Developing a Transmission Power Grid Maintenance Budget Decision Support System

by

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Declaration

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Abstract

Sustainable value adding in asset-intensive organisations requires well-coordinated activities between tangible and intangible assets at all stages of the asset life cycle. One of the core asset management principles is ensuring alignment between organisational objectives and management decisions. Operational and maintenance decision-making are regarded as crucial in maintaining business sustainability. Decision-making is a fundamental management output and a critical action to reach business imperatives.

Many asset-intensive power grid companies across the globe are experiencing a rapidly changing supply and demand landscape driven by technical, socio-economic and environmental factors. Existing business models are challenged to maintain financial viability whilst ensuring acceptable levels of supply in a highly regulated environment. Business budget reforms are driven by the need to restrict expenditure and to improve financial performance. Traditionally businesses employ incremental budget models during times of fiscal constraint, where equal cutbacks are implemented across all levels without focus on specific expenditures (Ibrahim, 2017). This creates conflict at the operational level where maintenance managers are required to make decisions that impact on short-term expenditure which, in turn, impact medium- to long-term power system performance.

Operational and maintenance management decisions are often characterised by human judgement, discussions and previous experience where action is required despite limitations on time and knowledge. The study presents a transmission power grid Maintenance Budget Decision Support System (MBDSS) that will support maintenance managers in delivering related management decisions, considering essential information that is aligned to the current business objectives.

The model and process are based on existing maintenance prioritisation models that consider the criticality of preventive maintenance tasks as well as maintenance expenditure risks. The study investigates the apparent and latent relationships between maintenance planning, budget expenditure and grid performance in order to establish relevant criteria and limitations in developing the MBDSS.

The model uses the risk priority number (RPN) method in conjunction with the analytical hierarchy process (AHP) technique. AHP is used to determine the weights for the different probability and severity criteria. The model improves on existing prioritisation models by modifying the constant failure rate data of equipment taking into account the health and work-rate of the equipment in calculating the failure probability. The model is validated by following the Borenstein decision support system validation process.

Opsomming

Volhoubare waardetoevoeging in bate-intensiewe ondernemings verg goed gekoördineerde aktiwiteite tussen tasbaar en nie-tasbare batesoorte. Hierdie koördinasie moet regdeur die lewensiklus van die onderskeie bates plaasvind. Een van die kern batebestuursbeginsels is om te verseker dat bestuursbesluite belyn is met besigheidsdoelwitte. Operasionele- en instandhoudingsbesluite is van kardinale belang om besigheidsvolhoubaarheid te handhaaf. Besluitneming is ‘n fundamentele bestuursuitset en ‘n kritieke aksie om besigheidsdoelwitte te bereik.

Bate-intensiewe kragnetwerkondernemings wêreldwyd ervaar ‘n vinnig veranderende omgewing na die vraag en aanbod van elektrisiteit. Hierdie tendens word gedryf deur tegniese, sosio-ekonomiese en omgewingsfaktore. Die finansiële lewensvatbaarheid van bestaande sakemodelle word getoets terwyl aanvaarbare elektrisiteitsvoorsieningsvlakke verseker moet word in 'n streng gereguleerde omgewing. Die hervorming van sakebegrotings word gedryf deur die behoefte om uitgawes te beperk en om finansiële prestasie te verbeter. Tans gebruik besighede tradisionele differensiaal toenemende begrotingsmodelle, waar besnoeiing eweredig oor alle vlakke geïmplementeer word sonder om te fokus op spesifieke uitgawes. Dit skep konflik deurdat daar van bedryfsbestuurders verwag word om besluite te maak rakende korttermyn uitgawes waar dit dienooreenkomstig medium- tot langtermyn stelselprestasies beïnvloed.

Operasionele en instandhoudingsbestuursbesluite word gekenmerk deur menslike oordeel, besprekings en vorige ervaring waar optrede vereis word ten spyte van tydsbeperkings en gebrekkige kennis. Die studie stel ‘n Bedryfsbegroting Besluitsteunstelsel (BBS) voor wat van toepassing is op ‘n verspreidingskragstelsel. Hierdie BBS word ontwerp om bedryfsbestuurders te ondersteun in besluitneming, inaggenome noodsaaklike inligting wat verband hou met huidige besigheidsdoelwitte.

Die model en proses word gebaseer op bestaande instandhoudingsprioriteitsmodelle wat die noodsaaklikheid van voorkomende instandhoudingstake oorweeg, sowel as risiko’s verbonde aan bedryfsuitgawes. Die studie ondersoek die sigbare en onderliggende verwantskappe tussen instandhoudingsbeplanning, begrotingsuitgawes en stelselprestasie om sodoende die relevante kriteria and stelselbeperkinge van die BBS te bepaal.

Die model gebruik die risiko prioriteitssyfer (RPS) metode tesame met die analitiese hiërargie proses (AHP) tegniek. AHP word gebruik om die onderskeie gewigte van die verskillende waarskynlikheid en felheidskriteria te bepaal. Die model verbeter op bestaande prioriteitsmodelle deur die konstantefalingstempo data van toerusting aan te pas om sodoende die huidige toestand en werkstempo van die toerusting in ag te neem in die berekening van die falingswaarskynlikheid. Die validasie van die model word gedoen deur die Borenstein Besluitsteunvalideringproses.

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Glossary

Acronyms and Abbreviations

AM	Asset Management
AHP	Analytical Hierarchy Process
BCP	Budget Constraint Planning
CLN	Customer Load network
CMMS	Computerised Maintenance Management System
DSS	Decision Support System
EDI	Electricity Distribution Industry
ERP	Enterprise Resource Planning
ESI	Electricity Supply Industry
FMEA	Failure Mode Effects Analysis
FMECA	Failure Mode Effects and Criticality Analysis
GP	Goal Programming
HAZOPS	Hazard and Operability Analysis
ICT	Information and Communication Technology
KPIs	Key Performance Indices
MCDM	Multi-criteria Decision-making
MOP	Multi-objective programming
MS	Management Science
OR	Operational Research
PAM	Physical Asset Management
PCA	Principle Component Analysis
PLS	Partial Least Square
PMS	Performance Management System
RCM	Reliability Centred Maintenance
RPN	Risk Priority Number
ROI	Return on Investment
QRPMS	Quantitative Relationships at Performance Management System
TBB	Target Based Budget
TPM	Total Productive Maintenance
TPG	Transmission Power Grid
USA	United States of America
ZBB	Zero Based Budgets

Nomenclature

Symbol	**Description**
A	Comparison Matrix
CI	Consistency Index
CR	Consistency Ratio
E	Environment
FL	Functional Location
H	Health
L	Loading
N	Number of columns and rows of a matrix
RI	Random Consistency Index
λ	Eigenvalue
$\pi(k, l)$	Multi-criteria preference index
$\Phi^{+}(k)$	PROMETHEE leaving flow
$\Phi^{-}(k)$	PROMETHEE entering flow
$\Phi(k)$	PROMETHEE net-flow

Chapter 1

1.1. Background

The Transmission Power Grid (TPG) is the backbone of any electricity power system. Base generation plants are often located some distance away from distribution load centres. A TPG effects the transportation of bulk electrical power at high voltages, between a generation plant and distribution load centres. It requires complex operational and maintenance management to ensure adequate levels of network availability as well as reliability at acceptable costs.

1.2. Introduction

The worldwide trend of restructuring and deregulation in the Electricity Supply Industry (ESI) (Leautier, 2001) as well as changes in customer demand patterns in the Electricity Distribution Industry (EDI) add to the complex nature of TPG management (Brown, 2000).

Financial and environmental challenges in the power electricity utility environment, especially in the South African context, are placing pressure on the utilities' working capital management (Jahed, 2017). Jahed (2017) provides evidence of a "…report by the World Bank Independent Evaluation Group (2016) [which] shows that of a sample of 40 leading power utilities across developing countries only 10 were profitable". Capital structure strategies are forcing reviews on cash flow generated by investments with a higher focus on improved operational effectiveness and efficiency through improved asset management methodology.

Kostic (2003) reports that the fundamental objectives of electrical utilities are to manage their assets in such a way as to provide their customers with sufficient levels of electricity, at an acceptable level of quality and at least cost. Swart (2015) provides evidence of a renewed focus on asset management due to an increasingly constrained economic climate. The driving factors for this focus are the need to reduce operational budgets and maximise the return on investments in asset intensive organisations (Swart, 2015).

Ma *et al.* (2014) describe power grid companies as asset intensive and set Asset Management (AM) as "the core business of power grid companies". Khuntia *et al.* (2016) state that the electrical power industry is changing rapidly due to technical, socio-economic and environmental developments and that AM would be critical in this transformation process. The CIGRE Joint Task Force further defines AM, in a transmission power system context, as "…the central key decision making system for the network business to maximise long term profits, whilst delivering high service levels to customers, with acceptable and manageable risk" (Khuntia, *et al*., 2016).

"Asset management does not focus on the asset itself, but on the value that the asset can provide to the organisation" (GFMAM, 2014). According to the Global Forum of Maintenance and Asset Management (GFMAM) the organisation and its stakeholders, in accordance with the organisational objectives, determine this value. Burnett (2014) emphasises the critical nature of decision-making in the AM environment and in particular the operational and maintenance space. Burnett (2014) further argues that decision-making in the operational and maintenance environment is often based on emotional rather than technical rationale. This trait often leads to unpredictable and unwanted equipment performance that negatively affects organisational value realisation in an asset management context.

According to the Institute of Asset Managers (IAM), the operations and maintenance decision-making aspect of asset management is a critical component that deals with the determination of operational and maintenance activities that are important for achieving asset management objectives. One of the key aspects that this decision-making process considers is the cost and risk balance when determining maintenance execution tactics. Maintenance activity is normally funded from operational expenditure (OPEX) rather than capital expenditure (CAPEX). Normally operational decisions do not take into account the time-value of money as they are funded from a current year's budget (IAM, 2015).

Original Equipment Manufacturers (OEM) provide maintenance and inspection manuals that recommend maintenance tasks and frequencies. These recommendations are often very generic and give little consideration to functional importance, mechanical or electrical duty cycles, plant health and environmental aspects. The IAM (2015) states that resultant times-based maintenance execution strategies can be hugely risk averse. This provide opportunities to reduce maintenance frequencies, and cost, with limited impact on asset condition and performance. The opposite scenario is also relevant but the more common reality is that the OEM's recommendations are usually very conservative (IAM, 2015).

Maintenance engineering methods like Reliability Centred Maintenance (RCM) are commonly used in the TPG environment to assist with maintenance execution determination at concept phase with an overreliance on the reliability aspect. The method employs a Failure Mode Effects and Criticality Analysis (FMECA) based maintenance engineering technique to identify critical equipment failure modes and to employ appropriate maintenance interventions, whether preventative, corrective or design-out strategies, to limit the probability and consequence of failure modes. Risk-based methodology is also employed to evaluate criteria like functional importance, duty cycle, asset health, environmental factors and performance. Campbell and Reyes-Picknell (2016) warn, however, that decision support systems depend on accurate input data to produce optimum results. Data collections in organisations are often inaccurate and incomplete (Fernandez & Marquez, 2012). Experienced and seasoned maintenance crews often neglect the recording of detailed maintenance and failure information in work reports or the capturing of correct plant information during work execution (Campbell & Reyes-Picknell, 2016). This could lead to incorrect data analysis and costly expenditures.

The IAM (2015) argue that maintenance decision models must include maintenance cost of planned and unplanned activities. In addition, the modelling of maintenance decisions requires the prediction of future performance inclusive of risk profiles.

