)\ln\frac{X_i}{\eta}\right] - \sum_{i=1}^{N}\left(\frac{X_i}{\eta}\right)^{\beta} \tag{4.7}$$

where N is the number of failures and X_i refers to the inter-arrival time between the component's $(i-1)^{th}$ and i^{th} failures.

Returning to Equation 4.6 and integrating $f(x)$ with respect to time (x) gives the probability of component failure *before* a certain instant x:

$$F(x) = 1 - \exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right] \tag{4.8}$$

The complement of $F(x)$ is $R(x)$, which is the probability of component survival up to a certain instant x, and is given by:

$$\begin{aligned} R(x) &= 1 - F(x) \\ &= \exp\left[-\left(\frac{x}{\eta}\right)^{\beta}\right] \end{aligned} \tag{4.9}$$

The ratio between Equations 4.6 and 4.9, $f(x) : R(x)$, yields the instantaneous failure rate of the component, which was introduced in Equation 4.5:

$$\begin{aligned} h(x) &= \frac{f(x)}{1 - F(x)} = \frac{f(x)}{R(x)} \\ &= \frac{\beta}{\eta}\left(\frac{x}{\eta}\right)^{\beta-1} \end{aligned} \tag{4.10}$$

Equation 4.10 denotes the *probability of impending failure* and the higher $h(x)$ for a component, the higher the probability of that component failing.

Consequences of Component Failure

The purpose of this consequence analysis is to quantify the potential costs of the failure scenario. According to Rausand (1998) and Wang *et al.* (2012), when the failure scenario occurs, the consequences cost is often judged on three key features, namely *personnel safety*, *environmental threat* and *economic loss.*

The consequences associated with certain failure scenarios can be catastrophic. For example, Cowing *et al.* (2004) state that accidents can result in catastrophic and unrecoverable failures with large financial, human, and environmental costs. Assigning financial costs to personnel health, loss of life and environmental damages is a sensitive issue. For this reason, the SMPF focuses solely on economic losses and assumes organisations are insured against personnel safety and environmental costs. Economic losses can be evaluated directly in terms of monetary value.

Krishnasamy *et al.* (2005) point out that a consequence analysis involves the estimation of production loss costs and maintenance costs. Hence, the consequences cost in terms of economic loss can be defined as:

$$\begin{aligned} C_{conseq} &= \text{Cost of lost production} + \text{Cost of component repair} \\ &= (\text{DT} \times \text{PL}) + (C_f + \text{DT} \times C_v) \end{aligned} \tag{4.11}$$

where DT is the downtime resulting from the failure, PL is the production loss per unit time, C_f is the fixed cost (e.g. spares) of the failure, and C_v refers to the variable cost (e.g. labour) per unit downtime to repair the failure.

It is important to take note that a component can suffer several different failure modes. Therefore, each failure mode may lead to different DT, C_f

and ultimately C_{conseq} values. Analysing the various failure modes, the one resulting in the largest C_{conseq} value is taken as the consequences cost.

RDC Before and After Maintenance Intervention

With the discussions on determining the probability of component failure $h(x)$ and the consequences cost of component failure C_{conseq} concluded, the focus can now return to the calculation of the RDC (see Equation 4.4).

Consider for example component ij which has an effective age A_{ij} at the start of a shutdown and is put forward for maintenance during the shutdown. The RDC before maintenance, RDC_{BM}, for this component is simply its probability of failure at its effective age, denoted $h(A_{ij})$, multiplied by its consequences cost C_{conseq}. As for the RDC after maintenance, RDC_{AM}, it is calculated in the same way, but at the component's effective age after maintenance t_{ij}. The consequences cost remains the same regardless of whether the failure incident occurs before or after the shutdown maintenance is performed. Therefore, in order to determine the RDC_{AM}, the work to follow describes how to calculate the component's effective age after maintenance t_{ij} and consequently its probability of failure $h(t_{ij})$ after maintenance.

Section 3.5 introduced the concept of imperfect maintenance and discussed the age reduction factor b_{ij} used to determine t_{ij}. The theory behind the age reduction factor and its formulation are thoroughly explored in the said section. The reader is encouraged to revisit Section 3.5 for a more detailed explanation and a better understand of this factor. For the sake of brevity, only the pertinent steps used to determine b_{ij} and consequently t_{ij}, $h(t_{ij})$ and RDC_{AM} are discussed next.

Returning to the considered component ij, the process starts by determining the component's Mean Residual Life (MRL). With the effective age before maintenance A_{ij} and the reliability R as a function of time (x) known, the component's MRL can be calculated using Equation 3.27.

$$\text{MRL} = \frac{\int_{A_{ij}}^{\infty} R(x)\mathrm{d}x}{R(A_{ij})} \tag{4.12}$$

Next, the ratio between the component's effective age before maintenance A_{ij} and MRL is used to determined whether the component is relatively young

($A_{ij} <$ MRL) or relatively old ($A_{ij} >$ MRL). This ratio is measured using the characteristic constant $m(A_{ij})$ defined in Equation 3.28:

$$m(A_{ij}) = \frac{A_{ij}}{\text{MRL}} \tag{4.13}$$

As discussed in Subsection 3.5.4, the underlying assumption here is that more money is needed for maintenance on a relatively older component, compared to a relatively younger component, in order to attain a similar improvement in their conditions.

During the shutdown, a discrete number of maintenance levels, $I_{ij} = [1, 2, \ldots, N_{ij}]$, can be performed on the component. If $I_{ij} = 0$, it means no maintenance is performed and if $I_{ij} = N_{ij}$, the component is replaced. Finally, $2 \leq I_{ij} \leq N_{ij} - 1$, refers to imperfect maintenance where any form of maintenance can be performed up to, but not including component replacement. Each maintenance level has an associated cost denoted by $C_{ij}(I_{ij})$. For a component in a failed state, denoted $Y_{ij} = 0$, the maintenance level $I_{ij} = 2$ refers to the maintenance necessary to restore the component to condition as bad as old with no further improvement in the component's condition. The associated cost in this case is referred to as the minimal repair cost C_{ij}^{MR}. For a component in a functioning state $Y_{ij} = 1$, there is no C_{ij}^{MR} and any maintenance level including $I_{ij} = 2$ will improve the component's condition. Finally, the replacement cost of the component is denoted by C_{ij}^{R}.

For a component in the failed state, where $Y_{ij} = 0$, the age reduction factor is calculated using Equation 3.29:

$$b(I_{ij}) = 1 - \left(\frac{C_{ij}(I_{ij}) - C_{ij}^{MR}}{C_{ij}^{R}} \right)^{m(A_{ij})} \tag{4.14}$$

whereas for a component in the functioning state, where $Y_{ij} = 1$, the age reduction factor is calculated without the minimal repair cost as follows:

$$b(I_{ij}) = 1 - \left(\frac{C_{ij}(I_{ij})}{C_{ij}^{R}} \right)^{m(A_{ij})} \tag{4.15}$$

The effective age after maintenance for component ij can subsequently be obtained using Equation 3.24:

$$t_{ij} = b_{ij} \times A_{ij} \tag{4.16}$$

Now that the effective age after maintenance t_{ij} is known, the probability of component failure after maintenance $h(t_{ij})$ for component ij can be determined with Equation 4.10:

$$h(t_{ij}) = \frac{\beta}{\eta}\left(\frac{t_{ij}}{\eta}\right)^{\beta-1} \tag{4.17}$$

Finally, the RDC_{BM} and RDC_{AM} can be calculated using Equations 4.18 and 4.19 respectively:

$$\text{RDC}_{MB} = h(A_{ij}) \times C_{conseq} \tag{4.18}$$

$$\text{RDC}_{AM} = h(t_{ij}) \times C_{conseq} \tag{4.19}$$

The difference between Equations 4.18 and 4.19 indicates the reduction in risk cost achieved for component ij when the MP is performed.

4.5.3 Resources Dimension Cost

The Resources Dimension Cost (ReDC) consists of all the *direct costs* incurred to perform the *planned* maintenance work. It is supported by the allocated budget which serves as upper limit on the amount of money that can be spent. According to El-Haram and Horner (2002), direct maintenance costs include labour, materials, spares, overheads such as equipment and tools. Al-Najjar and Alsyouf (2004) add that instruments, training, administration, other maintenance related expenses and services offered by the original equipment manufacturers or outsourcing can be added to the list of direct maintenance costs.

The second term in Equation 4.11 encompasses the direct maintenance costs in the event of a failure scenario. For planned maintenance actions, the direct maintenance costs can be calculated in the same way. Hence, in the SMPF, the ReDC is calculated as:

$$\text{ReDC} = C_f + \text{DT} \times C_v \tag{4.20}$$

where DT is the planned maintenance downtime, C_f and C_v denote the fixed and variable costs associated with the MP.

4.6 Step 5: Calculate Prioritisation Indices

The preceding section defined and outlined the calculations of the ODC, RDC and ReDC for the SMPF. This section builds on the previous section by formulating three maintenance prioritisation indices (MII, TI and BI) in terms of the aforestated decision dimension costs. These indices are similar to those introduced in Subsection 3.2.2, but modified in order to make them more applicable to the shutdown environment. Furthermore, these indices will be used as decision criteria to rank order the proposed MPs in the subsequent step (Section 4.7) of the SMPF. The following three subsections describe the formulation of each maintenance prioritisation index.

4.6.1 Maintenance Investment Index

The Maintenance Investment Index (MII) was defined in Equation 3.1 as the return maintenance provides relative to the cost incurred to perform the maintenance. In the SMPF, the MII is defined as:

$$\text{MII} = \frac{\text{RDC}_{BM} - \text{RDC}_{AM}}{\text{ODC} + \text{ReDC}} \tag{4.21}$$

where return is measured as the reduction in risk dimension cost achieved by performing the MP, i.e. the difference between Equations 4.18 and 4.19. The cost incurred to perform the MP includes both direct and indirect maintenance costs. Hence, the cost of lost production (ODC) and the cost of resources (ReDC) to perform the MP are added to give the total cost incurred to achieve the return. Equation 4.21 therefore denotes the *return on investment* of a particular MP.

4.6.2 Time Index

The Time Index (TI) is a reflection of how long it takes to complete a MP with regards to the time available to perform it. In the SMPF, the TI in Equation 3.2 is redefined as:

$$\text{TI} = \frac{\text{MPDT}}{\text{AST} - \text{TF}} \tag{4.22}$$

where MPDT is the downtime associated with completing the MP and AST denotes the time available to complete the MP. The Time Factor (TF) is introduced in the SMPF in order to make provision for possible scope changes during the shutdown. In other words, the purpose of the TF is to set aside time for unplanned maintenance work that may arise during the shutdown, such as the discovery of a hidden failure. For example, disassembling a pump for planned repairs on the impeller and discovering a worn-out seal which needs immediate replacement.

The TF can be a specific amount of time or a percentage of the AST and should be determined by an organisation's shutdown expert. This expert should have a reasonable idea of how much time needs to be set aside for the unplanned maintenance work of a specific asset and its shutdown. The TF can also be based on the shutdown history of that particular asset and whether the durations of its shutdowns generally exceed the AST.

4.6.3 Budget Index

The Budget Index (BI) indicates the portion of the Shutdown Budget (SB) that will be consumed by the MP. Equation 3.3 is redefined in the SMPF to give the following formulation of the Budget Index (BI):

$$\mathrm{BI} = \frac{\mathrm{ReDC}}{\mathrm{SB} - \mathrm{BF}} \tag{4.23}$$

where SB is the maintenance budget made available for the forthcoming shutdown. Similar to the TF, the Budget Factor (BF) makes a provision for possible scope changes during the shutdown. Its purpose is to set aside funds for the discovery of hidden failures or unplanned maintenance work. The BF can be a specific monetary value or a percentage of the SB and should also be determined by an organisation's shutdown expert.

4.7 Step 6: Rank Prioritisation Indices

This section ranks-orders the proposed MPs using the maintenance prioritisation indices described in the section before. It was shown in Section 3.4 that the ranking of the MPs relate to a MCDA problem, which can be expressed as a decision matrix similar to Table 3.4. In the SMPF, the MPs denote the alternatives and the maintenance prioritisation indices denote the criteria by which the MPs are evaluated as a MCDA problem. That is to say, alternative $A_1 = \mathrm{MP1}$, $A_2 = \mathrm{MP2}$, $\ldots$, $A_m = \mathrm{MP}_m$ for m number of alternatives. Since there are only $n = 3$ criteria, criterion $C_1 = \mathrm{MII}$, $C_2 = \mathrm{TI}$ and $C_3 = \mathrm{BI}$.

Unlike the TPMPF, the SMPF is more flexible in that is does not assume that all three indices are equally important and therefore have the same weighting. Organisations facing challenging deadlines or cash flow issues may deem the TI or BI to carry more weight respectively. Similarly, should time and budget constraints not be that pressing, the emphasis, and therefore the weighting, of the MII may be greater. The weightings corresponding to the n number of criteria are given by weighting $w_1 = w_{\text{MII}}$, $w_2 = w_{\text{TI}}$ and $w_3 = w_{\text{BI}}$. The sum of the weighting of these three weightings equals unity.

Section 3.4 investigated four MCDA methods, namely, the additive value function, multiplicative value function, ELECTRE II and PROMETHEE II. Each method was thoroughly examined and supplemented with a worked example for better understanding. For this reason, the procedural steps for each method will not be repeated in this section.