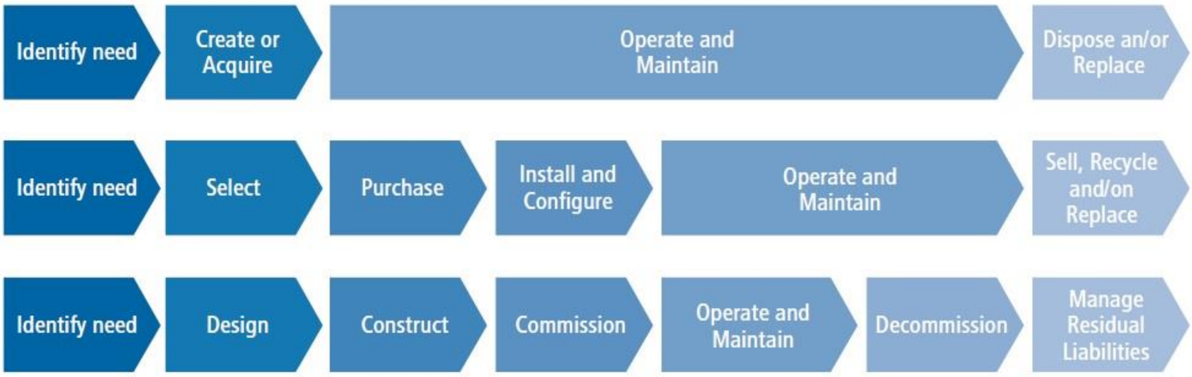


Figure 1.1 Example of Asset Management life cycle (Adopted from AIM,2015)

Maintenance management is often viewed as a subcomponent of the greater asset management life cycle as described in Figure 1.1, adopted from IAM (2015). Maintenance management refers to "all the activities of management that determine the maintenance objectives or priorities, strategies and responsibilities and implement them by means such as maintenance planning, maintenance control and supervision, and several improving maintenance methods including economical aspects" (Fernandez & Marquez, 2012). The definition describes maintenance management at three levels of management i.e. strategic, tactical and operational. These three levels can be associated with the different AM subject groups "Strategy and Planning", "Asset Management Decision Making" and "Lifecycle Delivery" respectively as described by GFMAM (2014).

The available budget of a department is considered as the main limitation as the economic criteria are always inversely proportional to quality and reliability (Fernandez & Marquez, 2012). The maintenance budgeting process is therefore an essential component of the maintenance management control-system, as it provides a system of planning, coordination and control for management. Traditionally, state-owned utilities employ incremental/decremented budgeting methods whereby the current period's actual spend is taken as basis with incremental amounts then added/subtracted for the new budget period (Hopkins, 2015). The advantage of this approach is that it is simple and creates a more stable and consistent environment for maintenance managers. However, this approach encourages spending up to the budget limit so that the budget is maintained for the subsequent year. This is normally done to preserve the budget for the following years.

Government-owned utility budgets are also characterised by high levels of "wage expenditures" (Ma, 2006) which makes the application of a more rationalised budget approach difficult. Normally the justification towards the employee benefit expense will fall outside the control of maintenance managers in a public utility environment. The control maintenance managers would have on this expense account would be limited to the regulation of overtime and contingency costs.

Traditionally, TPG technical performance is measured by system availability, power quality, supply security and individual plant performance indices. The relationship between system performance and maintenance budget is often reactively controlled due to the nature of budget setting (Brown & Humpfrey, 2005). Performance KPI levels are determined based on the previous term's achievement as well as inter-utility benchmarks. Often the predictive performance impact is not quantified in terms of available budget.

Fernandez & Marquez (2012) consider the accounting system a critical element in the maintenance management framework. They further propose an activity-based accounting system, which involves the following:

a. Select the cost basis;
b. Tracing resources to activities;
c. Determine the activity measure;
d. Assign secondary activities;
e. Calculate the activity cost; and
f. Determine the activity performance

This system will then allow for:

a. a direct traceable cause-and-effect relationship between cost/activities and the provision of the service;
b. verifiable relationship between the equipment and the output of the service; and
c. a direct causal relationship with a pool of common cost or revenues and relative use.

In their approach, they make use of a PAF (Prevention, Appraisal and Failure) cost scheme that divides the budget in terms of the nature of the cost. These costs are then linked to the network and customers. These relationships are then used to measure the impact of activities on maintenance effectiveness and efficiencies.

Campbell & Reyes-Picknell (2016) report that many companies struggle to obtain accurate and relevant maintenance cost information. Labour cost is often charged through cost centres and only significant materials cost is charged directly to the equipment. Labour cost is sometimes reported on work-orders which, in turn, are linked to equipment. These costs are often found to be misreported or inaccurate. Companies often track costs in a way conducive to accurate accounting but not against specific equipment in the asset register.

The increasing size, aging of equipment and TPG complexity within an overly financially constrained environment have made maintenance engineering methods, beyond RCM and TPM, a necessity in maintaining adequate levels of reliability and availability. Maintenance decision support systems could support maintenance managers to ensure adequate system reliability within a constrained budget environment.

1.3. **Problem Statement and Research Objectives**

Various approaches to budget setting of maintenance activities exist in the public and private sector. The predominant method is incremental budgeting as it is a far more predictable model and much easier to implement. Some organisations implement a more rational approach to sections of the budget. Incremental changes over a long term, during a period of good performance, can lead to a hugely inflated fixed cost budget portion with limited value realisation. The cost of high volumes of abnormal maintenance, in a single year, is captured as a base-line for the specific year. This will form part of the base for the budget setting for the following years. Surplus maintenance budget can be absorbed by non-critical maintenance activities.

The preferred maintenance management engineering method in the network utility industry is Reliability Centred Maintenance. This approach focuses more on equipment reliability at a strategic and tactical level and less on organisational efficiency.

1.3.1. Problem Statement

The challenge with the South African power utility's power system maintenance budget is that current maintenance budget procedures do not relate to the maintenance objectives in terms of ensuring adequate levels of reliability and availability in a budget constrained environment.

1.3.2. Research Questions

In support of the problem under investigation the following research questions need to be addressed:

- a. What is the relationship between maintenance planning and budget setting?
- b. What is the relationship between maintenance planning and power system performance?
- c. How can maintenance plans be optimised to ensure maintenance objectives are met in a financially constrained environment?
- d. How can a maintenance management decision support model be constructed and validated for improving maintenance planning and budget compliance?

1.3.3. Research Objectives

The primary objective of this study is to develop a maintenance management decision support model that can identify the combination of maintenance tasks in a TPG that will achieve the best alignment to the stated maintenance objectives within a constrained financial budget environment.

To achieve the primary objective the following sub-objectives are defined:

1. Investigate the relationship between maintenance planning and budget setting and spending.
    - a. Review the different types of maintenance budget methods, how budgets are spent and budget key performance indices.
    - b. Study the different maintenance strategies and challenges in the TPG environment.
    - c. Examine the relationship between maintenance budgets and planning.

2. Investigate the relationship between power system performance and maintenance planning.
    - a. Study the measurement of performance in a TPG environment.
    - b. Examine how TPG performance is considered during maintenance planning activities.
    - c. Investigate the comparison between transmission performance and maintenance plans.

3. Develop a maintenance decision support model in a budget constrained environment.
    - a. Identify the factors influencing maintenance planning decisions within a complex transmission network.
    - b. Determine the inputs and outputs to be included in the model.

4. Model validation: Perform a case study on a predefined TPG maintenance strategy.
    a. Perform data collection based on model input variables.
    b. Apply to achieve outputs by utilising optimised model.
    c. Consider and evaluate the results to determine the potential cost and performance impact of the maintenance strategy employed.

1.3.4. Importance of Research Problem

In periods of fiscal contraction there is always a challenge between policymakers and maintenance managers insofar as cutback management is concerned. The most convenient option is often across-the-board cuts from top-down (Ibrahim, 2017). This often has detrimental effects on sustainable long-term performance and improvements, as far as technical and financial considerations are concerned (Jimenez, 2014).

Recent experiences in the public utility environment demonstrated multiple budget cutbacks within a single budget period. This placed pressure on maintenance managers to react appropriately and still comply with stated maintenance objectives. It is often difficult to cut without the knowledge of the existing base and how cuts will impact the performance of the TPG.

This maintenance decision support model will provide guidance to decision-makers to cut optimally with minimal impact on long- and short-term performance of the TPG.

1.3.5. Delimitation and Limitations

The following delimitations and limitations described the boundaries set for the study as well as the characteristics of the research design that could impact the findings of the research.

1.3.5.1. Delimitations

1. The study focuses on a transmission power grid environment. The study will be limited to a portion of the 400kV transmission network defined as a customer load network (CLN).
2. The study will be limited to the impact of planned maintenance on system performance and will exclude any outage requirements required by capital projects.
3. The study will assume local maintenance support teams' availability except for specialised maintenance activities i.e. transformer tap-changers and live-line maintenance activities which are supported by central service providers.
4. The study assumes a (N-1) compliant TPG network with no abnormal network configurations which could impact maintenance decisions.

1.3.5.2. Limitations

Interviewing is a time consuming and challenging process, specifically with respect to gaining access to senior managers. It could also be deemed as encroaching on an individual's work time and therefore increases difficulty in gaining access. This will have to be managed proactively by the researcher. The structure of maintenance costing data within an organisation and how it is linked to assets could also provide a challenge for investigating relationships between maintenance cost and network performance.

1.3.6. Ethical Implications of the Research

This study includes qualitative data collection, which involves research methods such as semi-structured interviews. A written consent and information letter is signed by both the principal investigator and the research participant as a formal agreement that research participants will remain anonymous. Ethical clearance was obtained from Stellenbosch University.

1.4. Research Design

A mixed methods research approach is employed which is based on a convergent parallel research design as described by Creswell (2014). In the proposed research design, the data collection approach will be both of a quantitative as well as qualitative nature and these will occur concurrently.

Data collection methods during the phases of investigating the relationships between budgets, maintenance planning and power system performance will include:

a. A literature review;
b. Semi-structured interviews with maintenance managers and performance managers; and
c. Secondary data collection from organisational documents, outage, maintenance cost and reliability data databases.

Qualitative content analysis techniques are used to analyse secondary data as well as the interview information collected. These qualitative analysis techniques are used concurrently with multivariable analysis (regression analysis) to identify the direction and strength of relationships. These studies are used to develop the decision support model.

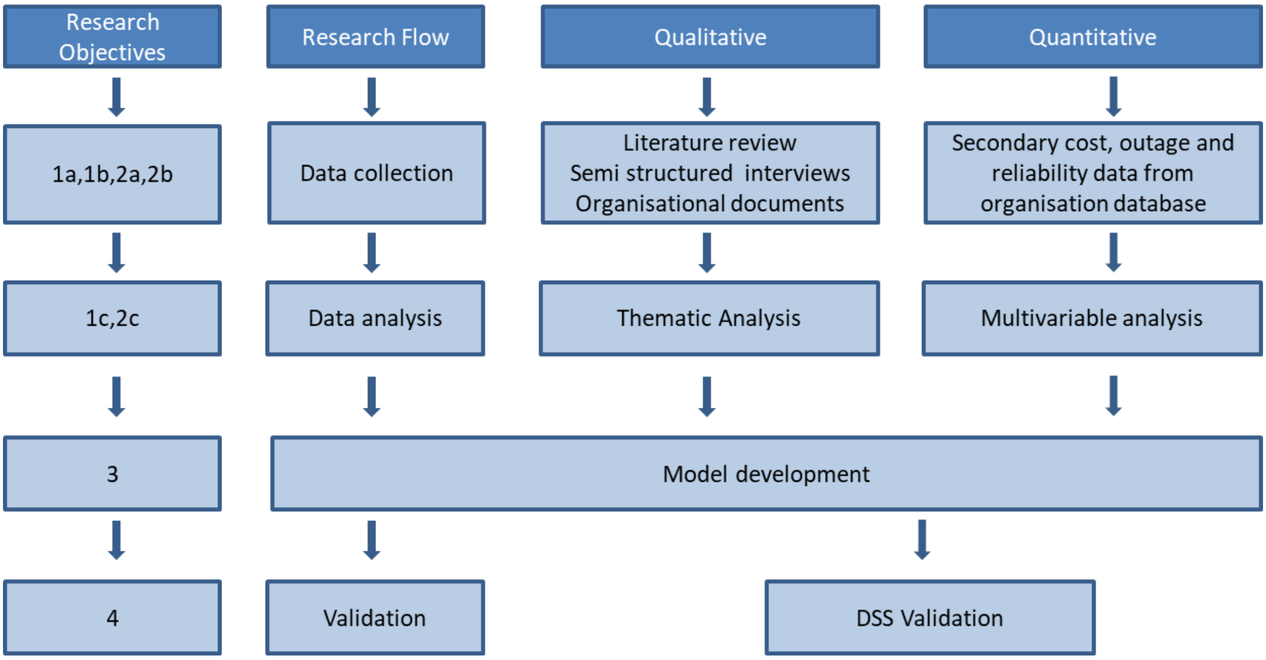


Figure 1.2 Research Study Strategy

This is followed by validating the decision support model with the use of a mixed method validation process that includes face validation, sub-system verification and validation, predictive validation and user assessment.

As illustrated in Figure 1.2 the research design techniques that support research objectives 1a, 1b, 2a and 2b are:

a. Literature review;
b. Semi-structured Interviews;
c. Organisational documents; and
d. Secondary data.

Objectives 1c and 2c are supported by Thematic-, Multivariable- and Regression analysis. The Maintenance Decision Support System (DSS) is developed as objective three while a DSS validation process is employed to support objective four.

1.5. Thesis Outline

Chapter 1: Introduction

This chapter introduces the background of the study and sets the scene to formulate the problem statement. The research questions are established based on the problem statement and research objectives are developed to address the research questions. The research design is discussed as well as the thesis outline.

Chapter 2: Literature Study

Chapter 2 describes the literature study that was conducted and the relevant literature that supports the study is reflected. The literature study covers the relevant research domains, i.e. Asset Management, Maintenance Management, Budget Cutback Management as well as Maintenance Performance and DDS development and validation.

Chapter 3: Research Design and Methodology

In this chapter the research design and methodology to execute the study are discussed. It provides an explanation of the philosophical worldview, research design and research methods followed.

Chapter 4: Identification of the Model Variables

This chapter provides a detailed overview of the collection and analysis of the quantitative and qualitative data sets. It further describes the results as input into the development of the Maintenance Budget Decision Support System (MBDSS).

Chapter 5: Model Development and Validation

Chapter 5 provides a detailed process description of the development of the MBDSS.

Chapter 6: Conclusion and Recommendations

This chapter provides a summary of the key findings from conducting the study. Recommendations on further research possibilities are proposed that could benefit similar asset intensive originations.

1.6. Chapter Summary

In this chapter, a complete introduction of the research is provided with the research objectives, research methodology and research outline. The main purpose of this study is to develop a decision-making system that will assist maintenance managers with the management of assets in the operational and maintenance environment. The study is limited to a Transmission Power System environment.

The following chapter covers the literature review and details with the fields of asset management, maintenance management and budgeting.

Chapter 2

Literature Study

The objective of this chapter is to review the existing literature related to the problem statement and research goals. The first part of the chapter covers literature describing the asset management knowledge base with specific reference to maintenance management and decision-making in the operational and maintenance environments. The second part deals with literature on maintenance performance is reviewed as well as DDS development and validation. The third part concludes with reviews on maintenance budgeting with the emphasis on literature that focuses on budget cutback theory.

2.1. Asset Management

Asset Management (AM) principles form the basis of this research. In this section asset management is introduced with a high-level overview of the development of AM standards. It further defines the characteristics of an asset management model and a brief description of the 39 asset management subjects. The section concludes with an overview of maintenance decision support systems and basic reliability engineering concepts.

2.1.1. Introduction to Asset Management

The Institute of Asset Management (IAM) notes in “Asset Management – An Anatomy” that organisations have been managing assets for a long time. The term asset management, however, was only introduced in the 1980s by private and public sectors in relation to physical assets (IAM, 2015). Since then AM has undergone a significant growth period which climaxed with the establishment of the first specification for asset management, Publicly Available Specification 55 (PAS 55), in 2004 through the cooperation of more than 25 organisations and institutions (Campbell & Reyes-Picknell, 2016). PAS 55 was seen as one of the first steps towards bridging the organisational gaps between higher and lower level management in the field that used to be known as maintenance (Hastings, 2010). This specification was revised in 2008 with the addition of 28 aspects of asset management best practices (Ma, et al., 2014). These aspects ranged from life cycle strategies to routine maintenance management. Over 50 organisations from 15 industry sectors in 20 countries contributed to the development of PAS 55 (Jooste & Vlok, 2015).

In 2011 the IAM published its report “Asset Management – An Anatomy”. In addition to this, the Global Forum for Maintenance and Asset Management (GFMAM) published its first edition paper, “The Asset Management Landscape” (Campbell & Reyes-Picknell, 2016). The GFMAM released its second edition in 2015 (IAM, 2015). These documents describe the fundamental concepts and philosophy of AM. They further describe the 39 AM subjects, each with its own knowledge and practice areas (Campbell & Reyes-Picknell, 2016).

The ISO 55000 suite of AM standards was released in 2014 and largely replaced PASS 55 (Ma, *et al.*, 2014). Campbell & Picknell (2016) report that like PAS 55, ISO 55000 specifies what is required from an AM system but not necessarily how it must be implemented. ISO 55000 provides the scope, principles and terminology while ISO 55001 specifies the requirements of an AM system. ISO 55002 provides an application guide (Campbell & Reyes-Picknell, 2016). ISO 55001 also covers organisational culture, leadership, planning, support, operation, performance operation and improvement within an asset management system (Minnaar, *et al*., 2013).

2.1.2. Asset Management Models

Amadi-Echendu *et al.* (2010) states that AM relates to "the productive use of those assets that provide the value supporting all assets in the organisation". Minnaar *et al.* (2013) describes AM as "the optimal management of assets to reach strategic organisational objectives and to meet stakeholder requirements". Although various definitions exist for AM, the ISO55000 standards define AM as "the coordinated activity of an organisation to realise value from assets" (IAM, 2015). It further describes an asset as an "item, thing or entity that has potential or actual value to an organisation". The standard also notes that the actualisation of value will normally consist of balancing cost against risk, opportunities and performance.

The IAM describes a conceptual AM model consisting of 39 asset management subjects grouped in six subject groups (Figure 2.1):

a. Strategy and Planning;
b. Asset Management Decision-making;
c. Life Cycle Delivery;
d. Asset Information;
e. Organisation and People; and
f. Risk and Review.

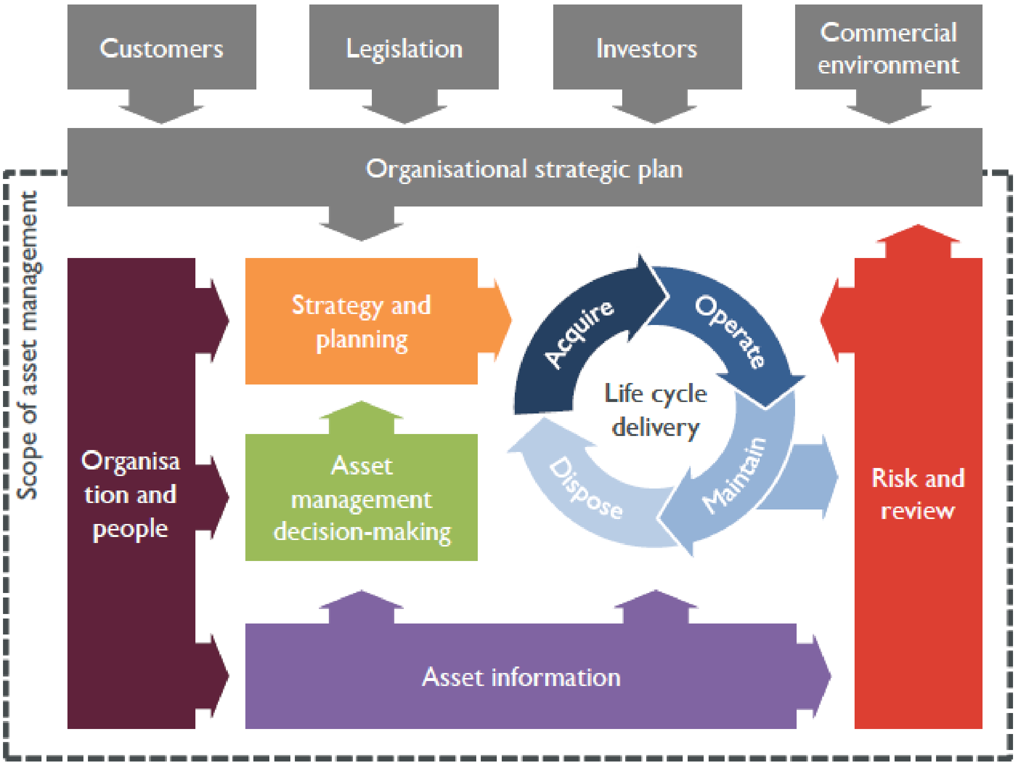


Figure 2.1 The IAM Conceptual Asset Management Model (Adopted from IAM,2015)

This "…model describes, at the highest level: the key aspects of asset management, how these interact with each other and how they link to the overall corporate objectives and business plan" (GFMAM, 2014). The IAM motivates that the development of the model was to complement the ISO55000 suite of standards. Ultimately, the form and shape of an AM model will be determined by the nature and needs of the organisation in which it exists.

The AM standard will define the requirements of the asset management system but the model will assist in how asset management is implemented. The AM subject groups, defined in the model, are strongly aligned to the asset management subjects defined in the "Asset Management Landscape" published by the Global Forum on Maintenance and Asset Management (GFMAM, 2014) and depicted in Figure 2.2. The intention of the asset management subjects is to support the AM model and to describe the AM activities in detail. The IAM explains that an organisation's objectives and context will determine which subject is more important than the other. It is important not to view these subjects in isolation as they are only a portion of a bigger system. The GFMAM (2014) explains that the list of AM subjects "…was derived from an international review of an extensive list of asset management models and methodologies".

Figure 2.2 Landscape AM Subjects within the 6 Subject Groups (Adopted from AIM,2015)

2.1.3. Maintenance Decision-making

Burnett & Vlok (2014) stress the importance of decision-making in asset management. "Effective decision making is a vital task that enables an organisation to function appropriately. It also helps it to use all the available resources to achieve its objectives". The GFMAM published the "Maintenance Framework" report in 2016. In this report "Maintenance Management" is defined as the decision-making process that aligns maintenance delivery activities with corporate objectives and strategies (GFMAM, 2016).

Operations and maintenance decision-making forms part of AM. It focuses on the operational and maintenance activities necessary to meet the AM objectives and aligns with the definition of Maintenance Management (GFMAM, 2016). According to GFMAM (2014) the decision process typically considers,

a. Customer Quality;
b. Current Capability;
c. Performance of maintenance engineering methods (i.e. RCM, TPM, FMECA) to determine maintenance activities;
d. Cost-risk balance to establish activity intervals including asset and network criticality considerations;
e. Forecasting medium- and long-term service requirements based on projected demand;
f. Perform financial analysis on services tactics;
g. Documentation of maintenance requirements in specifications and standards; and
h. Evaluate operational and maintenance impact on capital project proposal alternatives.

According to IAM (2015) operational and maintenance decision models should consider the cost of planned interventions as well as risk and the cost of failure. It further recommends that decision-making modelling should include future performance predictions inclusive of risk profiles whether failure patterns are random or wear-and-tear related.

In Figure 2.3, the IAM (2015) explains the impact of planned maintenance frequency optimisation in maintenance decision-making. The model illustrates that the more frequently maintenance is performed on a planned basis, the less risk is accepted but the impact on the potential overall cost could be extremely high. Conversely, the less frequently maintenance is performed on a planned basis, the higher risk is accepted with an equally detrimental cost impact. An economic optimum is suggested where the total cost impact on the business is at its lowest.

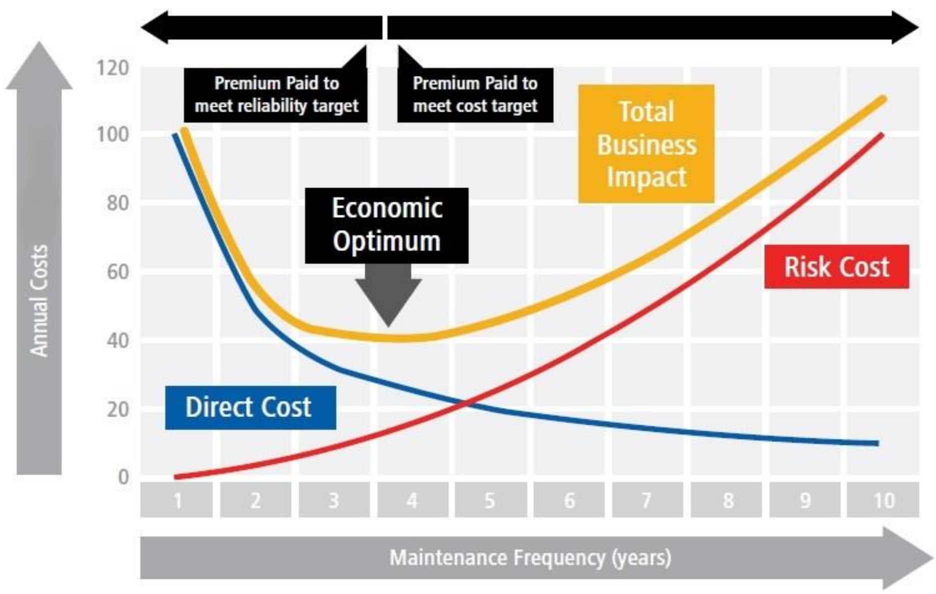


Figure 2.3 Optimising frequency of planned maintenance (Adopted from IAM ,2015)

This model is based on a wear-and-tear failure mode curve as the risk of failure increases with time. "Third Generation research has revealed that not one or two but six failure mode patterns occur in practice" (Moubray, 1997). Moubray (1997) further argue that "…a great many traditionally derived maintenance tasks achieve nothing, while some are actually counterproductive and even dangerous". Mesic & Plavsic (2013) as well as Murugan & Ramasamy (2015) explain how failure analysis on transmission components is used to determine maintenance frequencies. In both approaches there is a high reliance on condition and performance data to determine maintenance frequencies that impact the availability of plant.