Four MCDA methods might appear excessive, however there are good reasons for this. According to Kangas *et al.* (2001), in many strategic planning problems there is no precise measure to select a correct method. Moreover, Zanakis *et al.* (1998) suggest that in such situations it is reasonable to examine different methods, which usually yield different solutions, before making a final decision. Furthermore, Section 3.4 identified the ranking of MPs as an *evaluation* problem where decision makers analyse a finite set of predetermined alternatives. The favoured methods to solve these problems were highlighted as *goal* (additive and multiplicative value functions) and *outranking* (ELECTRE II and PROMETHEE II) methods. Goal methods output cardinal numbers, which showcase the degree to which one alternative is preferred to the other, e.g. a rank value of 1 is twice as good as a rank value of 2. On the other hand, outranking methods output ordinal numbers which orders alternatives without any degree of preference, i.e. 1^{st}, 2^{nd}, ..., etc. For example, it is not possible to say whether or not the 1^{st} ranked alternative is twice as good as the 2^{nd} ranked alternative.

Although four MCDA methods are presented, not all of them need to be employed. The additive value function is the most widely used MCDA method (Botti and Peypoch, 2013) owing to its simplicity (Sen *et al.*, 2015) and proven record of providing robust and effective support to decision makers (Dodgson *et al.*, 1999). For this reason it is suggested to be used first. It rank orders the MPs in addition to giving the degree of preference of the MPs. To supplement the additive value function, it is suggested the PROMETHEE II be used. The reason being it is easy to use (Velasquez and Hester, 2013). With both a goal and outranking method implemented, a decision can be made. However, should these two methods not with corroborate each other, the decision maker can then consult the multiplicative value function and ELECTRE II method.

4.8 Step 7: Present Recommendation

Leading from the previous section, the decision maker can choose how many of the four MCDA methods to implement. A comparative analysis of the ranking results of each method can assist the decision maker in this regard. Figure 4.3 shows a comparative analysis of the haul truck selection problem in Subsection 3.4.1. It can be seen that all four methods coincide that haul trucks A_3 and A_4 are the best and second-best ranked alternatives.

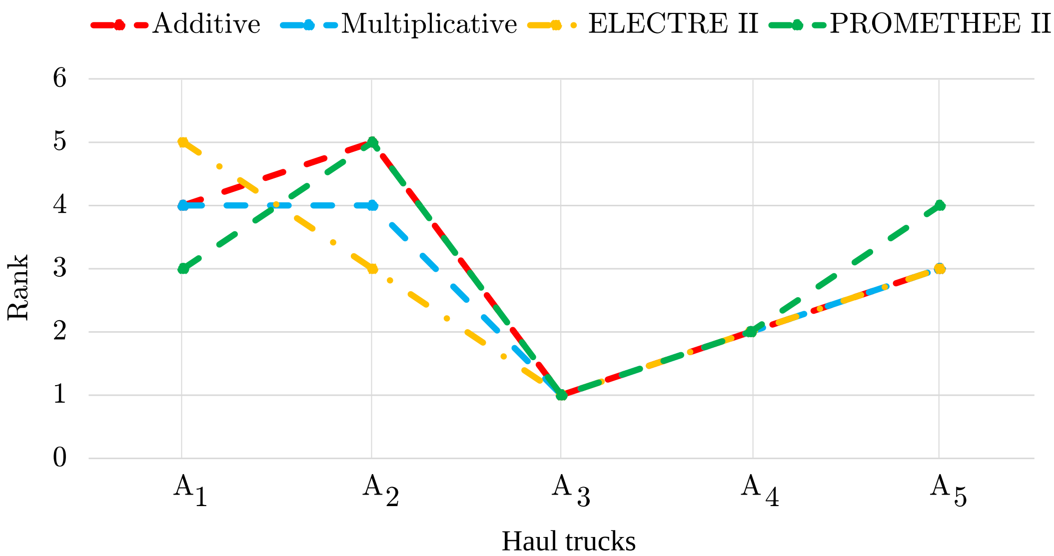


Figure 4.3: Comparative ranking analysis of four MCDA methods for the haul truck selection problem

As with the haul truck selection problem, a comparative analysis can help determine the top ranked MPs to perform during the forthcoming shutdown. Before selecting the top ranked MP, a summary table such as the illustrative example in Table 4.2 should be set up. The table shows important information to consider such as the time and budget remaining after the MP has been performed. Take for example the top ranked MP, MP5, after it is performed 11 hours and ZAR70,000 will remain. Should the organisation seek to start operating as soon as possible and use as little of the SB as possible, this MP would be the ideal selection relative to the other top ranked MPs.

Table 4.2: Summary of the top five ranked MPs for the forthcoming shutdown

MP rank	MP#	AST left (in hrs)	SB left (in ZAR)	ODC (in ZAR)	ReDC (in ZAR)	RDC_{AM} (in ZAR)	Total cost (in ZAR)
1	5	11	70,000	0	100,000	483,578	583,578
2	2	7	100,000	0	70,000	557,235	627,235
3	25	−2	0	40,000	170,000	409.642	619,642
4	1	3	60,000	0	110,000	519,911	629,911
5	12	−14	−10,000	340,00	180,000	440,393	960,393

On the other hand, if the shutdown duration is fixed and the SB non-transferable to the next shutdown, MP25 may be considered the better option. Although ranked as 3rd best, it fully utilises the SB and the AST. In fact it causes two additional hours of shutdown at an ODC of ZAR40,000. Should the organisation not want to incur any ODC, the decision maker can return to the top ranked MP and simply add maintenance tasks to utilise the remaining time and budget.

If the decision maker finds a satisfactory MP to the organisation's particular shutdown need in Table 4.2, the MP is selected and put forward as the maintenance plan for the forthcoming shutdown. However, another option for the decision maker is to perform a scenario and/or sensitivity analysis before committing to a particular MP.

Scenario/Sensitivity Analysis

A scenario analysis, according to Firer *et al.* (2012), can be thought of as a basic *what-if* analysis. In a scenario analysis, different what-if questions are asked and consequently variables are altered to see how the results are affected by the changes. A sensitivity analysis, on the other hand, freezes all the variables except for one. This means a sensitivity analysis is useful in pinpointing the variables that have a significant impact on the results. Depending on what the decision maker is trying to achieve, both analyses can be useful.

Table 4.1 illustrated the SMPF variables. Each variable can change and may therefore impact the results. Both analyses start by populating the variables with expected values. This is known as performing the *base case*. Next, the variable(s) are altered in order to analyse the *optimistic* and *pessimistic* cases. Take note that these cases do not refer to the "best" and "worst" cases respectively. The best and worse cases can be extremely unlikely and may lead to misleading results. Even though the number of possible scenarios are endless, the decision maker should strive for realistic and probable variable values when performing the optimistic and pessimistic cases. The reason for only having three cases is to avoid what is known as *analysis paralysis*. This is when an abundance of information inhibits the ability to gain valuable knowledge from the analysis and subsequently make good decisions.

Once the scenario and/or sensitivity analysis is concluded, the selected MP for the forthcoming shutdown is confirmed and then performed.

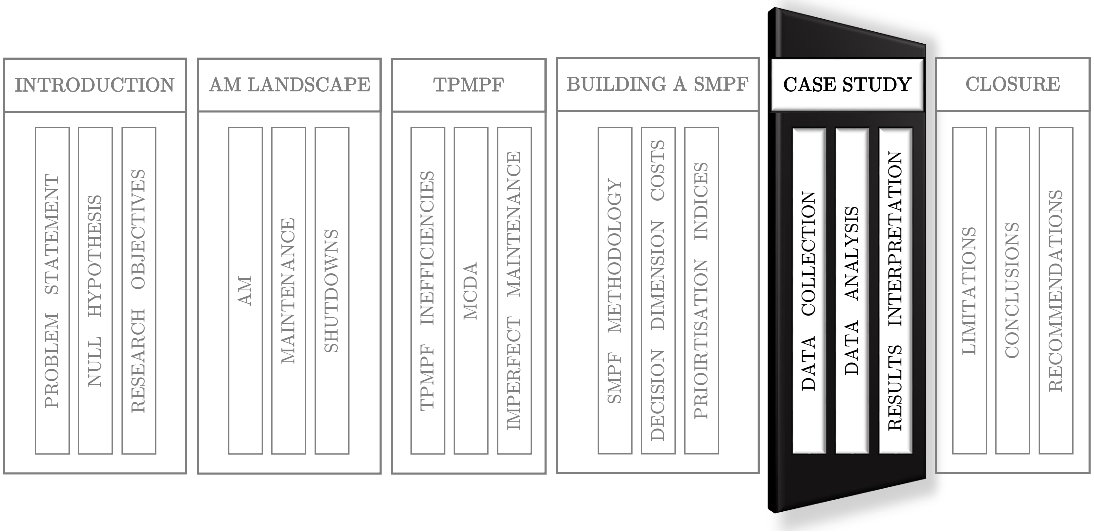
4.9 Chapter 4 Concluding Remarks

In this chapter the SMPF application methodology was proposed to satisfy the requirements of the problem statement in Section 1.2. The development of the SMPF was supported by a thorough literature analysis presented in Chapters 2 and 3. The SMPF was broken up into seven distinctive steps and each step was thoroughly explained in a separate section of this chapter. The aim of the SMPF was to provide a new approach to prioritise the maintenance work of a critical asset for an impending shutdown. Unique features in the SMPF include a value based approach, which considers limited maintenance resources in prioritising the maintenance work, as well as the incorporation of beneficial features from both MCDA and imperfect maintenance fields.

The proceeding chapter, Chapter 5, will apply the SMPF application methodology in a case study with the aim of assessing the validity of the framework.

Chapter 5

Case Study



Chapter Aims:

Chapter 5 comprises of a case study conducted at a South African thermal coal mine in cooperation with Anglo Coal South Africa. The aim of this chapter is to validate the proposed SMPF application methodology in Chapter 4 by applying it to a real world problem. An overview of the case study is presented along with discussions on the data collection and analysis processes. The results are interpreted and used as basis for the conclusions drawn in Chapter 6.

Chapter Outcomes:

⇒ Introduction to case study environment.
⇒ Demarcation of the system analysed.
⇒ Validation of case study results.

5.1 Introduction to the Case Study

This chapter aims to validate the SMPF, developed in Chapter 4, by applying it to the South African mining industry. More specifically, this case study is implemented on a critical asset, called a dragline, at an open-pit thermal coal mine. Several factors prompted the selection of a case study with this particular demographic.

Firstly, the South African coal mining industry is plagued by the gloomy current financial climate depicted in Chapter 1. Fin24 (2015) reports that "South Africa lost out on ZAR23 billion in coal export revenues last year [2014] due to a drop in prices for the commodity". According to Mathews (2015), the price of South African coal exports plummeted from \$170 to \$66 per tonne between late 2008 and the end of 2014. On the local front, Eskom's recent implementation of rolling blackouts have further disrupted the productivity of many coal mines (Mdluli, 2015). Therefore, in order to survive in these tough financial times, South African coal mines must seek to operate as efficiently and effectively as possible .

Secondly, a thermal coal mine is a prime example of an asset-intensive organisation where its revenue and therefore survival depends on the utilisation of its assets. In order to effectively utilise their assets, these coal mines must ensure their assets are appropriately managed, maintained and shut down (as discussed in Chapter 2). These inherently difficult tasks become even harder when they are insufficiently financed. Mathews (2015) reveals that "weak coal prices and uncertainty about when they will strengthen has deterred investment in big projects". An example of a big project at a coal mine is the shutdown of a critical asset such as a dragline. These shutdowns are notoriously expensive yet vital endeavours, which is why organisations often look to perform the most critical maintenance tasks during one of these shutdowns.

The SMPF offers a possible solution to determining which critical maintenance tasks to perform during a dragline shutdown, given the constraints that apply. This case study therefore evaluates the adequacy of the SMPF by applying it to a real world situation. The previous two paragraphs provided a broad, but brief, contextualisation of the case study and the following subsections will further elaborate on this. By the end of this section, the case study will be fully contextualised and succeeded by the SMPF application process.

5.1.1 Anglo Coal South Africa

Anglo American is a public limited company (plc) with its headquarters situated in London, United Kingdom. It is a major producer of copper, diamonds, iron ore, manganese, nickel, niobium, phosphates, platinum, metallurgical coal (for steel manufacturing) and thermal coal (for electricity generation). In addition to being diversified, it is a multinational mining company which operates in Asia, Australia, Europe, North and South America as well as southern Africa.

A subdivision of Anglo American plc is Anglo Coal South Africa (ACSA), which fully owns and operates seven thermal coal mines in South Africa. In 2014, ACSA produced 37.6Mt of coal, of which 59% was used for domestic power generation and 18.2Mt was supplied to the export market (Anglo American, 2015). Anglo American plc funded the research in this thesis and arranged that the case study be conducted at one of ACSA's mines.

5.1.2 Open-pit Mine

With the support of ACSA, the case study was conducted at an open-pit thermal coal mine in the northern part of South Africa. Owing to the sensitive nature of some of the data obtained for this case study, the mine requested to remain anonymous. Thus, for confidentiality reasons, the mine will consistently be referred to as Open-pit Mine (OP Mine) for the remainder of this thesis. Furthermore, whether the mine supplies the domestic or export market with coal will not be disclosed.

Coal mining can be classified as either being an underground or surface mining practice (Kashyap *et al.*, 2014). The former involves tunnelling into the earth in order to extract coal seams, whereas the latter burrows into the earth's exterior. Moreover, the latter is commonly referred to as being an open-pit/open-cast mine and this surface mining practice is used when the layers of coal seams lie relatively close to ground level. OP Mine is an example of such a mine and its mining process is summarised in Figure 5.1.

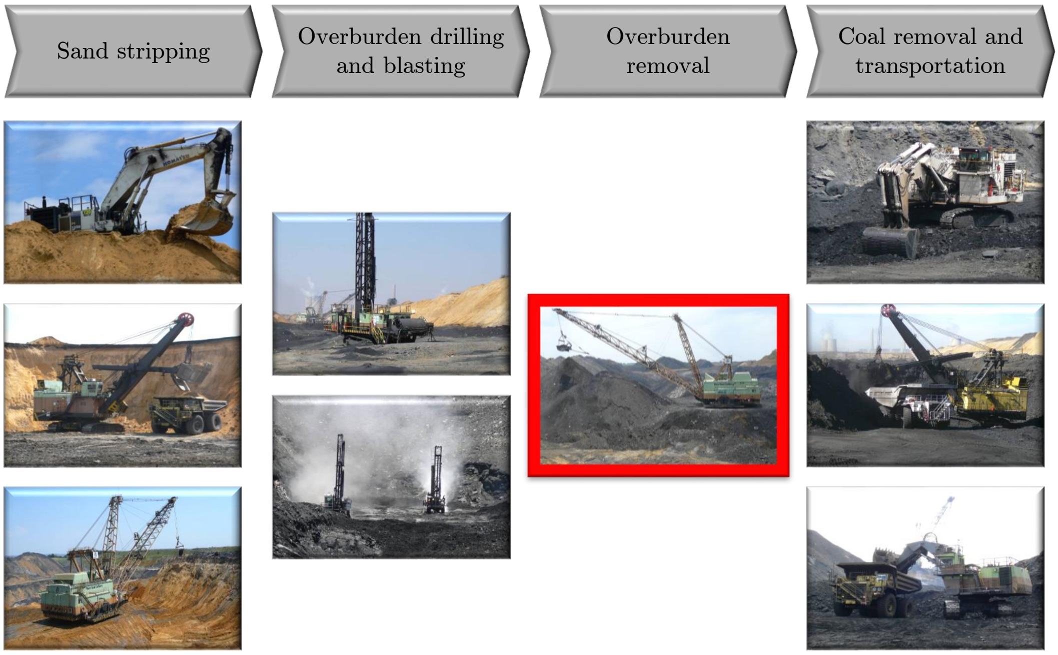


Figure 5.1: Mining process at OP Mine

Images courtesy of OP Mine

The mining process at OP Mine starts by identifying the area of land that needs to be excavated in order to expose the desired seam of coal. The sand or top layer of soil is stripped away using rope shovels, back actor shovels, track dozers and occasionally draglines. Haul trucks are then used to transport the stripped sand away. Removing the sand exposes what is called the overburden, which is a generally a layer of clay, pebble bed, sandstone and/or siltstone. Next, drilling machines drill into the overburden and explosives are inserted and detonated. The overburden is then removed using a dragline, as emphasised in Figure 5.1, to uncover the seam of coal. If the exposed coal is too hard to penetrate and remove, the drilling and blasting sequence is repeated. Finally, the coal is removed by the aforementioned shovels and transported using the same haul trucks.

5.1.2.1 Draglines at Open-pit Mine

OP Mine owns and operates three draglines and they are referred to as Dragline-A (DL-A), Dragline-B (DL-B) and Dragline-C (DL-C) for the purposes of this case study. These draglines were acquired from the supplier Bucyrus Erie and commissioned in 1983, 1985 and 1987 respectively. Each dragline is a BE 1570W model and its primary duty, as mentioned in the previous subsection, is the removal of overburden. A schematic view of the main subsystems of the draglines at OP Mine are illustrated in Figure 5.2.

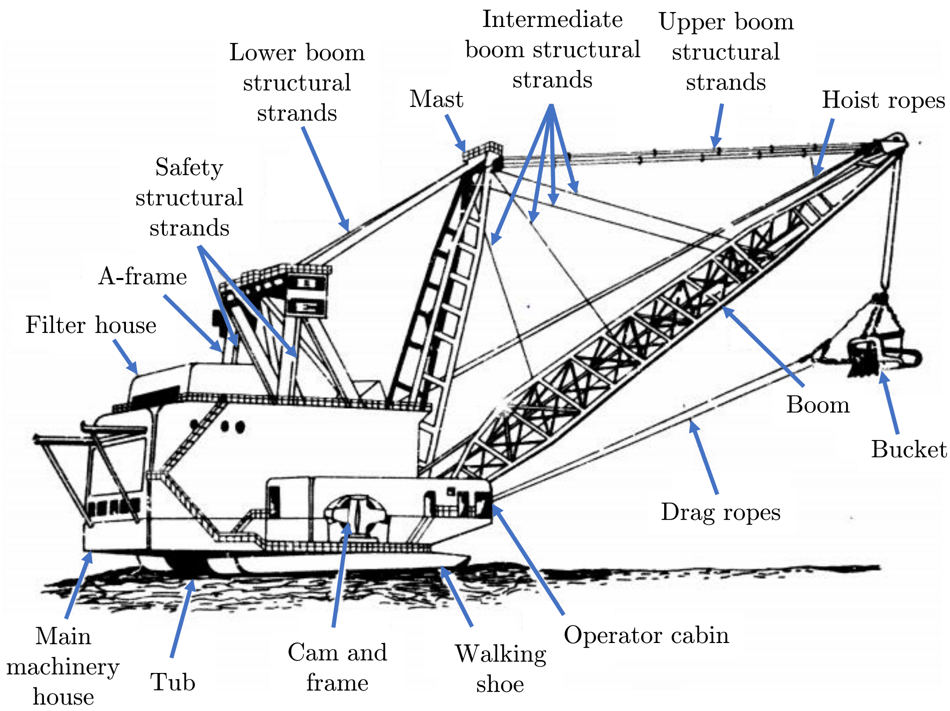


Figure 5.2: Bucyrus Erie 1570W walking dragline

Adopted from Jones (2007)

Draglines consist of a rotating assembly, a tub and two walking shoes (Winstanley *et al.*, 1999). At OP Mine, the rotating assembly comprises of the main machinery house (which lodges swinging, propelling and hoisting motors as well the operator's cabin), a 97.5m boom and a 56m^3 capacity bucket. This rotating assembly can swivel an overburden filled bucket weighing up to 168 tonnes from one side to another in a single movement. The main machinery house rotates on a large diameter ring gear situated beneath the house and on top of the tub. The tub rests firmly on the ground until it is dragged forward by two eccentrically driven walking shoes beside it. This dragging motion enables the dragline to move forward and gives it the appearance of walking.

Williams (2005) states that aside from coal treatment plants, draglines are the largest pieces of machinery at coal mines and consequently carry significant operational and maintenance costs. At OP Mine, one of the biggest maintenance costs associated with their draglines is the full shutdown of each dragline, which is scheduled every 12 to 18 months. The following section discusses the current shutdown practice at OP Mine and focuses in particular on the recently completed shutdown of DL-B, shown in Figure 5.3.

Figure 5.3: Dragline-B in operation at OP Mine

Image courtesy of OP Mine

5.1.2.2 Current Dragline Shutdown Practice at Open-pit Mine

A key reason for conducting the case study at OP Mine is the fact that it has a resident Shutdown Foreman. Unlike the majority of the other thermal coal mines, OP Mine has someone who's primary responsibility is to focus on the shutdowns that occur at the mine in order to ensure they are properly planned and executed. This indicates how serious OP Mine is about its shutdowns and how dedicated it is to deriving maximum value from each shutdown.

Visiting OP Mine and interacting with the Shutdown Foreman and other key role players[1] at the mine revealed that the largest, most stressful, complex and expensive shutdowns are those executed on the draglines. The personnel at OP Mine endorsed the claim made by Williams (2005) that "for most mines which use draglines, the dragline is the central focus of productivity". In fact, they often refer to the draglines as the "lifeblood" or "heart and soul" of the mine. Thus, it is imperative to OP Mine that these draglines undergo shut-

[1]Reliability Engineer, Maintenance Planning Officer, Sub-assembly Controller, Dragline Foreman and the Dragline, Reticulation, Boiler Making and Rigging Engineer.

downs that are appropriately planned and properly executed.

The shutdown practice for all three draglines at OP Mine are identical and for convenience DL-B (see Figure 5.3) is used as the example to describe this practice. Once a month, DL-B is shut down to perform what is called a "search and find mission". During this mission, which usually lasts between 9 to 12 hours, the dragline is inspected and serviced as part of a continuous risk elimination exercise. Risks are identified and fixed immediately, if possible, or noted as work for the following mission. However, if the risk is not severe at present and will it require significant resources to remedy, its work can even be postponed until the next dragline shutdown.

As mentioned in the previous sub-subsection, DL-B undergoes a full shutdown every 12 to 18 months. During this major shutdown, DL-B is taken out of service for weeks at a time, typically between two to four weeks depending on the amount of work scheduled. A dragline shutdown site, similar to the example given in Figure 5.4, is mobilised on-site at OP Mine in the days leading up to the shutdown. After the site is mobilised and all pre-shutdown preparations are made, the shutdown commences.

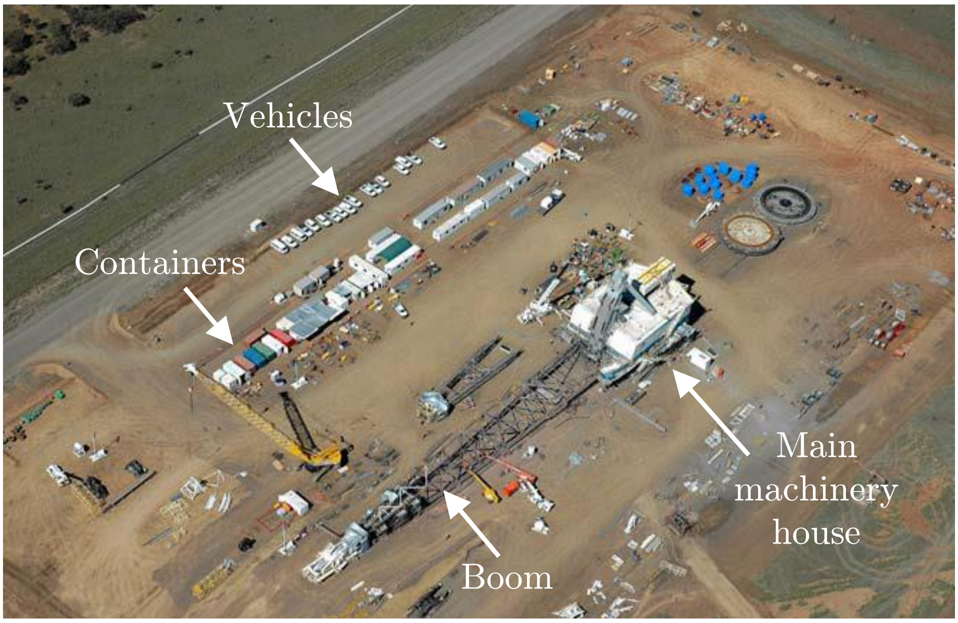
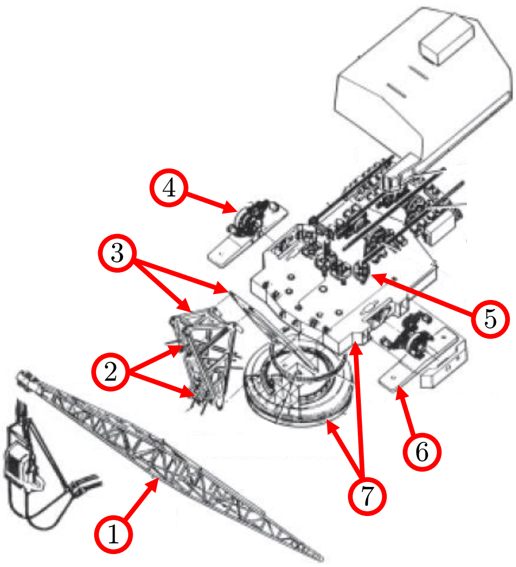


Figure 5.4: Aerial view of a dragline shutdown site

Adopted from Jones (2007)

Figure 5.4 helps put into perspective the enormity of a dragline shutdown. What is more, it gives an indication of the logistical support necessary for such a massive endeavour. Unsurprisingly, these shutdown sites quickly turn into beehives of activity owing to the amount of work scheduled relative to the time available to complete the work. OP Mine does not have sufficient manpower nor the expertise, in some instances e.g. rigging, to complete all the scheduled shutdown work. Hence, a contractor specialising in dragline shutdowns is employed to execute the shutdown, which is then closely monitored by OP Mine.