Campbell *et al.* (2016) reason that decision optimisation tools can enhance reliability and reduce cost. Decision-making support systems can "… add value to the output of RCM and could lead to modifications in RCM output decisions". Campbell *et al.* (2016), however, warn that these systems are very dependent on the quality of input data. In some cases the data required is absent and requires special programs to collect it.

2.1.4. Reliability Engineering

In a network utility environment, reliability is dependent on changing environmental conditions as well as cyclic operating conditions. Tracking reliability in a utility environment is therefore critical to ensure the required levels of system performance are achieved (Birolini, 2007). Fernandez & Marquez (2012) classify the wide range of failure causes in the utility environment as follows:

- Physical failure caused when the cause is related to the item's physical failure to perform its intended function.
- Human failure caused when the failure is due to a human error.
- Latent failure when the failure is induced by deficiencies in the management system that allows the human error to continue unchecked (flaws in procedures or systems).

Fernandez & Marquez (2012) stress the importance of understanding the behaviour of the random variables that represent historical failure data due to the uncertainty of the failure appearance.

Reliability data is commonly described by the failure rate function, cumulative distribution function (CDF), probability density function (PDF) and the reliability function. The PDF, denoted by *f(t)*, is a continuous representation of a histogram indicating the number of component failures distributed in time. The PDF is the curve that results as the bin size approaches zero.

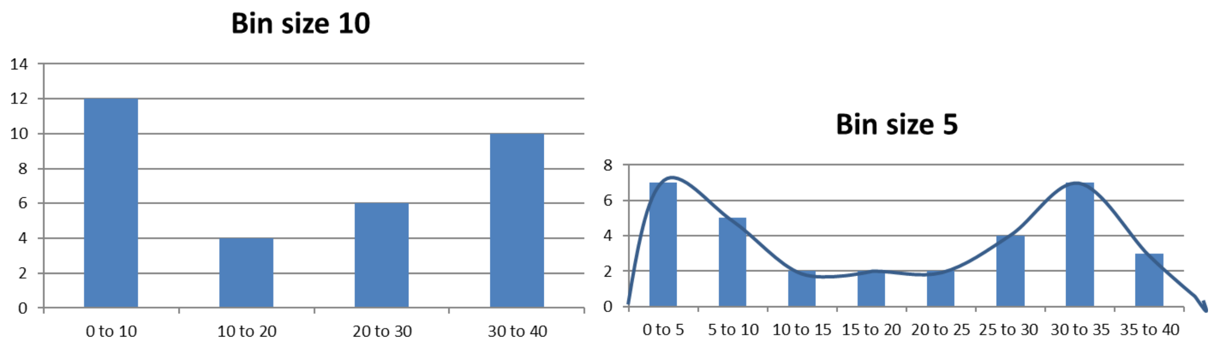


Figure 2.4 Histogram representation of failure data over a time period of 40 years

The PDF is the continuous line in Figure 2.4. The PDF is always normalised so that the area under the PDF is 1.

The CDF is sometimes referred to as the unreliable function or the probability of failure and is denoted as *Q(t)*. The CDF represents the probability that a brand new component will fail at or before a specified time. The CDF is calculated by computing the area under the PDF to the left of the specified time.

$$Q(t) = \int_0^t f(s)ds \qquad 2.1$$

Conversely, the probability density function can be calculated by

$$f(t) = \frac{dQ(t)}{dt} \qquad 2.2$$

The reliability function, also known as the survivor function, is denoted by *R(t)*. The reliability function represents the probability that a component will survive longer than a specified time. It is calculated by finding the area under the PDF to the right of a specified time.

$$\mathrm{R(t)} = \int_{\mathrm{t}}^{\infty} \mathrm{f(s)ds} \qquad 2.3$$

Conversely, the probability density function can be calculated by

$$\mathrm{f(t)} = -\frac{\mathrm{dR(t)}}{\mathrm{dt}} \qquad 2.4$$

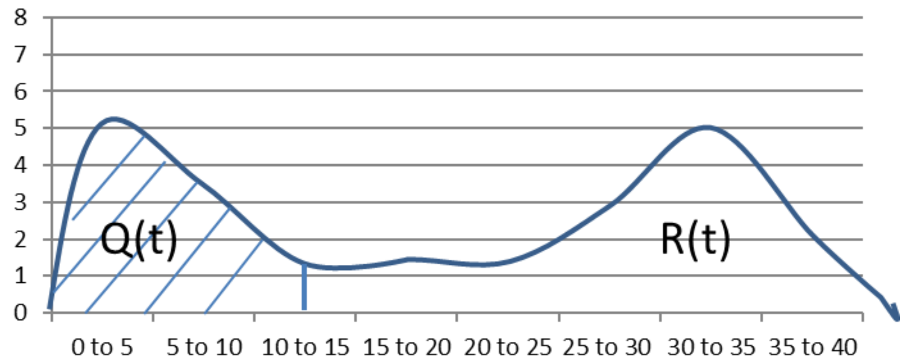


Figure 2.5 The probability density function and the relationship between Q(t) and R(t)

Figure 2.5 illustrates the relationship between the reliability function and the probability of failure function as:

$$\mathrm{Q(t) + R(t) = 1} \qquad 2.5$$

The failure rate or hazard rate, is denoted as *λ(t)* and is indicative of the probability of failure per unit time, *t*, given that the component has already survived to time *t*. Mathematically the failure rate is a conditional form of the probability density function and is calculated as:

$$\lambda(t) = \frac{f(t)}{R(t)} \qquad 2.6$$

The relationships between component failure rate and the other three reliability indices, described above, can be simplified by substituting *f(t)* in equation 2.6 with the argument in equation 2.4:

$$\lambda(t) = -\frac{1}{R(t)} \times \frac{dR(t)}{dt} \qquad 2.7$$

$$\int \lambda(t)dt = -\int \frac{1}{R(t)} \times dR(t) \qquad 2.8$$

defining the relationship as:

$$R(t) = e^{-\int_0^t \lambda(s)ds} \qquad 2.9$$

$$f(t) = \lambda(t) \times e^{-\int_0^t \lambda(s)ds} \qquad 2.10$$

$$Q(t) = 1 - e^{-\int_0^t \lambda(s)ds} \qquad 2.11$$

Other critical basic concepts in reliability engineering are mean-time-to-failure (MTTF), mean-time between failures (MTBF), mean-time-to-repair (MTTR) and mean availability (A).

The *MTTF* is defined as the mean time it takes for a non-repairable component to fail. It is also referred to as the mean failure free time. The *MTTF* of components with a failure probability density function f(t) is calculated by:

$$\mathrm{MTTF} = \int_0^\infty t f(t) dt \qquad 2.12$$

In the network utility environment, the systems and components are mostly regarded as repairable and therefore the *MTBF* indicator is more relevant. *MTBF* is the average time between failures and excludes repair-, testing- and detection time. It is intended to measure the time the component is available and operating:

$$MTBF = \frac{operation\ time}{number\ of\ failures} = \int_{-\infty}^{+\infty} tf(t)dt = \int_0^\infty R(t)dt \qquad 2.13$$

The mean-time-between-failure index implies that the underlying distribution has a constant failure rate (e.g. exponential distribution). Therefore where $R(t) = e^{-\lambda t}$,

$$\mathrm{MTBF} = \int_0^\infty e^{-\lambda t} dt = \frac{1}{\lambda} \qquad 2.14$$

The *MTTR* index relates to average repair time of components and is calculated as:

$$\mathrm{MTTR} = \frac{\sum \text{repair time}}{\text{number of failures}} \qquad 2.15$$

The failure rate $\lambda(t)$ or conditional probability failure is calculated as:

$$h(t) = \frac{f(t)}{R(t)} \qquad 2.16$$

and the cumulative failure rate:

$$H(t) = \int_0^t h(t)dt = -\ln(\frac{R(t)}{R(0)}) \qquad 2.17$$

The mean availability is calculated as:

$$A = \frac{\mathrm{MTBF}}{\mathrm{MTBF} + \mathrm{MTTR}} \qquad 2.18$$

Fernandez & Marquez (2012) note that the probability density functions mostly used in Reliability Engineering (RE) are exponential and Weibull. The former is preferred for easy calculations while the latter allows for representation of other probability functions. The combination of Weibull curves can produce the three asset life cycles i.e. early failure, normal life and wear-out failure. The shape parameter (β) of the Weibull distribution describes the rate of occurrence of failures and the scale parameter (α) the spreading of the distribution of time.

$$F(t) = 1 - e^{-(t/\alpha)^\beta} \qquad 2.19$$

$$R(t) = e^{-(t/\alpha)^\beta} \qquad 2.20$$

If β=1 the Weibull PDF becomes exponential, for values between 1.5 and 2.5 it indicates stress deterioration and for values exceeding 3.2 it approaches a normal distribution.

According to GFMAM (2014) RE is an AM subject in the Life cycle delivery AM subject group. RE is defined as the process that ensures an item operates to a defined standard for a defined period of time in a defined environment. The typical output artefacts for RE are Reliability, Availability, Maintainability and Safety (RAMS) modelling outputs, RCM analysis outputs, Weibull plots and analysis as well as root cause analysis. RE outputs influence AM strategies, capital management investment strategies, whole life cost and value optimisation as well as asset performance and health monitoring.

2.2. Maintenance Management

Fernandez & Marquez (2012) refer to maintenance as "the combination of all technical, administrative and managerial actions during the lifecycle of an item intended to retain it in or restore it to a state in which it can perform the required function". Likewise they define maintenance management as "all the activities of management that determine the maintenance objectives or priorities, strategies and responsibilities and implement them by means such as maintenance planning, maintenance control and supervision, and several improving maintenance methods including economical aspects". Marquez (2007) defines maintenance management effectiveness as "the ability of maintenance to contribute to the business plan objectives while efficiency measures how well maintenance was performed, irrespective of objective, taking into account the assigned resources".

2.2.1. Maintenance Management Process

According to Marquez (2007) the maintenance management process consists of three distinct pillars as described in Figure 2.6. In this context the maintenance process relates the course of action while the framework gives reference to the supporting structure. The maintenance management process is aligned to three levels of business activity – strategic, tactical and operational. At the strategic level, business objectives are transformed into maintenance objectives and displayed in a generic maintenance plan. Maintenance objectives can be classified in three classes or groups:

a. Technical objectives – In general technical objectives related to equipment availability and people safety.
b. Mandatory regulations – This objective relates to conforming to requirements set out in existing regulations.
c. Financial objectives – The objectives set out to conform to the operational imperatives, enshrined in the technical objectives at a minimum cost.

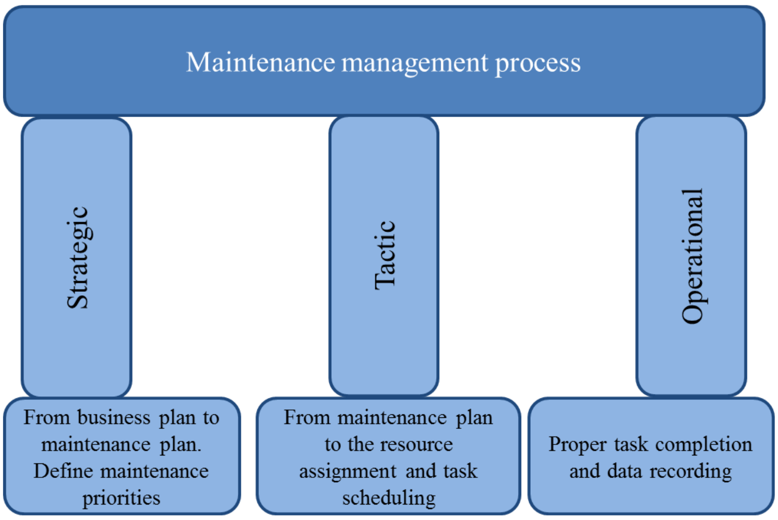


Figure 2.6 Maintenance management process (Adopted from Marquez,2007)

Maintenance objectives include equipment reliability, availability, risk, safety, regulatory compliance and maintenance budget (Marquez, 2007). At a strategic level the budget is regarded as the end point of the company's planning process and is considered a statement of the company's objectives and plans in revenue and cost terms (Kelly, 2006). This long-term budget is based on maintenance plans where the planning window is in the order of five to six years and is dependent on the company's planning horizon.