The logistical issues surrounding the shutdown of a dragline mean the scope of work must be determined and fixed (called scope freezing) well in advance. Take for example DL-B, which is the most recent dragline at OP Mine to undergo a shutdown. This shutdown was scheduled from the 8th of June until the 3rd of July 2015, however its scope of work had been frozen six months prior (December 2014). In December, OP Mine and its contractor discussed this scope of work and the contractor was requested to submit a formal quotation. The quotation was received and further negotiations ensued concerning the projected shutdown times and costs. A second quotation was received, accepted and the scope of work was consequently frozen. The frozen scope of work for DL-B is given in Table 5.1 and relates to the subsystems indicated in Figure 5.5.



1. Boom
2. Fairleads
3. Mast & A-frame
4. Propel machinery
5. Swing machinery
6. Walking shoes
7. Tub & Revolving frame

Figure 5.5: Dragline-B subsystems in shutdown scope of work

Adapted from Bucyrus (2002)

Table 5.1: Dragline-B shutdown scope of work

Subsystem	Shutdown work description
Boom	Boom lowering and raising - rigging work
	Boom lowering and raising operation
	Boom upper immediate deflection tower
	Boom lower immediate deflection tower
	Boom miscellaneous repairs
	Boom handrail and walkway repairs
	Boom point assembly
	C-chord repairs
Mast & A-frame	Mast deflection tower repairs
	Mast & A-frame miscellaneous structural, walkway and handrail repairs
Swing machinery	Swing No 1 gear case repairs
	Swing No 2 gear case repairs
	Swing No 3 gear case repairs
	Swing No 4 gear case repairs
Propel machinery	Left-hand propel brake assembly repairs
	Left-hand cam bush replacement
	Right-hand propel brake assembly repairs
	Right-hand cam bush replacement
Walking shoes	Remove both shoes, turn place on steel stands and replace iron angles on both shoes.
Fairleads	Horizontal fairlead repairs
	Vertical fairlead repairs
Tub & Revolving frame	Tub crack and guide roller repairs. Replace cracked swing rail SS clamps and tub liners.

Scope of work courtesy of OP Mine

The approved quotation for the shutdown scope of work in Table 5.1 revealed direct contractor labour costs in excess of ZAR2.1 million. Maintenance consumables (e.g. welding rods and spares) and the equipment and tools (e.g. scaffolding towers and boom stands) necessary to execute the shutdown work were quoted as approximately ZAR700 and ZAR670 thousand respectively. Other expenses such as the shutdown site mobilisation and demobilisation as well as the accommodation, living-out allowances and transportation to the shutdown site for the contractor teams increased the final quotation close to a total of ZAR8.7 million. The projected time-line for the scheduled shutdown of DL-B from the 8th of June to the 3rd of July 2015 is shown in Figure 5.6.

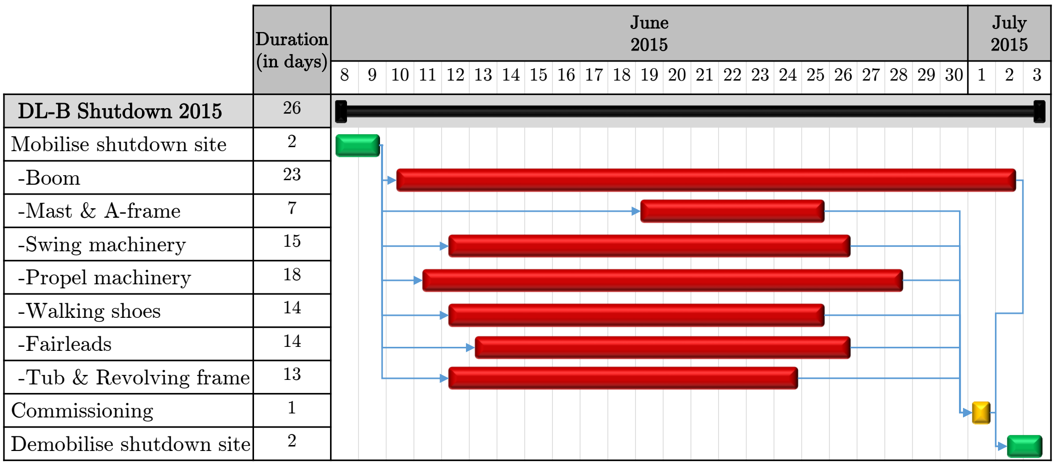


Figure 5.6: Dragline-B recently completed shutdown schedule

Schedule courtesy of OP Mine

5.1.3 Deviation from Initial Case Study Plan

The initial case study plan upon arriving at OP Mine was to prioritise the shutdown maintenance tasks of a critical asset, such as those shown in Figure 5.1, *before* its next scheduled shutdown. Rope shovels and haul trucks were seriously considered owing to the abundance of available shutdown data. However, OP Mine believed it would derive more value from the case study if the SMPF were to be applied to its most important, stressful and expensive shutdowns, namely those concerning its draglines. Unfortunately, there were no imminent dragline shutdowns to which the SMPF could be applied.

DL-B had already completed its shutdown about a month ago, as discussed in the preceding subsection, and DL-A was about to undergo its scheduled shutdown. DL-A had been taken out of service a few days prior and its shutdown site was almost fully mobilised. Moreover, its scope of work had already been frozen and the personnel at OP Mine, involved with the shutdown, were extremely busy putting the final pre-shutdown preparations in place. DL-C, on the other hand, had been earmarked for a shutdown sometime in April/May

2016. The date had not yet been confirmed as it was more than six months ahead of time, hence the discussions between OP Mine and its contractor had not yet been initiated.

Interactions with OP Mine's key role players revealed fears that the current financial climate and weak coal prices may inhibit the procurement of sufficient funds and/or downtime for the forthcoming shutdown on DL-C in 2016. What is more, these role players were intrigued by the scenario analysis capability of the SMPF (see Section 4.8) and wanted to put it to the test. Hence, OP Mine suggested using the SMPF as tool to evaluate different shutdown scenarios it feared. OP Mine wanted to analyse how each scenario affects what maintenance should be performed during the shutdown and thus remain flexible to the possibility of an underfunded or even shortened shutdown for DL-C. The three scenarios proposed by OP Mine are given in Table 5.2.

Table 5.2: Case study scenarios considered

Scenario	Available shutdown time	Shutdown budget
Budget case	Remains the same	Decreases by 10%
Time case	Decreases by 5 days	Remains the same
Pessimistic case	Decreases by 5 days	Decreases by 10%

To OP Mine, it is important to understand the impacts of different posited scenarios such as those detailed in Table 5.2. It helps the mine stay informed and puts it in a stronger negotiating position with its contractor six month prior to a dragline shutdown. What is more, an analysis of the different scenarios adds some objectivity to the negotiation table, which is often brimming with the different opinions of the various parties involved.

5.1.4 Case Study Delimitations

As discussed in the preceding subsection, the initial case study plan had to be altered as there were no imminent dragline shutdowns at OP Mine. Thus, the SMPF will no longer be used to prioritise numerous MPs before an impending shutdown in order to reveal a subset of critical maintenance tasks to perform during the shutdown. Rather the subset of maintenance tasks are known upfront and through an evaluation of the different scenarios, this subset is prioritised and recommendations are made. This enforced simplification does not affect the validation functionality of the framework as the same process will be applied, just at a deeper level. Thus a more in-depth analysis is possible.

The SMPF and the scenarios in Table 5.2 are applied to the shutdown data of DL-B as it is the most recent and relevant dragline shutdown data available at OP Mine. The case study will therefore put itself in the shoes of OP Mine in December 2014 when it was discussing and freezing the DL-B shutdown scope of work with its contractor. Moreover, the case study will only use the data that was available to OP Mine at the time, namely the proposed scope of work (Table 5.1), projected shutdown time-line (Figure 5.6) and its internally recorded sub-assembly information.

By applying the case study to DL-B's shutdown data and assessing the results, OP Mine aims to determine whether the SMPF can add value to its forthcoming negotiations with its contractor regarding DL-C. With the case study now fully contextualised, the succeeding section describes how the SMPF was implemented on the shutdown data of DL-B.

5.2 SMPF Application

The procedural steps of the SMPF (see Figure 4.1, but also repeated on the next page for convenience) mean the framework is rather straightforward to apply in the form of a case study. Moving sequentially through these seven steps, the following subsections describe the application of each step as well as the data used and the results obtained.

5.2.1 Step 1: Identify System and Sub-assemblies of Interest

The first step of the SMPF, as discussed in Section 4.2, is to identify the critical system and its component of interest. Sub-subsections 5.1.2.1 and 5.1.2.2 were devoted to contextualising the system of interest for this case study, which is a BE 1570W walking dragline called DL-B at OP Mine (see Figure 5.3). Owing to the sheer size and complexity of the system as well as the granularity of the available shutdown data, DL-B could not be analysed at component level. The available shutdown data was recorded at subsystem and sub-assembly levels, hence the system is analysed at sub-assembly level. A breakdown of the system, its subsystems and sub-assemblies of interest are detailed in Table 5.3.

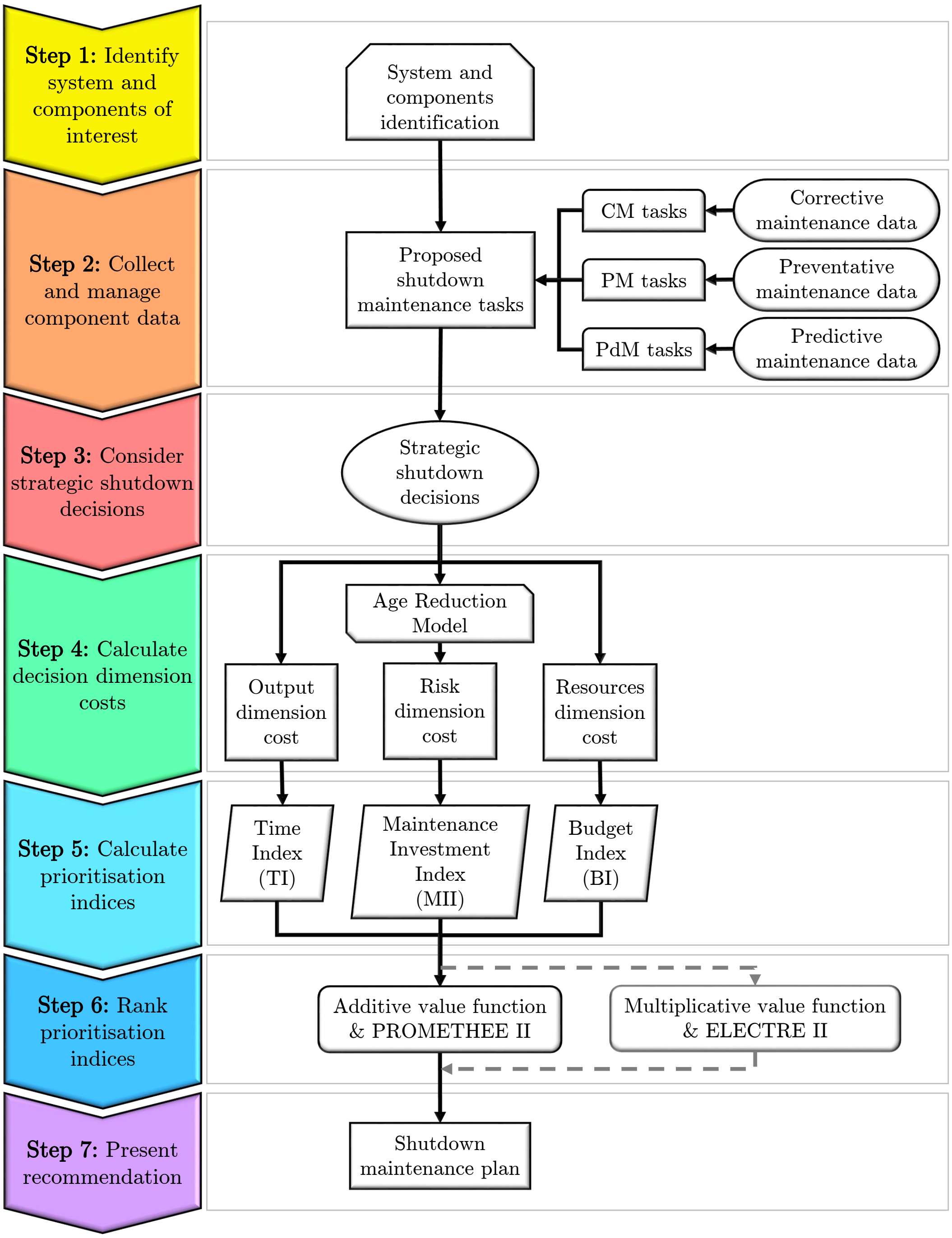


Table 5.3: Case study system, subsystems and sub-assemblies of interest

System	Subsystem	Sub-assembly
Dragline-B	Boom	Upper immediate deflection tower: sheave assembly
		Lower immediate deflection tower: sheave assembly
		Point assembly: sheave swivel assembly
		C-chord
	Mast	Mast deflection tower: sheave assembly
	Swing machinery	Swing No 1 gear case
		Swing No 2 gear case
		Swing No 3 gear case
		Swing No 4 gear case
	Propel machinery	Right-hand propel: brake assembly
		Left-hand propel: brake assembly
	Walking shoes	Right-hand walking shoe
		Left-hand walking shoe
	Fairleads	Horizontal fairlead: sheave assembly
		Vertical fairlead: sheave assembly
	Tub	Guide rollers

The breakdown of the system of interest is obtained from the scope of work in Table 5.1, however the following maintenance work in the original scope of work is removed from further analysis:

1. Boom miscellaneous repairs;
2. Mast & A-frame miscellaneous structural, walkway and handrail repairs;
3. Left-hand and right-hand propel bush replacements; and
4. Revolving frame cracked swing rail SS clamp and tub liner replacements.

Insufficient detail regarding the maintenance work performed (hence the recurrence of "miscellaneous"), its cost and the time taken to complete it are reasons for removing the work from further analysis. These details are necessary for implementing the remaining steps of the SMPF.

5.2.2 Step 2: Collect and Manage Sub-assembly Data

The second step of the SMPF concerns the collection and management of all the pertinent sub-assembly data needed to implement the succeeding steps of the framework. Table 4.1 provided a summary of all the necessary data and where that data is typically recorded. Since DL-B is analysed at a sub-assembly level, the resident Sub-assembly Controller at OP Mine was able to provide the effective age before maintenance, replacement cost and lead time of each sub-assembly shown in Table 5.3. The fixed and variable maintenance costs were taken from the accepted contractor quotation in December 2014 and the determination of the consequences cost is described in Subsection 5.2.4.

The Maintenance Planners in charge of managing the failure histories of the dragline sub-assemblies were occupied with the current shutdown on DL-A and could not supply the sub-assembly failure data of DL-B upon request. An internal ACSA report containing the Weibull distribution shape (β) and scale (η) parameter values of major dragline sub-assemblies at all seven thermal coal mines, including OP Mine, was consulted to populate Table 5.4. This January 2014 report contained OP Mine dragline sub-assembly information from 30-01-1989 until 27-11-2013. This meant the β and η values were outdated by about 18 months. However, none of the sub-assemblies were replaced in that time and the assumption was made that these parameters did not change significantly in the 18 months relative to the almost 25 years that preceded it.

Using the sub-assembly information detailed in Table 5.4, seven MPs are formulated where each MP relates to a particular subsystem of DL-B. The MP downtime, fixed and variable cost values in Table 5.5 are not just the cumulative value of the sub-assemblies that reside in each subsystem. Take for example the mast subsystem, an additional 144 hours of downtime and ZAR114, 999 of contractor labour cost are added since the boom has to be lowered and raised before and after maintenance is performed on the mast. This extra downtime and cost relating to the boom lowering and raising operations will be incurred even if no maintenance were to be performed on the boom itself.

Table 5.4: Dragline-B sub-assembly information

Sub-assembly	Effective age (in hrs)	Lead time (in hrs)	Fixed maintenance cost (in ZAR)	Variable maintenance cost (in ZAR)	Replacement cost (in ZAR)	Consequences cost (in ZAR)	β Weibull dist.	η Weibull dist.
Upper immediate deflection tower: sheave assembly	50,224	1,344	7,389	14,264	1,200,750	243,120,750	1.5	40,187
Lower immediate deflection tower: sheave assembly	52,377	1,344	7,389	14,264	1,200,750	243,120,750	1.075	40,321
Point assembly: Sheave swivel assembly	70,771	1,344	33,632	64,921	1,200,750	243,120,750	1.726	66,462
C-chord	91,771	1,848	179,640	346,767	4,750,000	337,390,000	1.59	89,928
Mast deflection tower: sheave assembly	43,638	1,344	7,389	14,264	1,200,750	243,120,750	1.191	33,793
Swing No 1 gear case	62,019	1,008	21,236	40,992	2,040,600	183,480,600	1.358	66,706
Swing No 2 gear case	62,019	1,008	21,236	40,992	2,040,600	183,480,600	1.358	66,706
Swing No 3 gear case	62,019	1,008	21,236	40,992	2,040,600	183,480,600	1.358	66,706
Swing No 4 gear case	62,019	1,008	21,236	40,992	2,040,600	183,480,600	1.358	66,706
Right-hand propel: brake assembly	59,453	336	67,017	129,365	210,000	60,690,000	1.291	47,009
Left-hand propel: brake assembly	59,453	336	67,017	129,365	210,000	60,690,000	1.291	47,009
Right-hand walking shoe	131,528	1,344	34,179	65,978	2,240,000	244,160,000	1.59	89,928
Left-hand walking shoe	131,528	1,344	34,179	65,978	2,240,000	244,160,000	1.59	89,928
Horizontal fairlead: sheave assembly	40,182	1,344	27,641	53,357	3,100,000	245,020,000	1.153	32,473
Vertical fairlead: sheave assembly	42,093	1,344	33,911	65,460	3,100,000	245,020,000	1.175	45,609
Guide rollers	48,568	672	113,819	219,710	850,000	121,810,000	1.216	31,607

Table 5.5: Proposed Dragline-B subsystem maintenance packages

Maintenance Package	Subsystem	Downtime (in hrs)	Fixed cost (in ZAR)	Variable cost (in ZAR)
MP1	Boom	456	228,050	555,215
MP2	Mast	312	7,389	129,263
MP3	Swing machinery	360	84,942	163,968
MP4	Propel machinery	216	134,033	258,730
MP5	Walking shoes	336	68,359	131,956
MP6	Fairleads	336	61,552	118,817
MP7	Tub	288	113,819	219,710

The seven MPs relating to a particular subsystem of DL-B in Table 5.5 are used to create different combinations of possible MPs that can be performed during the shutdown. Therefore, any combination of one, two, three, four, five or six MPs in addition to all seven can be performed on DL-B and are therefore a possible combination. That means in total a $\sum_{n=0}^{7} \text{MP}_n^7 = 127$ possible MP combinations can be performed on DL-B. Table 5.6 shows a selected few of these MP combinations in order to give an overall impression of the entire list of combinations.

Take note that the fixed and variable costs in Table 5.6 are the cumulative values of their constituent MP values in Table 5.5. However, this is not the case for the downtimes and there is an exception for the variable costs. Figure 5.6 illustrates how shutdown maintenance work is performed concurrently on the various subsystems of DL-B. Therefore, performing MP1 and MP2 incurs downtimes of 456 and 312 hours respectively, however performing MP12 will not incur 768 (= 456+312) hours of downtime. Instead, it will incur 456 hours as both MPs can be performed simultaneously. What is more, the shutdown schedule in Figure 5.6 is amended owing to the maintenance work (e.g. Boom handrails and walkway repairs) which was not considered for further analysis, as discussed at the end of Subsection 5.2.1. Figure 5.7 shows, using the boom subsystem as example, how removing this miscellaneous work shortened the shutdown downtime associated with the boom subsystem. The exception is the earlier mentioned additional boom operation expense of ZAR114, 999 which is subtracted once from MPs containing a '1' and '2' as the aforestated cost was added to the variable cost of both MP1 and MP2 already.

Table 5.6: Combinations of Dragline-B maintenance packages

Maintenance Package	Downtime (in hrs)	Fixed cost (in ZAR)	Variable cost (in ZAR)
MP1	456	228,050	555,215
MP2	312	7,389	129,263
⋮	⋮	⋮	⋮
MP12	456	235,440	569,479
MP13	456	312,993	733,447
⋮	⋮	⋮	⋮
MP123	456	320,382	848,446
MP124	456	369,473	828,209
⋮	⋮	⋮	⋮
MP1234	456	454,415	992,177
MP1235	456	388,741	865,403
⋮	⋮	⋮	⋮
MP12345	456	522,774	1,124,133
MP12346	456	515,967	1,110,994
⋮	⋮	⋮	⋮
MP123456	456	584,326	1,242,950
MP123457	456	636,593	1,343,843
⋮	⋮	⋮	⋮
MP1234567	456	698,145	1,577,659

With all 127 possible MPs now formulated, the following subsection describes the strategic shutdown decisions that apply to the shutdown of DL-B.

5.2.3 Step 3: Consider Strategic Shutdown Decisions

The third step of the SMPF is the consideration of the strategic decisions made by top management that influence the selection of which MP to perform during the shutdown of DL-B. OP Mine calculated the PL per unit time for

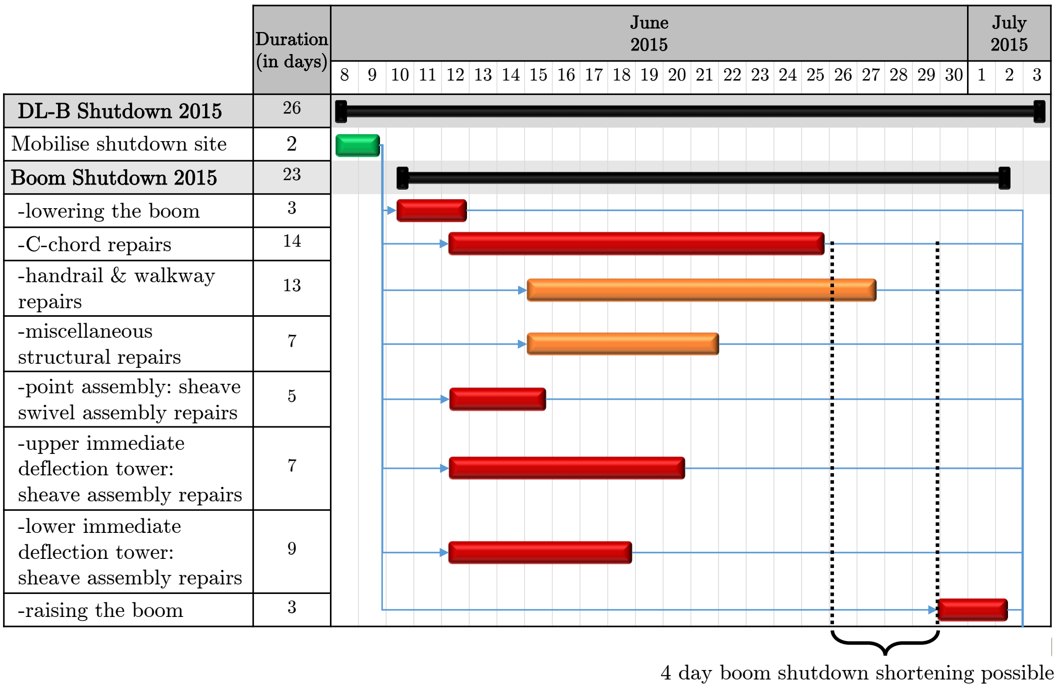


Figure 5.7: Dragline-B boom subsystem shutdown schedule shortening

DL-B at ZAR180,000 per hour. The AST and SB are taken as 23 days (552 hours) and ZAR2,160,805 respectively. These values are selected as base case values as they allow all seven subsystem to be performed during the shutdown (i.e. performing MP1234567). Other expenses that are not directly related to the shutdown maintenance work (e.g. contractor accommodation) are not considered. Furthermore, OP Mine was comfortable with a TF and BF of 24 hours (an extra day to commission DL-B) and 5% of the SB. These values may appear conservative, but the reason for this is that OP Mine recalled the scope of work and shutdown schedule had contingent time and funds worked into it "here and there". Therefore, in line with the case study scenarios proposed in Table 5.2, the strategic shutdown decisions for DL-B are defined in Table 5.7.

5.2.4 Step 4: Calculate Decision Dimension Costs

The fourth step of the SMPF involves the calculation of the decision dimension costs of all 127 formulated MPs in Table 5.6. Following the procedure outlined in Section 4.5, this subsection explains using examples the calculation of the ODC, RDC and ReDC for each MP. This procedure is completed for all three scenarios considered in the case study.