Maintenance management actions at the tactical level focus on the correct assignment of resources taking into consideration local conditions. This results in a detailed yearly maintenance plan with all tasks specified and resources assigned. This plan then forms the base of the detailed budget forecast for the year.

The operational focus ensures maintenance tasks are performed by skilled technicians, in the time scheduled, following the correct procedures and using the correct tools. In this phase, operational managers focus on maintenance management control through the continuous monitoring of maintenance performance and, where required, the initiation of corrective action (Kelly, 2006). Kelly suggests that the best practical mechanism to control overall maintenance performance is a properly designed maintenance budget and costing system. Critical in this costing system is the identification of the relationship between maintenance expenditure and relevant maintenance output, ranking them to indicate areas of low reliability, high maintenance cost and poor performance.

Historically, utilities have inadvertently focused on optimising maintenance strategies and plans at strategic and tactical level by utilising Information and Communication Technology (ICT) maintenance management functionality and condition monitoring technologies in conjunction with reliability centred maintenance (RCM) methodologies. Operational efficiencies are often neglected and not measured adequately (Marquez, 2007).

2.2.2. Maintenance Management Framework

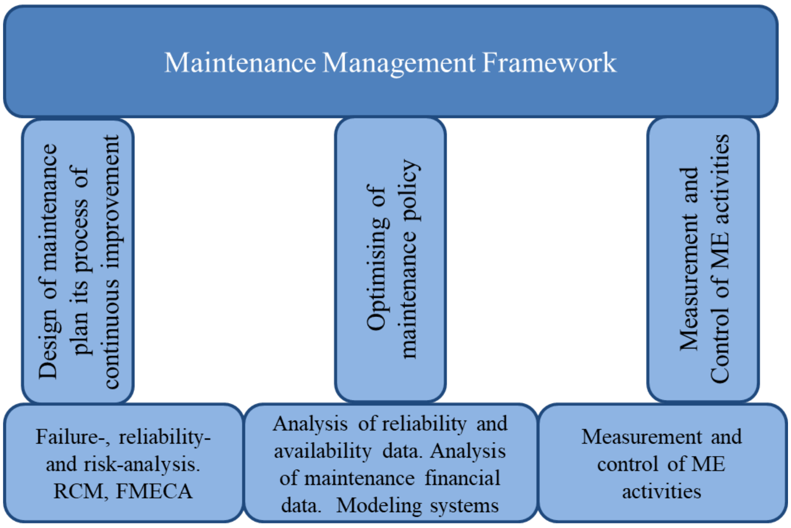


Figure 2.7 Maintenance Management Framework (Adopted from Marquez,2007)

According to Marquez (2007) information and communication Technology (ICT), maintenance engineering methods and organisational techniques form the pillars in the maintenance management framework as shown in Figure 2.7.

2.2.2.1. Information and Communication Technology

ICT systems are valuable tools in performing time-consuming maintenance support tasks in large and complex equipment systems (Campbell & Reyes-Picknell, 2016). Campbell & Reyes-Picknell (2016) caution, however, against the use of only ICT systems as an enabler to improve maintenance management.

Campbell & Reyes-Picknell (2016) suggest that corporate Enterprise Resource Planning (ERP) systems are currently dominating the ICT maintenance management market although they have a strong affinity towards corporate financial management. "Most company budgeting and costing systems are designed by accountants for corporate financial control and are not sufficiently equipment-orientated to shed light on the problems of maintenance control, e.g. cost centres may not be plant-specific and, even when they are, each one may encompass too large an area of plant to be of any use in maintenance management" (Kelly, 2006). ERP systems are normally equipped to serve as financial data collection and reporting tools first with maintenance planning offered as add-ons. Fernandez & Marquez (2012) further report that up to 70% of ERP system implementations fail to achieve stated goals as system functionality ranges between 20% and 30%. These systems are often restricted to asset record creation and work-order tracking. Therefore, maintenance-planning activities frequently reside outside of these IT packages in home-grown spreadsheets and databases. In addition, condition-monitoring technologies are normally not integrated with ERP systems and require manual input for meaningful implementation. Fernandez & Marquez (2012) argue that the full implementation of a Computerised Maintenance Management System (CMMS) could reduce maintenance annual budgets by 10%–30%.

Focusing on network utilities, Fernandez & Marquez (2012) further report on four issues concerning ICTs in companies:

a. Large geographical areas of network deployment complicate remote access;
b. Elements of different vendors add to complexity of management;
c. Dynamic and automatically configured work that has to be released according to different required capacities; and
d. Need for scalability with respect to network growth.

Surveys done on network utilities by the Plant Maintenance Resource Centre (PMRC) indicates that 82% of the sample space implemented a CMMS, but only 77% (Managers and maintenance supervisors) know why their company implemented it.

On its own, ICT systems cannot deliver a return on maintenance investment on the system (Campbell & Reyes-Picknell, 2016). It must work in support of a maintenance management framework and process.

2.2.2.2. Organisational Techniques

Organisational techniques are designed to provide flexibility to a maintenance organisational design. They also assist with the communication and coordination of functional areas within and outside of the maintenance function. Lastly, these techniques also focus on improving relationships within and external to the company.

Utilities adapt their organisational designs to improve effectiveness by moving from a centralised maintenance function to a more decentralised function. Marquez (2007) argues that while a centralised approach might favour efficient allocation of maintenance workload, a decentralised approach promotes effective communication and coordination. Campbell & Reyes-Picknell (2016) indicate that there is no correct maintenance organisational structure. Organisational techniques promote flexibility within a utility by the development of smaller multi-skilled groups in order to improve coordination and promote team work.

The use of advanced information processing technologies supports communication between different maintenance functions thereby assisting with coordination of complex maintenance activities. Organisational techniques also assist with establishing and maintaining effective relationships with OEMs, understanding and responding to customer needs and enquiring a strategic approach to maintenance outsourcing.

2.2.2.3. Maintenance Engineering Methods

The maintenance engineering pillar supports: (i) the design of the maintenance plan and its process of continuous improvement, (ii) optimising of maintenance policy and (iii) measurement and control of maintenance engineering activities (Marquez, 2007). Maintenance engineering is an analytical function that includes various techniques such as Failure Modes Effect Analysis (FMEA), Failure Modes Effect and Criticality Analysis (FMECA), and Hazards and Operability Analysis (HAZOPS). These techniques support maintenance methods like RCM that assist with the maintenance plan design and continuous maintenance plan improvement.

The methods set out in the ME methods pillar are implemented at various stages of the maintenance process. RCM is typically deployed at the strategic and tactical level of the organisation to assist with the design and definition of the maintenance plan to ensure desired equipment reliability. Lemmer (2016) argues that maintenance is principally an economic rather than solely a reliability problem, whereas RCM attempts at dealing with reliability and maintenance in relative isolation from costs and profit. Total Productive Maintenance (TPM) focuses on the operational level to improve overall equipment effectiveness while Quantitative tools, Tactical activity oriented stochastic tools, Operations Research (OR) and Management Science (MS) techniques are used at the tactical planning level to optimise policies, model failure and optimise maintenance resource management.

Maintenance Decision-making Techniques

Decision-making is a primary function of management, and so its importance should not be underestimated (Burnett & Vlok, 2014). Burnett & Vlok (2014) suggest that decision-making is a core managerial function and a critical enabler in managing an origination properly.

Fernandez & Marquez (2012) argue that decisions in maintenance management are generally accompanied by high levels of uncertainty. They further state that it is human nature to use emotional criteria to make decisions in instances where there is limited information and knowledge. In most cases, managerial decisions are based on human judgement, discussions and previous experiences, which are not ideal (Burnett & Vlok, 2014). Fernandez & Marquez (2012) highlight the problems associated with optimising the human decision-making processes and the need for a "deeper rational decision-making process" for strategic decision-making.

In the decision-making process human participation is required, thus making the understanding of the motivational factor in reaching a decision critical. Maslow presents the five motivational factors to be considered as:

a. Physiological: those that seek primarily to maintain physical equilibrium and survival;
b. Security: they search for protection against danger or threat;
c. Social needs: to be accepted by others to feel part of social groups;
d. Recognition: to be appreciated and valued by others; and
e. Need for fulfilment: to push people towards a total development and to use their full potential.

In addition, maintenance managers also use their own experience, skills and knowledge to make decisions (Fernandez & Marquez, 2012). Fernandez & Marquez (2012) stipulate the following issues when reviewing decision-making in maintenance management:

a. "There are different organisational levels (strategic, tactical or operational) that should be aligned to the company goals;
b. The maintenance department is always balancing the highest quality with the lowest possible cost;
c. Decision-making in maintenance is usually characterised by handling conflicts in conditions of stress and uncertainty. However, in maintenance it is unreliable or unjustifiable to use "intuition" or "smell";
d. In practice, the maintenance technicians often feel more confident with their experience, and this would influence their decision;
e. The decision will be conservatively based on levels of satisfaction instead of being optimal;
f. Maintenance decision-making is a complex problem that must be addressed following a well-structured method that takes into account the different criteria, alternatives and priorities;
g. Maintenance managers deal with methods that are characterised to search for an easy way of implementation, discrete volume of alternatives and values; and
h. Modelling techniques should foster anticipation regarding developments of non-controlled variables, based on their historical evolution individually, or on their relationship with other variables."

Burnett & Vlok (2014) discuss the requirement for numerical decision-making in AM, and specifically maintenance management. "Limited evidence of applying numerical decision-making techniques in practice was found and confirm…" (Burnett & Vlok, 2014). The real need for these techniques is to be simple and easy to use to make effective maintenance decisions, particularly in the operational environment. Decisions in this area are often required with little time and information available.

Burnett & Vlok (2014) mentioned that numerous types of decisions are required in physical asset management and specifically in maintenance. These decisions are mostly required at a tactical and operational level. They further comment that many different techniques can be used to support decisions of this type and include:

a. Critical analysis – focus on the identification and prioritisation of critical areas in a system by means of linear ranking;
b. Failure mode analysis – used to prioritise different failure modes and use linear ranking and tree analysis methodology;
c. Reliability analysis – focus on the statistical change of an event;
d. Failure statistics – investigate failure behaviours of systems or subsystems to calculate failure rates and estimated residual life;
e. Priority rating analysis – calculates importance in accordance to assigned weightings;
f. Decision tree analysis – maps logical events graphically to find alternatives to support decision-making process;
g. Alternative comparison methods – compare possible solutions relative to given criteria that relate to a given problem; and
h. Pareto Analysis (80/20 rule) – identifies 80% of the problems.

Fernandez & Marquez (2012) list a comprehensive list of maintenance management techniques and tools pertaining to decision-making. Current decision-making techniques that are relevant to Physical Asset Management (PAM) decisions are mostly designed to focus on one criterion while neglecting others (Burnett & Vlok, 2014). In maintenance management there is a need for decision-making techniques that support multi-criteria. Multiple attributes are involved when balancing different objectives such as minimizing consequences, maximising availability and reliability, to mention a few (Burnett & Vlok, 2014).

Multi-criteria decision-making (MCDM) methods are described as useful to maintenance managers as they "could be employed in both managerial levels on consort with other techniques…with the ability to relate as much quantitative and qualitative criteria" (Fernandez & Marquez, 2012). In prioritising possible solutions, maintenance managers require the evaluation of multiple criteria at strategic, tactical or operational level.