Table 5.7: Strategic shutdown decisions for scenarios considered

Scenario	Available shutdown time (in hrs)	Shutdown budget (in ZAR)
Budget case	552	$2,160,805 - 10\%$ $= 1,944,725$
Time case	$552 - 120$ $= 432$	$2,160,805$
Pessimistic case	$552 - 120$ $= 432$	$2,160,805 - 10\%$ $= 1,944,725$

Output Dimension Cost

The ODC equals zero for all the MPs in the budget case scenario since each MPDT is smaller than the AST. However, the MPDTs may be greater than the AST and incur an ODC for the other two scenarios. Using the time case scenario and MP12 as example, the ODC_{12} incurred equals:

$$\text{ODC}_{12} = (456 - 432) \times 180,000 = 4,320,000$$

Risk Dimension Cost

Calculating the RDC_{BM} and RDC_{AM} for each MP starts by determining the instantaneous failure rate before maintenance $h(x)$ and the consequences cost C_{conseq} of each sub-assembly in that MP. Using the sub-assembly information in Table 5.4 and taking the boom point assembly as example, the failure history curves of this DL-B sub-assembly can be determined and illustrated as shown in Figures 5.8 to 5.11. This instantaneous failure rate before maintenance is calculated directly as follows:

$$h(x) = \frac{1.726}{66,462}\left(\frac{70,771}{66,462}\right)^{1.726-1} = 2.718\text{E-05}$$

Similarly, the consequences cost of the boom point assembly uses the sub-assembly data in Table 5.4 in addition to the PL per unit time amount in order to determine C_{conseq}, which is equal to:

$$C_{conseq} = (1344 \times 180{,}000) + (33,632 + 64,921) = 243,120,750$$

The RDC_{BM} of the boom point assembly is equal to the product of its instantaneous failure rate before maintenance and its consequences cost.

$$\text{RDC}_{BM} = 2.718\text{E-05} \times 243,120,750 = 6,608$$

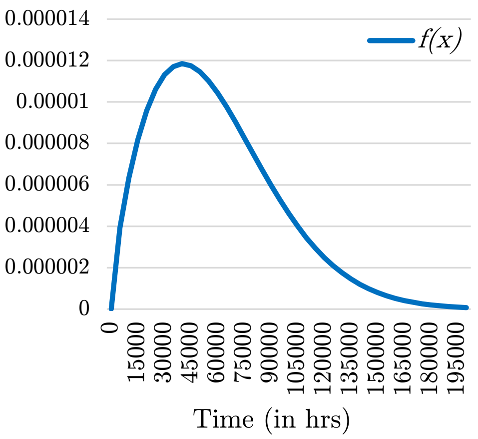


Figure 5.8: Probability density function curve of boom point assembly

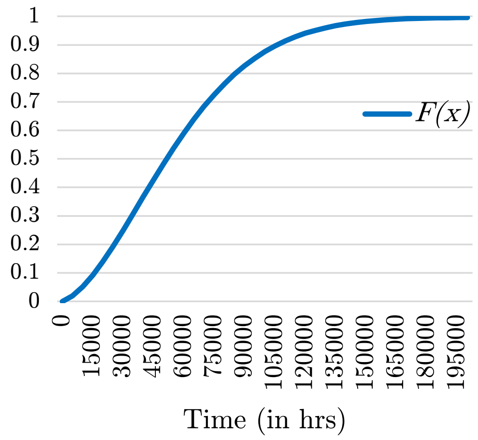


Figure 5.9: Cumulative probability density function curve of boom point assembly

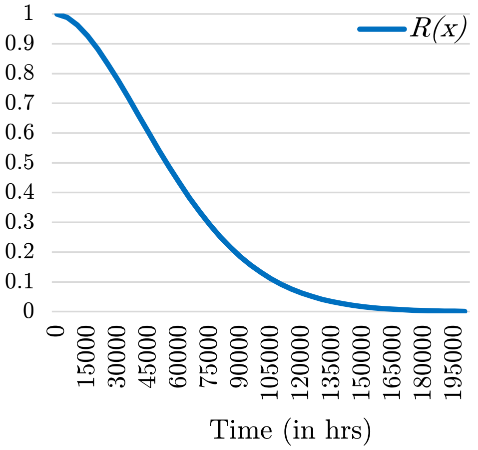


Figure 5.10: Reliability function curve of boom point assembly

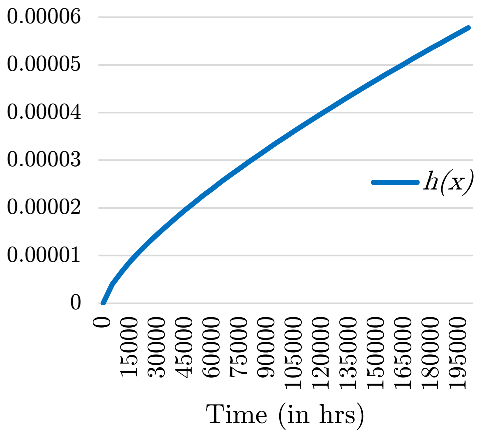


Figure 5.11: Instantaneous failure rate curve of boom point assembly

With the RDC_{BM} known, the RDC_{AM} for the boom point assembly is determined next. First, its MRL is computed as follows:

$$\text{MRL} = \frac{\int_{70,771}^{\infty} R(x)\mathrm{d}x}{R(70,771)} = \frac{9,690}{0.328} = 29,536$$

This MRL value is less than its effective age before maintenance, which indicates the sub-assembly is relatively old. The ratio between its effective age before maintenance and its MRL gives the characteristic constant of the sub-assembly.

$$m(70,771) = \frac{70,771}{29,536} = 2.396$$

Since the point assembly is in a function state before the shutdown, there is no minimal repair cost to consider and the age reduction factor of the boom point assembly is calculated as:

$$b = 1 - \left(\frac{98,553}{1,200,750}\right)^{2.396} = 0.9975$$

Multiplying this age reduction factor with its effective age before maintenance gives rise to its effective age after maintenance:

$$t = 0.9975 \times 70,771 = 70,594$$

Subsequently, the instantaneous failure rate after maintenance for the sub-assembly is calculated as follows:

$$h(70,594) = \frac{1.726}{66,462}\left(\frac{70,594}{66,462}\right)^{1.726-1} = 3.130\text{E-06}$$

Finally, the RDC_{AM} for the boom point assembly is as the product of its instantaneous failure rate after maintenance and its consequences cost.

$$\text{RDC}_{AM} = 3.130\text{E-06} \times 243,120,750 = 761$$

To get the RDC_{BM} or RDC_{AM} from a sub-assembly to a MP level, the RDC values of the sub-assemblies in that particular MP are added together.

Resources Dimension Cost

The ReDC for each MP is simply the total of the fixed and variables costs (with the aforementioned exception of MPs with a '1' and '2' in it) of the sub-assemblies or MPs that make up that particular MP. Using Table 5.5 and MP34 as example, the ReDC_{34} is equal to:

$$\text{ReDC}_{34} = 84,942 + 163,968 + 134,033 + 258,730 = 641,673$$

5.2.5 Step 5: Calculate Prioritisation Indices

The fifth step of the SMPF comprises of the calculation of three maintenance prioritisation indices, namely the MII, TI and BI. As formulated in Section 4.6, these indices are calculated using the three decision dimension costs described in the previous subsection. Table 5.8 displays a selected few of the prioritisation indices determined for the pessimistic case scenario.

Table 5.8: Dragline-B maintenance prioritisation indices for pessimistic case scenario

Maintenance Package	MII	TI	BI
MP1	3.84E-03	1.118	0.424
MP2	2.50E-02	0.765	0.074
⋮	⋮	⋮	⋮
MP12	0.004	1.118	0.436
MP13	0.005	1.118	0.559
⋮	⋮	⋮	⋮
MP123	0.006	1.118	0.570
MP124	0.005	1.118	0.648
⋮	⋮	⋮	⋮
MP1234	0.006	1.118	0.783
MP1235	0.008	1.118	0.679
⋮	⋮	⋮	⋮
MP12345	0.007	1.118	0.891
MP12346	0.007	1.118	0.881
⋮	⋮	⋮	⋮
MP123456	0.008	1.118	0.989
MP123457	0.007	1.118	1.072
⋮	⋮	⋮	⋮
MP1234567	0.008	1.118	1.170

5.2.6 Step 6: Rank Prioritisation Indices

The sixth step of the SMPF is concerned with the rank ordering of the MPs in Table 5.8. Following the procedure described in Section 4.7, these MPs are ranked using the four MCDA methods discussed in Subsections 3.4.2 and 3.4.3. The additive and multiplicative value measurement functions as well as the ELECTRE II and PROMETHEE II methods use the maintenance prioritisation indices as criteria to rank order the MPs. The weights assigned to each prioritisation index are given in Table 5.9. These weightings were kept the same in order to compare the results of the SMPF with that of the TPMPF.

Table 5.9: Case study prioritisation index weightings

	w_{MII}	w_{TI}	w_{BI}
weighting	0.333	0.333	0.333

5.2.7 Step 7: Present Recommendation

The seventh step of the SMPF follows from Section 4.8 and is the presentation of the MP ranking results determined in the previous subsection. The findings of the different MCDA methods for each of the case study scenarios considered are presented and discussed. It is important that the reader be reminded that MCDA methods do not guarantee the "right answer" or "optimal solution" to each and every problem (Belton and Stewart, 2002). Also, MCDA methods do not relieve the decision maker of carrying out difficult judgements and therefore remove the "difficulty" or "pain" of the decision-making process (Rangel *et al.*, 2009). Hence, the results presented in Sub-subsections 5.2.7.1 to 5.2.7.4 are interpreted and discussed in order to determine the answer/solution that best suits the particular needs or objectives of DL-B and OP Mine.

5.2.7.1 Scenario Analysis: Base Case

Before proceeding to the three case study scenarios defined in Table 5.2, a base case scenario is presented in order to provide some additional perspective. The base case scenario is set up so that all seven DL-B subsystems can be performed during the dragline shutdown. In other words, MP1234567 can be completed on schedule and within budget. Thus, using the values defined in Subsection 5.2.3, the SB and AST are equal to ZAR$2,160,805$ and 552 hours respectively. As for the TF and BF, they are taken as zero for this case. The results of the comparative ranking analysis for the base case scenario are shown in Figure 5.12. Only the top six ranked MPs for each MCDA method are shown in this figure.

The results indicate that all four MCDA methods are in agreement that MP123457 is the best MP to be perform on DL-B during its shutdown. However, the TPMPF disagrees and advocates MP1234567. The difference between the two MPs is the exclusion of MP6, which is the maintenance done on the Fairleads subsystem. Table 5.10 decomposes these two proposed MPs in or-

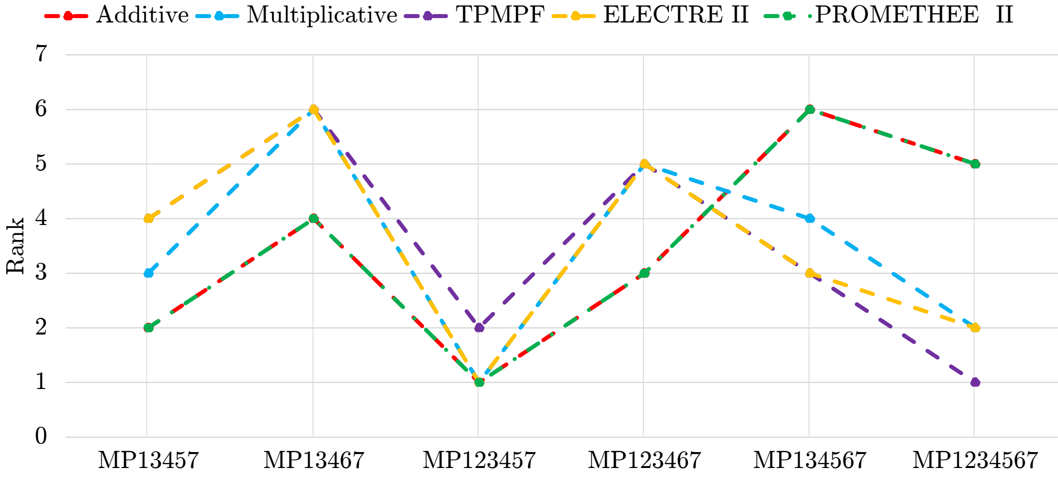


Figure 5.12: Base case scenario comparative ranking analysis

der to ascertain which is more suitable to the objectives of OP Mine for this scenario and therefore the better option.

Table 5.10: Base case scenario maintenance package composition

Maintenance Package	AST left (in hrs)	SB left (in ZAR)	MII	TI	BI
MP123457	96	180, 369	0.023	0.826	0.917
MP1234567	96	0	0.023	0.826	1.000

Both MPs, if performed, would finish within the AST. In fact, both would finish exactly 96 hours ahead of time and for that reason, they share the same TI value. Moreover, these MPs share the same MII value, which indicates that both give the same return relative to the amount of resources invested in each. Thus, with identical TI and MII values, the deciding factor is the BI. MP123457 consumes a smaller portion of the SB as opposed to MP1234567, which depletes it completely. Thus, for the same relative return and consumption of time, MP123457 is the better option for OP Mine as it uses ZAR180, 369 less of the SB.

The MP selected by the TPMPF is therefore not the best MP to perform for this particular base case scenario. It can be performed should OP Mine wish to expend the entire SB, however it would bring no additional benefit relative to the extra money it will cost to perform the MP.

5.2.7.2 Scenario Analysis: Budget Case

For the budget case scenario, the SB is reduced by 10% to ZAR1, 944, 725 as shown in Table 5.7 and the AST remains unchanged from the base case scenario at 552 hours. The TF is taken as 24 hours and the BF equals ZAR97, 236 which equates to 10% of the SB (as discussed in Subsection 5.2.3). Figure 5.13 shows the results of the comparative ranking analysis for the budget case scenario. Again, only the top six ranked MPs that can be supported by the AST and SB are illustrated in the figure.

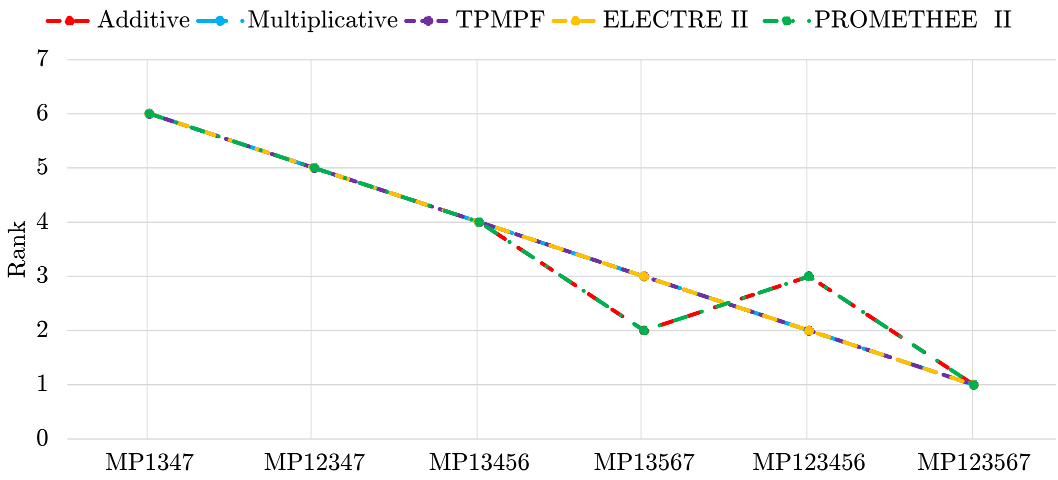


Figure 5.13: Budget case scenario comparative ranking analysis

The four MCDA methods and the TPMPF concur that MP123567 should be performed on DL-B during its shutdown. Should this, for whatever reason, not be possible, then the next best ranked MP should be considered. The second best MP to perform is MP123456 according to the TPMPF, ELECTRE II and multiplicative value function, whereas PROMETHEE II and the additive value function endorse MP134567. In order to analyse the three MPs in this sub-subsection, Table 5.11 provides a breakdown of each MP.

All three MPs in Table 5.11 have the same AST remaining and therefore identical TI values. This means time does not influence the budget case scenario as expected, rather the influencing factors are the return of each MP relative to the amount of funds invested into it. All the methods agree that MP123567 is the best MP to perform owing to its superior MII. Even though it consumes a slightly larger portion of the SB compared to MP134567, it makes

Table 5.11: Budget case scenario maintenance package composition

Maintenance Package	AST left (in hrs)	SB left (in ZAR)	MII	TI	BI
MP13567	96	101,100	0.026	0.864	0.945
MP123456	96	20,212	0.027	0.864	0.989
MP123567	96	79,446	0.028	0.864	0.957

better use of these extra funds as vindicated by its greater return.

As for the second best MP to perform, two MPs are put forward. The additive value function and PROMETHEE II prefer MP13567, whereas the other three methods make the case for MP123456. Again, looking at Table 5.11, the answer depends on the preference of the decision maker, which in this case is OP Mine. MP13567 uses less of the SB, but also provides an inferior return. On the contrary, MP123456 consumes more of the SB but delivers a greater return whilst falling within the allocated SB. Hence, with the SB procured and available for DL-B, OP Mine should aim to achieve the greatest return possible from the shutdown and perform MP123456. Thus, MP123456 should be the second choice MP for this particular scenario.

5.2.7.3 Scenario Analysis: Time Case

The SB is equal to ZAR2,160,805 for the time case scenario, however its AST is reduced by 120 hours (five days) to 432 hours (see Table 5.7). What is more, the TF and BF equal 24 hours and ZAR108,040 respectively. The results of the comparative rankings analysis for the time case scenario is depicted in Figure 5.14. It should be noted that these top six ranked MPs all exceed the AST by 24 hours. These MPs were kept in contention as the TF could cancel this excess time if the shutdown execution stays on schedule throughout. However, for the sake of argument, the analysis continues as if OP Mine would allow a MP which overruns the AST by a maximum of 24 hours.

The best MP to perform for this scenario is MP123457 according to the TPMPF and ELECTRE II, while the other three MCDA methods argue the case for MP124567. Similar to the previous scenarios, a deconstruction of these two proposed MPs, as shown in Table 5.12, helps determine which MP suits

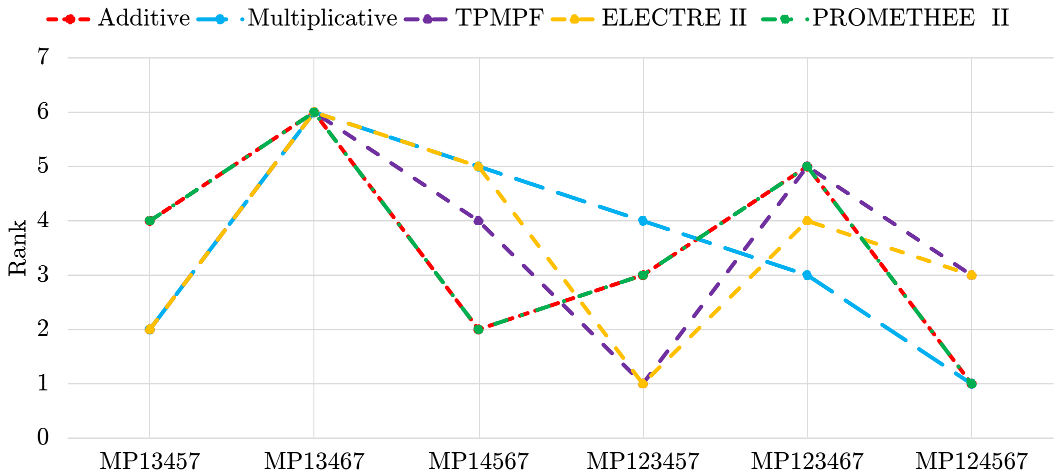


Figure 5.14: Time case scenario comparative ranking analysis

the needs of DL-B and OP Mine the best for this particular scenario.

Table 5.12: Time case scenario maintenance package composition

Maintenance Package	AST left (in hrs)	SB left (in ZAR)	MII	TI	BI
MP123457	−24	72, 329	0.007	1.118	0.965
MP124567	−24	140, 870	0.007	1.118	0.931

Both MPs in Table 5.12 consume the same amount of time and therefore have an identical TI. What is more, their MII values are equal to each other, which means they both deliver the same return relative to the amount of resources invested in each. The difference between the two MPs can be seen by the BI values where MP124567 consumes a smaller portion of the SB for the same return. Hence, with these MPs identical in terms of their returns and time consumption, the logical choice for OP Mine would be to choose the cheaper MP to perform. Therefore, the MP proposed by PROMETHEE II as well as the additive and multiplicative value function is selected as best MP to perform for this time case scenario.

5.2.7.4 Scenario Analysis: Pessimistic Case

The pessimistic case scenario is a combination of the budget and time constraints of the previous two scenarios. Here, the SB is reduced by 10% to

ZAR1, 944, 725 and the AST shortened by 120 hours to 432 hours. As for the TF and BF, they equal ZAR97, 236 and 24 hours respectively. The top six ranked MPs of the comparative ranking analysis is presented in Figure 5.15.

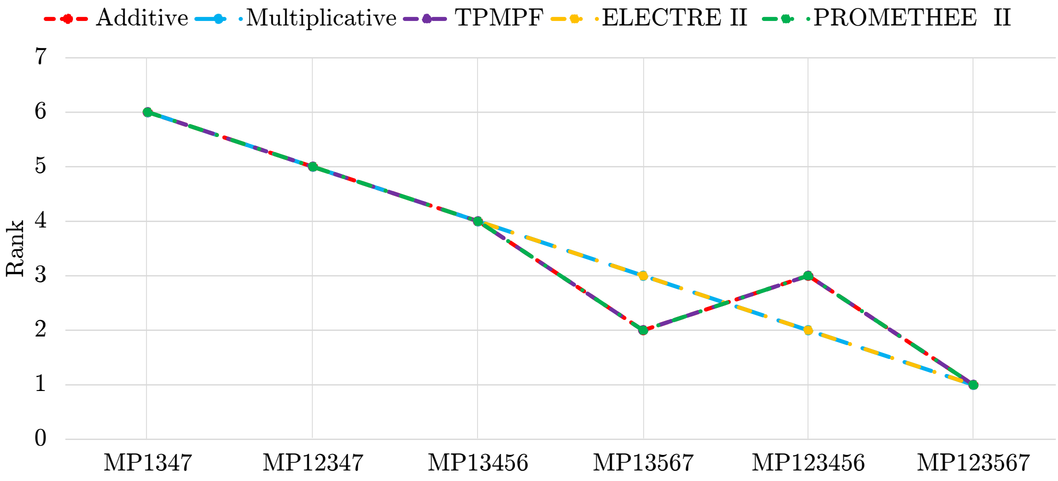


Figure 5.15: Pessimistic case comparative ranking analysis

The results indicate that the best MP to perform is MP123567 as all five methods consulted agree that OP Mine should select and perform this MP on DL-B during its shutdown. As for the next best MP, the TPMPF, additive value function and PROMETHEE II advocate MP13567, while the other two MCDA methods suggest MP123456. Again, these MPs were broken down as shown in Table 5.13 and analysed.

Table 5.13: Pessimistic case maintenance package composition

Maintenance Package	AST left (in hrs)	SB left (in ZAR)	MII	TI	BI
MP13567	-24	101, 100	0.007	1.118	0.945
MP123456	-24	20, 212	0.008	1.118	0.989
MP123567	-24	79, 446	0.008	1.118	0.957

MP123567 has the joint highest MII, however it achieves this return with a smaller portion of the SB compared to MP123456 and is therefore the best MP in this scenario. Between MP13567 and MP123456, it is a case of the latter depleting more of the budget but providing a better return. Thus, with the SB for DL-B allocated and available, OP Mine should perform MP123456 as its second choice MP in order to derive maximum value from the shutdown.

5.3 Results Discussion

The section before detailed the application of the SMPF on the shutdown data of DL-B at OP Mine. Three proposed case study scenarios, in addition to a base case scenario, were considered and the results of each were presented and interpreted in Sub-subsections 5.2.7.1 to 5.2.7.4. This section serves as an overall discussion of these results and the SMPF application process itself.

As repeated in the final step of the SMPF, MCDA methods do not guarantee correct answers nor do they alleviate the decision maker's responsibility in the decision making process itself. The results of the MCDA methods in the SMPF were generally in agreement, however differences between the methods could be analysed and were easily interpreted in order to determine which alternative (MP) best suited the objectives of the decision maker (OP Mine). What is more, the results of the different scenarios appear to make logical sense when compared to the base case scenario.

For example, the base case scenario advocates that MP123457 be performed and the budget case scenario suggests performing MP123567. The difference between these two scenarios is the removal of MP4 and the insertion of MP6 from the base to the budget case scenario. Looking at Table 5.14 and remembering that the SB of the budget case is 10% less than that of the base case, it therefore makes sense that MP4 with its higher BI is replaced with MP6. Although MP6 has an inferior MII and TI, its significantly smaller BI enables MP123567 to fit into the reduced SB and still be OP Mine's best option for the budget case scenario.

Table 5.14: Selected base case scenario prioritisation indices

Maintenance Package	MII	TI	BI
MP4	5.07E-03	0.391	0.182
MP6	2.74E-02	0.609	0.083

It should also be noted that the general agreement among the MCDA models, as well as with the TPMPF, can also be attributed to the small number of MPs used in the case study and the nature of these MPs. A single MP was formulated for each of the seven DL-B subsystems considered, which meant there were only 127 combinations of possible MPs. If 12, 15 or 20 MPs were formulated, the number of MP combinations would have been 4,096, 32,768 and 1,048,576 respectively. Hence, the number of MP combinations increases twofold with each additional MP that is formulated. Furthermore, the durations of the MPs were generally in excess of two weeks (see Figure 5.6), which meant it was often obvious which MP would be discarded if the AST were reduced. To conclude, it is expected that the rankings of the MCDA models and the TPMPF would have deviated more had there been a greater number of MPs in the case study and had these MPs consisted of prioritisation indices with similar values.

The formulation of a single MP for each subsystem of DL-B was also a positive aspect of the case study as it accurately reflected the reality of dragline shutdowns at OP Mine. Figure 5.7 shows the shutdown schedule of the DL-B boom sub-assembly. Different contractor teams concurrently perform maintenance on this and other sub-assemblies of DL-B during a single shutdown. With the logistical challenges concerning the dismantling of the dragline itself and organising the contractors teams for a particular shutdown, it makes sense to complete all the maintenance work of a major subsystem in a single dragline shutdown rather than over multiple shutdowns. Thus, formulating the MPs at sub-assembly level rather than sub-system level would have been impractical for OP Mine.

5.4 Validation of the SMPF

The purpose of this section is to validate or ascertain whether the SMPF has any value both theoretically and practically. The SMPF is built on the foundation of a thorough literature base and incorporates leading work from various fields such as AM, maintenance, shutdowns, imperfect maintenance and MCDA. What is more, it is the continuation of the promising work done by Tam and Price (2008*b*). The need for a framework such as the SMPF is supported by literature which calls for asset-intensive organisations to direct their maintenance efforts towards achieving their strategic goals more efficiently and effectively, especially in this gloomy current financial climate.

Anglo American plc and OP Mine provided the opportunity for the SMPF to be applied to a real problem in order to determine its practical applicability. The framework was applied to the shutdown data of a critical asset, namely a BE 1570W dragline called DL-B, at a open-pit thermal coal mine. Using only the dragline's shutdown scope of work, projected shutdown schedule and sub-assembly information, the SMPF prioritised the proposed shutdown maintenance work of DL-B. What is more, a comprehensive scenario analysis was performed in order to gauge how different possible future scenarios affect what maintenance should be performed during the dragline shutdown.

The SMPF was presented to, and discussed at length with, the key role players at OP Mine. Owing to the confidentiality agreement with OP Mine, the names of the key players cannot be disclosed. However, Appendix A lists the job titles of these key role players, their qualification(s), experience and a brief job description detailing their respective responsibilities at OP Mine.