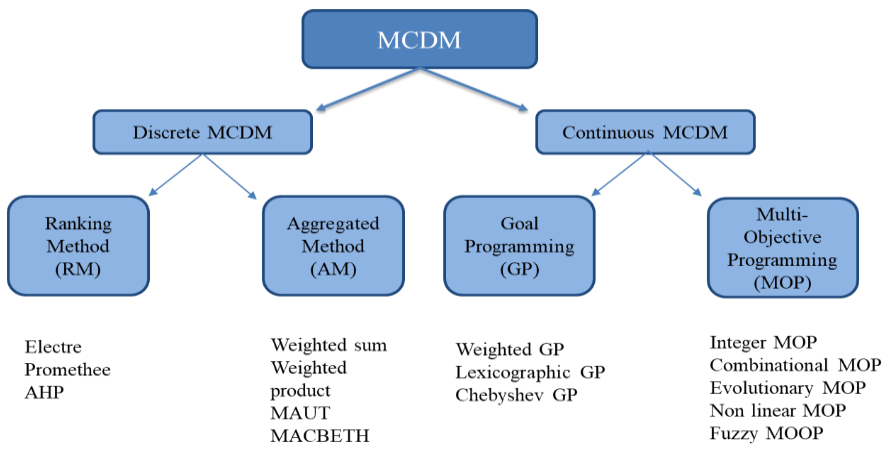


Figure 2.8 Multi-Criteria Decision-Making methods (Adopted from Fernandez, 2016)

MCDM methods and tools can be classified into the following classes and subclasses as described in Figure 2.8:

a. Continuous MCDM – an infinite set of options where efficient solutions are obtained by the optimisation of objectives according to determined restrictions, Multi-objective programming or satisfactory solutions could be determined by approximation of the set goals to predefined aspiration thresholds, goal programming.
b. Discrete MCDM – from a finite set of options where reasonable solutions could be ranked or aggregated employing criteria by weights of importance or preference prioritisation.

Fernandez & Marquez (2012) recommends that the choice of a MCDM method depends on:

a. Information required by the decision-maker;
b. Volume of alternatives to be managed;
c. Facilities for execution on computers; and
d. Volume of resulting information.

In cases where decision-making information is restricted and the volume of solutions is high multi-objective programming (MOP) methods are advised. Goal Programming (GP) methods can be selected when volumes of alternatives are high and a high degree of information is available for the decision-maker. Instances where the required information of the decision-maker is restricted and the resulting information can easily be obtained from a computer, the Ranking Method (RM) or Aggregation Method (AM) methods are preferred options (Fernandez & Marquez, 2012).

Decision-making in the operational environment is characterised by reduced information to the decision-maker. The numerical system should also be simple to implement. According to Figure 2.8, discrete ranking methods would be ideal for application in this environment. Typical ranking systems are:

- AHP
- ELECTRE
- PROMETHEE

Analytical Hierarchy Process

Analytical Hierarchy Process (AHP) is a typical ranking method developed by Thomas Saaty. Fülöp (2005) argues that an AHP is used to convert subjective data of relative importance in order to define a set of overall weights. Subjective data is constructed by comparing alternative pairs to determine relative importance. It follows thus that only two alternatives are considered at a time and are compared according to a given criteria.

The AHP models the required decision in a hierarchical structure showing the relationship of the goal, objectives (criteria), sub-objectives and alternatives (Fernandez & Marquez, 2012). AHP is based on three principles namely:

a) Decomposition;
b) Comparative judgements; and

c) Hierarchy composition or synthesis of priorities.

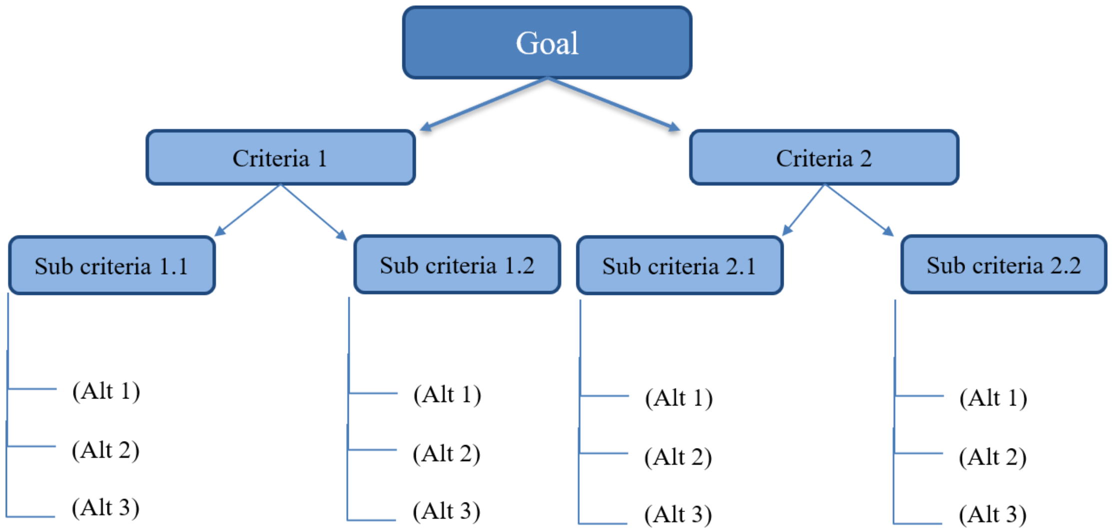


Figure 2.9 AHP decision hierarchy of clusters and sub-clusters (Adopted from Fernandez & Marquez,2012)

The decomposition principle is typically applied to deconstruct the required decision into a hierarchy of clusters and sub-clusters as indicated in Figure 2.9. Local priorities of the elements in a cluster are derived, with respect to their parents, with the use of pairwise comparisons (Fernandez & Marquez, 2012).

Alternatives are compared pairwise, with regards to a given criteria. This criterion is constructed as quantitative rates with qualitative descriptions as described in Table 2.1. Burnett & Vlok (2014) comment that knowledgeable decision-makers are required for these comparisons as it is subjective and based on the experience of the individuals.

Table 2.1 AHP Rating Scale (Adapted from Burnett & Vlok, 2014)

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

The comparison values are presented in an $n \times n$ square matrix, with the diagonal values equal to 1. Each level of the hierarchy is compared and assigned a comparison value. The highest level attributes are compared first. This matrix is labelled the comparison matrix or judgement matrix. This matrix is squared and normalised iteratively in order to find the steady state eigenvectors and eigenvalues for the $n \times n$ matrix. The decision-maker's consistency is measured to ensure that the comparisons remain consistent. The Consistency Ratio (CR) is calculated using the eigenvalue and the number of criteria

(Saaty, 1987). The *CR* must be below 0.1 to consider the judgement to be accurate. The *CR* is calculated by:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \tag{2.20}$$

$$\mathrm{CR} = \frac{\lambda - \mathrm{n}}{\mathrm{n} - 1} \tag{2.21}$$

where λ= eigenvalue, RI= Random Consistency Index and CI= Consistency Index, n = number of criteria.

AHP shows a high degree of accuracy and consistency compared to other ranking tools but as the size of the hierarchy increases, the number of required pairwise comparisons increases exponentially.

AHP is a popular ranking method but has two disadvantages associated with it (Saaty, 1987). Saaty (1987) identifies the first issue as a rank reversal problem should the alternatives become sizeable. The second problem that could arise is uncertainties when determining the pairwise comparisons.

ELECTRE process

Another prominent MCDS outranking method is the Elimination Et Choix Traduisant la Realité (ELECTRE), translated as "Elimination and Choice Expression Reality", family of methods. The first method in the ELECTRE outranking family of methods, ELECTRE I was developed by Bernard Roy in 1968. The following decade saw the development of this initial method in three more versions namely ELECTRE II (Roy and Bertier, 1971), ELECTRE III (Roy, 1978) and ELECTRE IV (Roy and Hugonard, 1982) (Swart, 2015).

Swart (2015) suggest that ELECTRE II is convenient for decision problems with few criteria and a large number of alternatives. In principle, ELECTRE II uses pairwise comparisons among alternatives under each one of the criteria separately. The relationship of two alternatives A_k and A_l, denoted $A_k \rightarrow A_l$, describes that in the event of A_k dominating or equal to A_l the decision-maker accepts the risk of regarding A_k more superior than A_l (Swart, 2015). Included in this approach is the notion of a benefit criterion and a cost criterion. In a benefit criterion the decision-maker expects to maximise the criteria whereas a cost criterion should minimise the criteria to attain the optimum alternative.

Saayt (1987) describes the steps of ELECTRE II as follows. It starts off after the structuring of the decision matrix that was described as part of the AHP criteria.

Step 1: Normalising the Decision Matrix.

In this step all the entries in the decision matrix are normalised. In so doing the entries are made dimensionless and thus comparable. Each entry x_{ij} is normalised to a value a_{ij} using the following equation.

$$a_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=0}^{m} x_{ij}^2}} \qquad 2.22$$

where $$x_{ij} = \begin{cases} x_{ij}, & for\ benifit\ criterion \\ \frac{1}{x_{ij}}, & for\ cost\ criterion \end{cases}$$

This leads to the construction of the decision matrix **A** as:

$$\boldsymbol{A} = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{m1} & \cdots & a_{mn} \end{bmatrix} \qquad 2.23$$

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

Step 2: Weighting the Normalised Decision Matrix

In this step the matrix A is multiplied by the weighting matrix ***W*** to provide the weighted normalised decision matrix $\boldsymbol{Y} = \boldsymbol{A} * \boldsymbol{W}$.

$$\boldsymbol{Y} = \begin{bmatrix} y_{11} & \cdots & y_{1n} \\ \vdots & \ddots & \vdots \\ y_{m1} & \cdots & y_{mn} \end{bmatrix} = \begin{bmatrix} w_{11}a_{11} & \cdots & w_{nn}a_{1n} \\ \vdots & \ddots & \vdots \\ w_{11}a_{m1} & \cdots & w_{Nn}a_{mn} \end{bmatrix} \qquad 2.24$$

where,

$$\boldsymbol{W} = \begin{bmatrix} w_{11} & 0 & \cdots & 0 \\ 0 & w_{22} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & w_{Nn} \end{bmatrix} \qquad 2.25$$

where N = n, and

$$\sum_{j=1}^{N} \sum_{k=1}^{n} w_{jk} = 1 \qquad 2.26$$

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,…,m and k ≠l) consists of all the criteria for which A_k is preferred to A_l.

$$C_{kl} = \{j, y_{kj} \geq y_{lk}\}, \qquad \text{for } j = 1,2,3\ldots,n \qquad 2.27$$

The complementary subset to C_{kl} is called the discordance set D_{kl} where,

$$D_{kl} = \{j, y_{kj} < y_{lk}\}, \qquad \text{for j = 1,2,3…,n} \qquad 2.28$$

These sets of concordance and discordance sets are calculated for each pair of alternatives.

Step 4: Calculate the Concordance and Discordance Matrices

The concordance index C_{kl} is used to calculate the relative value of the elements in the concordance matrix C (Swart, 2015). The sum of the weights associated with the criteria contained in the concordance set is equal to the concordance index c_{kl}. The concordance index can therefore never exceed 1 and never fall below 0.

$$c_{kl} = \sum_{j \in C_{kl}} w_{jj} \qquad \text{for j = 1,2,…,n} \qquad 2.29$$

where,

$$0 \leq c_{kl} \leq 1$$

The concordance index indicates the strength of the argument that alternative A_k outranks alternative A_l. The higher c_{kl} the stronger the argument that A_k is preferred to A_l as far as the concordance criteria are concerned. The concordance matrix ***C*** is defined as:

$$\boldsymbol{C} = \begin{bmatrix} - & c_{12} & \cdots & c_{1m} \\ c_{21} & - & \cdots & c_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ c_{m1} & c_{m2} & \cdots & - \end{bmatrix} \qquad 2.30$$

Where the concordance index is undefined for k = l. The discordance matrix D shows the strength of the argument that an alternative is worse than the competing alternative. The discordance index d_{kl} is defined as:

$$d_{kl} = \frac{max_{j \in D_{kl}} |y_{kj} - y_{lj}|}{max_j |y_{kj} - y_{lj}|} \qquad 2.31$$

where

$$0 \leq d_{kl} \leq 1$$

In the event of a higher discordance index, d_{kl}, the alternative A_k is less attractive than A_l and vice versa. The discordance indices are used to construct the discordance matrix *D*.

$$\boldsymbol{D} = \begin{bmatrix} - & d_{12} & \cdots & d_{1m} \\ d_{21} & - & \cdots & d_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ d_{m1} & d_{m2} & \cdots & - \end{bmatrix} \qquad 2.32$$

Similar to the concordance matrix ***C***, the entries of the discordance matrix ***D*** are not defined where *k* = l. Important to note is that matrices ***C*** and ***D*** are not symmetrical.

Step 5: Calculation of pure concordance and discordance indices

In this step both the pure concordance and discordance indices are calculated.. The pure concordance index is defined as:

$$C_k = \sum_{i=1, i\neq k}^{n} c(k,i) - \sum_{i=1, i\neq k}^{n} c(i,k) \quad 2.33$$

and the pure discordance index as:

$$D_k = \sum_{i=1, i\neq k}^{n} d(k,i) - \sum_{i=1, i\neq k}^{n} d(i,k) \quad 2.34$$

These indices are used to construct rankings of the alternatives. The average ranking between the concordance and discordance ranking of each alternative is calculated as the final ranking of the alternative.

PROMETHEE II

The "Preference Ranking Organisation Method for Enrichment of Evaluations"(PROMETHEE) method was first developed by Jean-Pierre Brans in 1982. Brans further developed the method in a family of PROMETHEE methods with various contributors listed below.

- PROMETHEE I (Brans, 1982)
- PROMETHEE II (Brans, 1982)
- PROMETHEE III (Mareschal et al.,1984)
- PROMETHEE IV (Mareschal and Brans, 1992
- PROMETHEE V (Mareschal and Brans, 1992)
- PROMETHEE VI (Brans and Mareschal,1995)
- PROMETHEE GDSS (Macharis et al., 1998)
- PROMETHEE GAIA (Mareschal and Brans, 1998)

The popularity of the PROMETHEE method can be credited to its being relative easy to understand. It is regarded as relatively simple compared to other MCDM ranking methods. As with the ELECTRE II method, the PROMETHEE II method is a complete ranking of alternative method.

Swart (2015) describes the PROMETHEE II method in six steps based on a three-phase approached procedure. In the first phase the objective is to build a value preference relation between alternatives for each criterion. The first step, in this phase, is to normalise the decision matrix. This is followed by weighting the normalised decision matrix. The last step in this phase is to use a predetermined preference function $P_j(k,l)$ to indicate the level of preference of intensity between alternative k over alternative l for criterion j.

Phase two continues with calculating a total multi-criteria level of the preference with which one alternative dominates over the other for each pair of alternatives. Thus in step four the multi-criterion preference index is calculated by summing the weighted values of the preference function for the complete set of criteria.

Phase three concludes with determining the rank by using the total multi-criteria level of the preference. In this phase the leaving and entry flows are calculated and used to calculate the net flows.

The six steps of the PROMETHEE II method are described in more detail below.

Step 1 Decision Matrix Normalisation

In this step the entries x_{ij} of the decision matrix are determined into dimensionless and cost/benefit entries as described in Equation 2.23. This step enables comparable a_{ij} values.

Step 2 Weighting the Normalised Decision Matrix

The normalised decision matrix, **A**, is multiplied by the weighting matrix, W, to produce the weighted matrix, **Y = A * W**. The entries y_{ij} indicate the relative importance of each criterion as described in Equation 2.24.

Step 3 Apply the Preference Function

In this step the pairwise comparison for each criterion is measured by using a predetermined preference function $P_j(k,l)$. The preference function indicates the strength of the level of preference of alternative k over alternative l with respect to criterion j.

$$P_{j(k,l)} = \left(a_{kj} - a_{lj}\right) \qquad if\, a_{kj} > a_{lj} \tag{2.35}$$

$$P_j(k,l) = 0 \qquad if\, a_{kj} \leq a_{lj} \tag{2.36}$$

Step 4 Calculate Multi-Criteria Preference Index

This index is calculated by summing the weighted values of the preference function for all the criteria. The index ranges between zero and one and indicates the preference of one alternative over the other with respect to all the criteria and is calculated as:

$$\pi\,(k,l) = \sum_{i=1}^{m} w_i P_i(k,l) \tag{2.37}$$

In the event of π (k,l) ≈ 0 the alternative k is a weak preference to alternative l whereas π (k,l) ≈ 1 is indicative of a strong global preference of alternative k.

Step 5 Calculating the leaving and entering flows

Following on from Step 4 the leaving flow, $\phi^{+}(k)$, provides for the sum of the indices, π (k,i) of a particular alternative k and gives an indication of the preference of this alternative over the rest of the alternatives.

$$\phi^{+}(\mathrm{k}) = \frac{1}{m-1} * \sum_{i=1, i\neq k}^{m} \pi(k,i) \qquad 2.38$$

The entering flow, $\phi^{-}(k)$, calculates the sum of indices π (i,k) and is indicative of the preference of all the other alternatives with respect to alternative k.

$$\phi^{-}(\mathrm{k}) = \frac{1}{m-1} * \sum_{i=1, i\neq k}^{m} \pi(i,k) \qquad 2.39$$

Swart (2015) states that alternative k is considered the superior alternative if its leaving flow, $\phi^{+}(k)$, is greater than, and its entering flow $\phi^{-}(k)$ smaller than, the corresponding flows of alternative l.

Step 6 (Calculate Net Flows)

The complete ranking of the alternatives is calculated by the difference of the leaving and entering flows for each alternative, called the net flow.

$$\phi(\mathrm{k}) = \phi^{+}(\mathrm{k}) - \phi^{-}(\mathrm{k}) \qquad 2.40$$

The dominant alternative will be characterised by a higher net flow.

Fernandez & Marquez (2012) suggest that a simple reference framework to facilitate the decisions making process in a maintenance management environment is considered a key criteria in choosing an appropriate MCDM technique. Simple MCDM techniques are associated with easier implementation strategies.

2.2.3. Maintenance Management Performance

Fernandez & Marquez (2012) proposes a network utility maintenance management performance framework that is based on the evaluation of maintenance management effectiveness and efficiency. Effectiveness is defined as the degree to which maintenance management ensures that the maintenance objectives are met (Marquez, 2007). Marquez (2007) further defines efficiency as the measure of how well maintenance is performed. It compares the quantity of services to the resource expenditure (Marquez, 2007).

Fernandez (2012) suggests the following categories for Maintenance Key Performance Indicators (KPIs) in a network utility maintenance environment:

a. Management and Organisation – Maintenance management leading activities and involved resources towards the defined objectives;
b. Financial – Maintenance management ensuring the generation of savings, reduction in the consequences of failures and pursuing business efficiency;

c. Business and Production – Maintenance management ensuring dependability of equipment or network service;
d. Quality and customer relationships –Maintenance management contribution to customer capture, retention and satisfaction;
e. Security and sustainability – Maintenance management protecting internal and external resources as well as the environment; and
f. Development and improvement – Maintenance management contribution to continuous improvement of processes and systems.

Kelly (2006) contends that a maintenance control system requires a maintenance efficiency and effectiveness measuring level with supporting objective hierarchy of maintenance key performance indices as shown in Figure 2.10. The left-hand leg of the hierarchy refers to typical KPIs controlling maintenance effectiveness while the right-hand leg refers to typical KPIs controlling maintenance organisational efficiencies (Kelly, 2006).

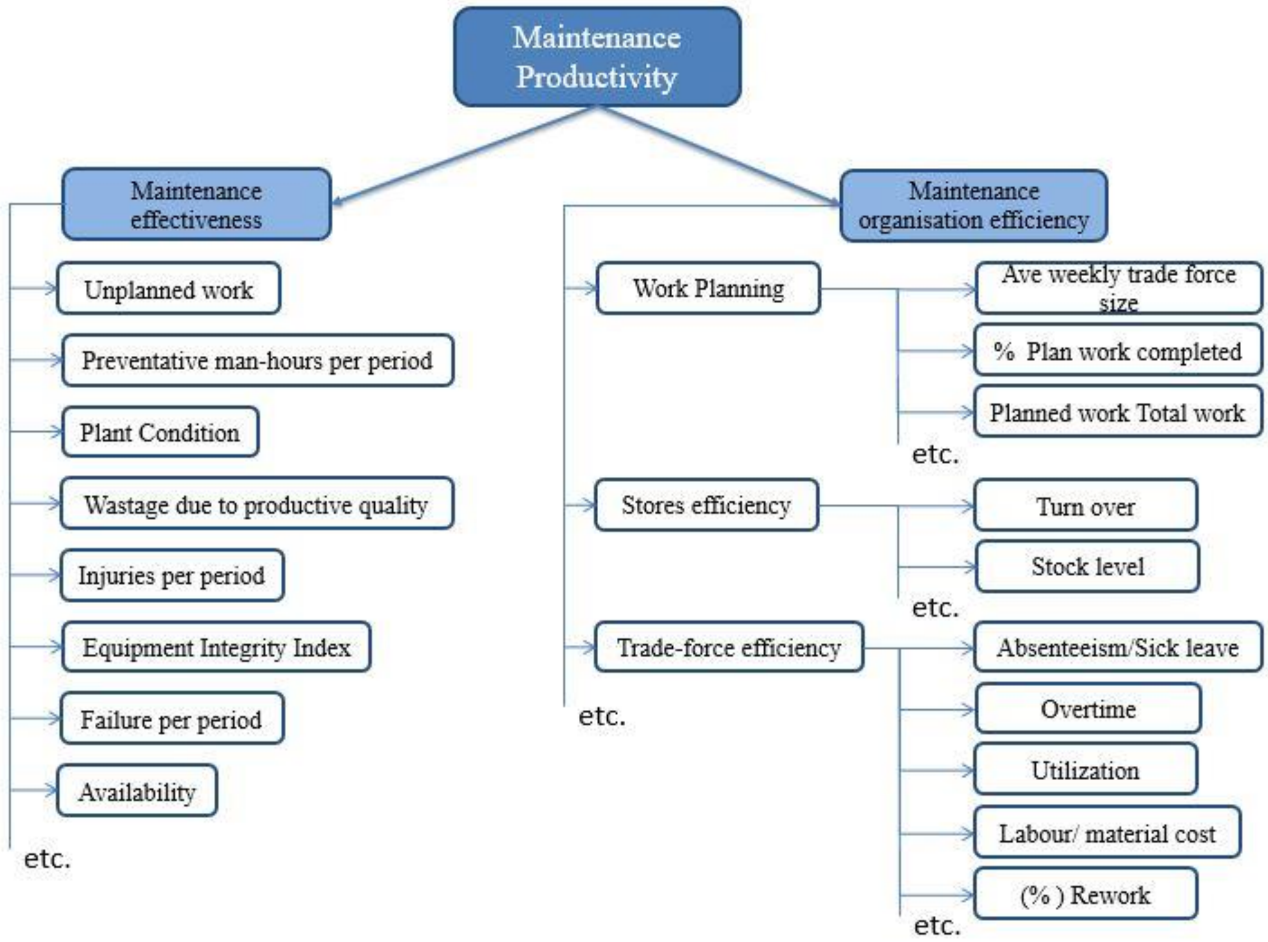


Figure 2.10 Hierarchy of maintenance performance indices (Adopted from Kelly, 2006)

Botha (2015) argues that the identification and quantification of relationships between KPIs within a performance management system (PMS) could greatly contribute to the decision-making process in Asset Management (AM). Botha (2015) introduces a modified Quantitative Relationships at Performance Management System (QRPMS) methodology. Traditionally, QRPMS is based on two mathematical techniques, Principal Component Analysis (PCA) and Partial Least Square (PLS), to identify and quantify inter-KPI relationships.

Rodriguez (2009) discusses the use of other multivariate statistical techniques; Factorial Analysis, Principle Component Analysis (PCA), Structural Equation Models (SEM) and Analysis of Variance (ANOVA). He concludes that depending on the number of variables (KPIs) for the study (number of columns in initial data matrix) and the number of observations for each of these variables (number of rows in the initial data matrix) the PCA and SEM method is the most appropriate technique. The SEM method is recommended if the ratio of variables to observations is at least 3:1."PCA is a multivariate statistical technique through which the important information in a multivariate data set can be reproduced… by newer and fewer variables called principle components (PCs)" (Botha, 2015). The technique uses the eigenvalues and eigenvectors of a covariance matrix containing observations from multiple variables. It then calculates new variables or principle components. Principle components are defined as linear combinations of the original variables. These linear combinations are uncorrelated to each other. The outcome of PCA is to calculate the correct number of PCs that will still produce an equal amount of information that was contained in the original multivariate data set. The critical step is to ensure minimal information loss from the original data set.

Traditional QRPMS uses Guttman-Kaiser criteria to determine the number of principal components to retain for further analysis. This criteria has been found unreliable and inaccurate (Botha, 2015). Botha proposes an improved methodology, Quantitative Identification of Inter-Performance Measure Relationships (QIIPMR). This methodology is based on the original QRPMS but replaces the Guttman-Kaiser criteria with the more reliable Parallel Analysis criteria and Scree plot. PCs are used to define "Business Drivers Key Performance Indicators" (BDKPI) and are assumed to be critical in terms of performance management in an enterprise (Rodriguez, 2009). The next step in QRPMS is to quantify relationships between the BDKPIs in terms of magnitude and sense. This is done through the application of Partial Least Square (PLS) models. The objective is to determine how good the applied PLS model is in predicting one effect BDKPI from one or more cause BDKPIs (PLS1 models) or more than one effect BDKPI from one cause BDKPI (PLS2 models). Rodriguez (2009) stresses the importance of the design of the PLS model that is to be construct with the input enterprise managers.