These key role players recognised the possible practical value of the SMPF to OP Mine and were adamant that it be applied to the shutdown of the most critical asset at the mine, namely one of their draglines. Their eagerness to test the SMPF is illustrated by their proposal to evaluate different future scenarios using existing dragline shutdown data when there were no imminent dragline shutdowns at OP Mine. According to key role players, the results of the SMPF proved to be insightful and OP Mine could consider using the framework to help strengthen their case during the discussions with its dragline contractor in the months leading up to the shutdown.

5.5 Chapter 5 Concluding Remarks

The purpose of the case study in this chapter is to test whether the SMPF has any practical value. In collaboration with Anglo American plc and ACSA, the case study was conducted at a South African thermal coal mine referred to as OP Mine. More specifically, the SMPF was implemented on a critical asset at the mine, namely a BE 1570W walking dragline called DL-B.

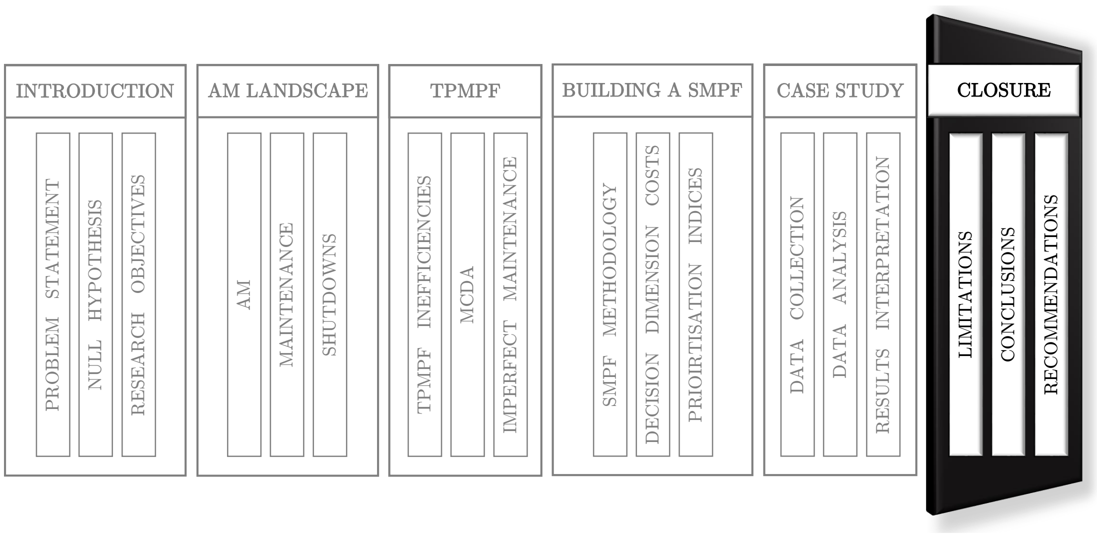
All seven steps of the SMPF application process were discussed extensively once the case study design (scope and objectives) as well as delimitations were established. These steps described the case study system of interest, the system data required, the collection and management of the system data as well as the manipulation of this data. This procedure was completed to determine which maintenance work should be performed on DL-B during its shutdown. What is more, this procedure was repeated for different possible scenarios in order to help OP Mine remain flexible in its decision making process prior to a shutdown of one of its draglines.

The SMPF was applied to the shutdown data of DL-B and the results of the different evaluated scenarios were analysed and interpreted. Subsequent recommendations were made and key role players at OP Mine validated the practical value of the SMPF. OP Mine is now considering using this framework as supporting tool in the scope freezing discussions and negotiations with its dragline contractors prior to major shutdowns.

The following chapter, Chapter 6, discuses the conclusions drawn from this case study, its limitations and the recommendations for future research.

Chapter 6

Closure



Chapter Aims:

Chapter 6 consolidates the research findings and presents the final conclusions of the study. An overview of the conducted study is provided and key findings are highlighted. Furthermore, the chapter shows that the research question in Chapter 1 is satisfied and the null hypothesis is rejected. Limitations of the study are disclosed and the chapter ends by making recommendations for future research.

Chapter Outcomes:

⇒ Summation of the study conducted.

⇒ Answer to the central research question and rejection of the null hypothesis.

⇒ Disclosure of study limitations.

⇒ Recommendations for future research.

6.1 Overview

Today, the competition among asset-intensive organisations is fierce. The margins of error are so small that these organisations need to exhaust every ounce of effort to ensure they stay ahead of their competitors. There is no longer any room for mediocrity nor complacency for these organisations. Having some sort of competitive advantage is not a "nice to have" any more, but rather a "must have", especially in this tough present financial climate.

Technological advances may offer new competitive advantages, but this happens few and far between and is usually accompanied by significant R&D costs. The other, more controllable, option for these organisations is to create a competitive advantage within the organisation, rather than trying to import one from the outside. Performing appropriate maintenance on their assets could be this internal competitive advantage as it benefits the organisation twofold. Firstly, it frees up the capital that would have been spent on unnecessary maintenance and secondly, it helps prevent expensive asset failure repairs and the consequent asset downtimes.

The difficulty, however, lies in determining which subset of maintenance tasks to perform given that there are usually more tasks seeking investment than there are resources (time and budget) available to support them. This is especially true for organisations that execute asset and/or plant shutdowns. It is therefore crucial for these organisations to select the subset of shutdown maintenance tasks that deliver the most value and can still be supported by the available shutdown maintenance resources. Popular maintenance prioritisation approaches such as the Pareto Analysis and FMECA have major weaknesses, which make then unsuitable solutions to this problem.

The TPMPF, on the other hand, was identified as a promising solution to this problem as its considers the value delivered by the maintenance as well as the budget and time constraints that may apply. Regrettably, the TPMPF has its own inefficiencies and is not tailor-made for the shutdown maintenance environment. The research in this thesis, therefore, set out to remedy these identified inefficiencies in the TPMPF and leverage the framework for the shutdown environment with the development of the SMPF.

A problem statement in Chapter 1 defined what the research was aiming to achieve. It was succeeded by the AM landscape, which introduced key concepts such as maintenance and shutdowns to help contextualise the problem statement. Special attention was afforded to discussing how important shutdown maintenance planning is to the execution and eventual success of a shutdown. Moreover, the research focused on the prioritisation step in the shutdown planning phase and subsequently reviewed the TPMPF. Inefficiencies in this framework, such as its semi-quantitative ranking procedure and its quantification of maintenance effectiveness, were dissected and discussed.

With the problem understood and the TPMPF inefficiencies known, possible solutions to these inefficiencies were proposed. An imperfect maintenance age reduction factor was used for the quantification of maintenance effectiveness and four MCDA models were consulted to replace the semi-quantitative ranking procedure. These proposed solutions were incorporated into the development of the shutdown maintenance application methodology, namely the SMPF. The seven procedural steps of the SMPF were described in detail and then applied to the shutdown data of a dragline (DL-B) at a South African thermal coal mine (OP Mine), in the form of a case study. The SMPF prioritised the shutdown maintenance tasks of DL-B for different possible scenarios and the key role players at OP Mine were used to validate the framework and its results.

6.2 Conclusion

As defined by the research question in Chapter 1, the aim of the research conducted in this thesis was to determine whether the TPMPF can be modified and leveraged for the shutdown environment. To answer this research question, it was broken down into the ten manageable research objectives, which are summarized in Table 1.2. Leading from the discussion in the previous section, it can be confirmed that all these research objectives were met at the completion of this thesis. That means the null hypothesis, defined in Table 1.1, can consequently be rejected as the SMPF demonstrated that it can be used to prioritise the shutdown maintenance tasks of a critical system for an impending shutdown.

H_0:	*The Tam and Price Maintenance Prioritisation Framework cannot be modified and leveraged for the shutdown environment in order to prioritises the shutdown maintenance work of a critical system.*

6.3 Limitations

The research conducted in this thesis has certain weaknesses or limitations which were discovered during the course of the study. In this section, these limitations are acknowledged and disclosed in order to help the reader gain a thorough understanding of the SMPF application methodology. The SMPF developed in this thesis was found to be limited in the following ways:

- The framework is inherently dependent on the availability as well as the quality of the data used. If the required data is unavailable, assumptions would have to be made, or if the data is of poor quality, the end results of the SMPF will ultimately reflect these insufficiencies.

- Tying in with the previous point, if no historical asset failure information is available, then the instantaneous failure rate before and after maintenance cannot be calculated. This means its RDC_{BM} and RDC_{AM} cannot be determined and consequently the return resulting from the maintenance performed on the asset cannot be quantified.

- The SMPF only uses the world's most popular distribution for describing the failure histories of assets, namely the Weibull distribution. Although not reflected by the DL-B sub-assemblies in the case study, the failure behaviour of other assets or sub-assemblies may be better characterised using other distributions found in practise, e.g. exponential distribution.

- The person or organisation implementing the SMPF requires a decent understanding of challenging areas such as MCDA and imperfect maintenance in order to interpret the results. Without this understanding, it is possible to become confused or even lost among the many alternatives possible and therefore struggle to determine which alternative best suits the needs and objectives of the particular asset and its organisation.

- The SMPF is not a once-off implementation process, important asset information (replacement cost, effective age and failure distribution parameters) and shutdown information (AST and SB) must be updated before the SMPF is applied. This is to ensure that the framework results are accurate and reflect the current reality of the asset and its shutdown.

With the identified limitations of the SMPF now disclosed, the following section presents the recommendations for future research. Some of these recommendations relate to the aforementioned limitations.

6.4 Recommendations for Future Research

Leading from the limitations described in the previous section, as well as renewed insight gained into the fields of shutdowns, maintenance prioritisation, MCDA and imperfect maintenance, the following considerations emerged during the course of the study as future work that may be worth investigating:

- The SMPF only considers the maintenance prioritisation step in the shutdown planning phase. However, other steps in this phase such as the scheduling and procurement of spares or specialised labour might mean the highest rank MP, according to the SMPF, cannot be performed. It would, therefore, be beneficial to incorporate these steps or additional constraints into the SMPF in order for them not to later knee-halter the results and recommendations of the framework. This would involve other topical areas in and around AM such as supply chain management and spare parts management.

- Many asset-intensive organisations have invested heavily in computerised maintenance management systems to track and record the operations and failures of their assets. Incorporating the SMPF into such a system would mean less manual intervention is necessary right before a shutdown. Also the maintenance planners and procurement staff will have a better, almost real-time, idea of what maintenance work will likely be in the frozen scope of work and can therefore plan accordingly

- The SMPF focuses on the shutdown of a single critical asset, however the ultimate goal for future research should be on incorporating multiple critical systems into the framework. This would lead the way towards prioritising the shutdown maintenance work of an entire plant or facility.

In other words, this would imply performing the SMPF at a total plant shutdown level rather than just at an asset shutdown level. Organisations, such as those in the process industry, which more often have full plant shutdowns rather than separate smaller shutdowns on their major assets, would greatly benefit from this research.

These listed recommendations offer interesting windows of opportunity for future research to be conducted in and around the development of the SMPF as studied in this thesis.

Appendices

Appendix A

Key Role Players at OP Mine

Section 5.4 discusses the validation of the SMPF. The practical validity of the framework was determined through a presentation of the SMPF results and formal discussions with the following key role players at OP Mine. The pertinent details that render these key role players as "experts" at OP Mine are given below.

Job title	**Reliability Engineer**
Qualifications	Government Certificate of Competency (GCC) Mechanical Engineering
Experience	Ten years working experience in the South African mining industry.
Job description	At OP Mine, the Reliability Engineer is responsible for: – condition monitoring on all pit and plant equipment (i.e. vibration, tribology, thermography, ultrasound and other industry leading techniques); – maintenance planning of all pit and plant equipment; – management of critical spares (i.e. sub-assemblies) and technical expediting; and – management of engineering systems, technology and related infrastructure.

Job title	**Shutdown Foreman**
Qualification(s)	N3 National Diploma
Experience	Twenty-five years working experience in the South African mining industry.
Job description	At OP Mine, the Shutdown Foreman is responsible for: – spares and resource scheduling for shutdowns; – supervision of shutdown crews; and – safety compliance of personnel during equipment shutdowns.

Job title	**Dragline, Reticulation, Boiler Making and Rigging Engineer**
Qualification	Government Certificate of Competency (GCC) Mechanical Engineering
Experience	Eleven years working experience in the South African mining industry.
Job description	At OP Mine, the Dragline, Reticulation, Boiler Making and Rigging Engineer is responsible for: – draglines engineering; – power reticulation; – boiler-making activities and dragline bucket repairs; and – rigging operations.

Job title	**Maintenance Planning Officer**
Qualification(s)	Senior National Certificate
Experience	Thirteen years working experience in the South African mining industry.
Job description	At OP Mine, the Maintenance Planning Officer is responsible for: – maintenance scheduling; – downtime capturing; and – monthly and weekly key performance indicator reporting.

Job title	**Sub-assembly Controller**
Qualification	National Diploma
Experience	Sixteen years working experience in the South African mining industry.
Job description	At OP Mine, the Sub-assembly Controller is responsible for: – sub-assembly asset control of new, repaired and disposed components; – dispatching and receiving of new, repaired and scrapped components; – expediting efficiency of components including quotation analysis; – creating detailed failure reports and purchase requisitions; and – asset management-naming conventions and logistics control.

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