The outcome of QRPMS, or QIIPMR, is the identification and quantification of relationships between KPIs defined in a PMS which is projected upstream towards the strategic level of the PMS. This method can thus identify the Causal Business Driver Key Performance Indices (CBDKPIs) whose variation could potentially lead to non-achievement of objectives different to the ones they are associated with (Rodriguez, 2009).

2.2.4. Maintenance Optimisation Model Development and Validation

Maintenance optimisation framework is considered a system of rules of how different rules and ideas or techniques integrate and operate together for optimal maintenance decision-making (Tam & Price, 2008). Marquez (2007) states that the maintenance framework is the vital supporting structure and the basic system needed to manage maintenance.

Tsang *et al.* (2000) categorise businesses into three operational scenarios which impact on the maintenance strategies namely,

a) Cost constrained;
b) Capacity constrained; and
c) Compliance constrained.

Tsang *et al.* (2000) define cost constrained companies as companies which could sell more products if prices were lower. The focus on these types of businesses would be to control cost. Companies where all the products produced can be sold are called capacity constrained companies. The focus in this instant would be to maximise the output by maximising reliability, availability and maintainability of assets. Companies that depend heavily on compliance are referred to as compliance constrained businesses. Tam & Price (2008), however, argue that all asset intensive companies must consider all of the above constraints. In general, all companies engaged in asset management are constrained by cost, capacity and compliance and therefore all of these should be considered when optimising maintenance decisions.

Tam & Price (2008) further developed a model to integrate business decisions for optimising maintenance investments. They identify the three business decision dimensions as:

a. Output dimension – achieving the required production and service delivery objectives for operating the asset;
b. Risk dimension – cost of unexpected incidents; and
c. Resource dimension – resource requirements to support the maintenance function in order to achieve optimum performance with minimum cost or best outcome for given budget.

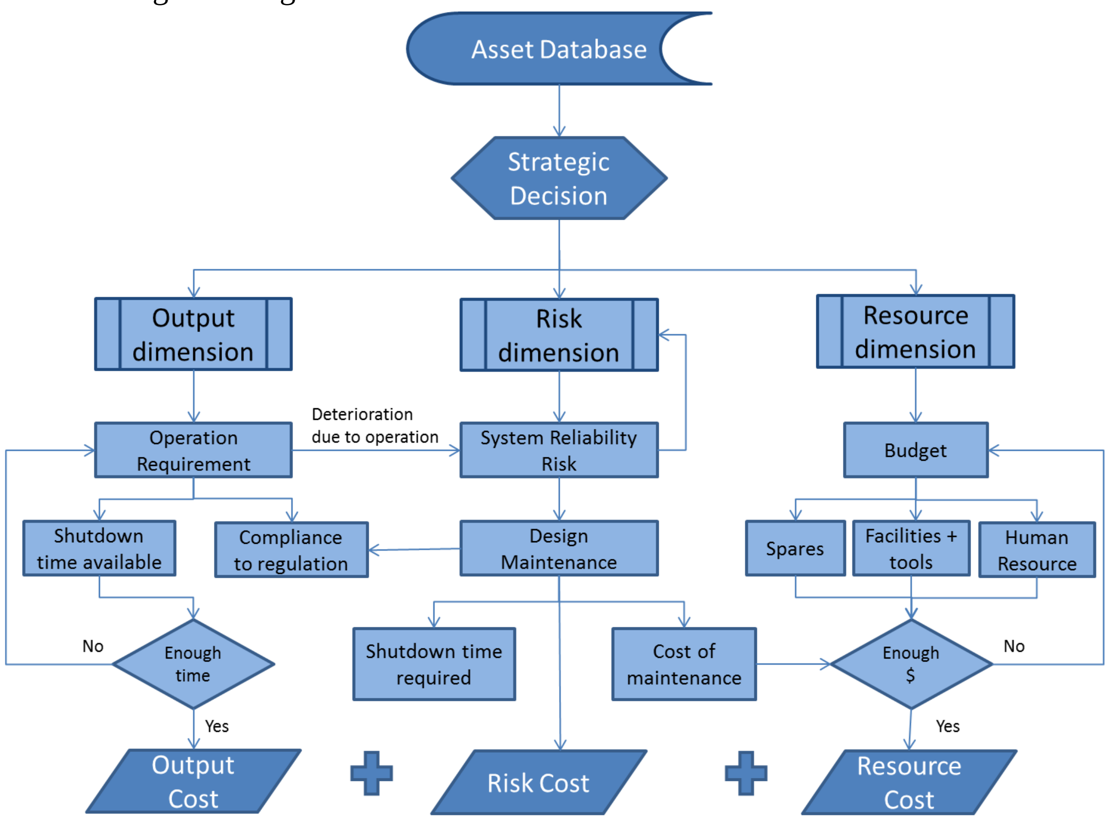


Figure 2.11 Maintenance Optimisation Framework (Adopted from Tam & Price, 2008)

According to Swart (2015) the Tam & Price Maintenance Optimisation Framework, as described in Figure 2.11, is "unique in that it prioritises… maintenance work in terms of maximising the return on maintenance investment under the constraints of both time and budget". Swart (2015) builds on to the framework to develop a shutdown maintenance priority framework. The building blocks are very similar but Swart (2015) introduces MCDM techniques such as ELECTRA and PROMETHEE to improve on the ranking of alternatives.

Marquez *et al.(*2015) proposes an asset criticality model that is based on risk- and cost-benefit analysis. The model ranks assets in terms of their importance in fulfilling certain business objectives. To generate a consistent criticality analysis the model is based on the use of the Risk Priority Number (RPN) analysis in conjunction with AHP to determine the weights of asset functional loss severity factors (Marquez, *et al*., 2015). This criticality methodology is focused on the operational phase to determine what assets should have priority within the maintenance management programme. The product of the functional-loss-frequency and the severity of the functional loss of the asset determine the criticality of the asset. The severity analysis is based on the business drivers set by management and shareholders. The model also considers "non-admissible functional loss effects" that will assign the maximum severity level, M_s, to the asset, regardless of any other criteria. This is required to highlight certain non-negotiable factors i.e. catastrophic safety considerations.

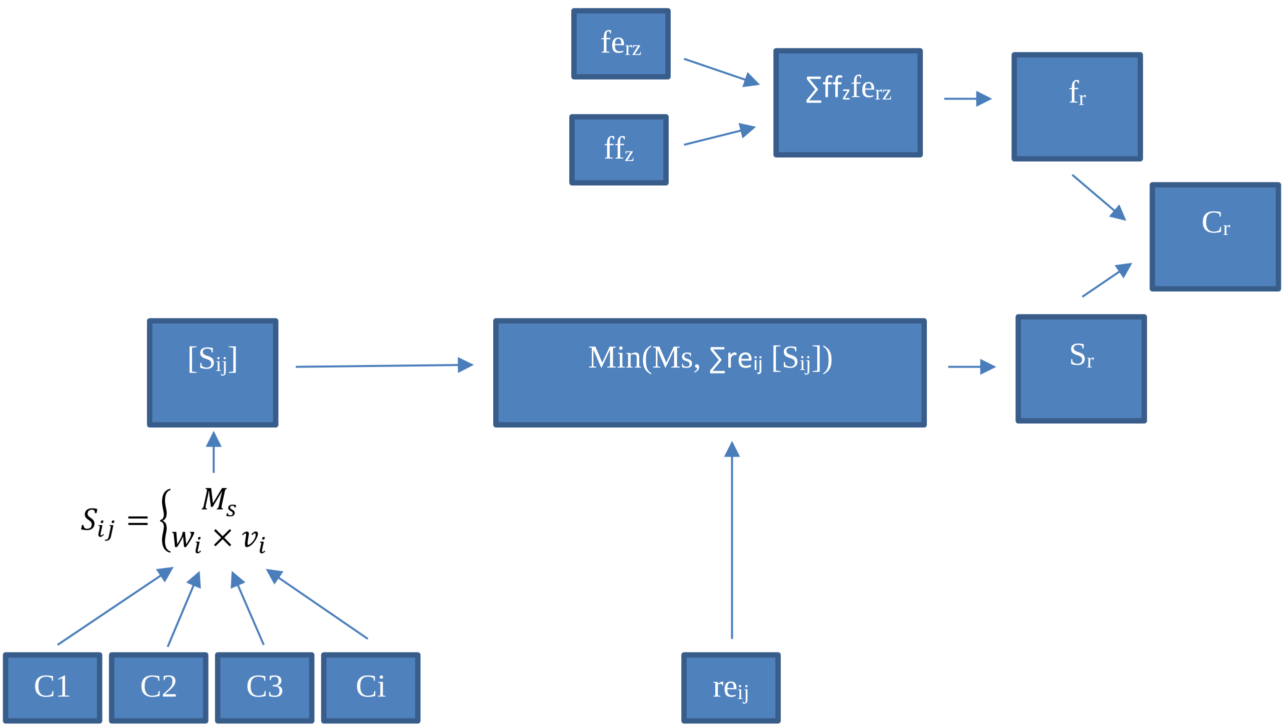


Figure 2.12 Asset Criticality Model (Adapted from Marques et al.,2015)

As indicated in Figure 2.12, the model uses frequency factors, ff_z, that are based on the functional failure rate of the assets under review. The assets are firstly ranked according to their functional failure rate and categorised as very high, high, medium or low functional-loss failure-rate levels. The average failure rate per category is calculated as af_z with z indicating the levels of functional loss frequency. The frequency factors are then calculated by

$$ff_z = \frac{af_z}{af_1} \; for \; z = 1 \ldots l \; levels \; of \; functional \; loss \; frequency$$

Where af_1 is the average failure rate of the lowest level. Actual frequency of functional loss data is captured in variables fe_{rz}. These variables are Boolean variables with the following values:

$$fe_{rz} = \begin{cases} 1, when \; z \; is \; the \; observed \; frequency \; category \; of \; element \; r \; functional \; loss \\ 0, otherwise \end{cases}$$

The frequency factor to apply to element r would then result in the following scalar product with:

$$f_r = \sum_{z=1}^{z=l} ff_z fe_{rz}$$

The severity of effects matrix, Sij, is calculated using "i" severity criteria. Each severity criteria is defined with "j" possible effects. Criteria with a non-admissible functional loss effects will force the severity potential to a maximum value, M_s, irrespective of the other criteria levels. In the event where business regards a potential fatality as a non-admissible functional loss safety effect, the model will secure the maximum severity potential, irrespective of other criteria. The AHP process determines the weighting of the criteria. The alternatives under consideration are limited to the number of severity criteria and not to the number of assets under evaluation. The limitation of AHP concerning the exponential increase of pairwise comparisons when there is an increase in alternatives to rank is thus negated. Marques further introduces a probability of criteria "i" with effect "j" variable, re_{ij}, to calculate the probability of the effect j due to the functional loss of asset "r".

$$S_r = Min\left(MS, \sum_{i=1}^{i=n} \sum_{j=1}^{j=m} re_{ij} S_{ij}\right)$$

The frequency factor for the specific asset, together with S_r is then used to calculate the asset criticality factor C_r. Marquez (2015) states that this asset criticality analysis is utilised during the operational phase and is different from the criticality analysis carried out during the asset design phase. Assets are prioritised based on quantified risk caused by asset failure as well as the severity of the failure affecting key business imperatives. Marquez (2015) highlights that potentially planned maintenance (PM) activities could be discarded on non-critical assets but care should be taken on activities that monitor asset condition and early asset deterioration. The severity of failure should be under control before PM activities are removed. The evaluation of risk should also recognise the Resnikoff conundrum (substantial failure data requires substantial asset failures but failure critical assets impacting serious safety factors will exhibit good performance and maintenance programmes on such assets should be designed without the benefit of failure data). Marquez (2015) states that this model has been implemented, since 2007, on critical infrastructures in Spain and South America on electrical power generation plants, network utilities (electricity, water and gas) and various transportation systems.

Model validation is considered a fundamental step for more scientific and effective decision support systems (Borenstein, 1998). Validation of a decision support system is defined by Finlay (1994) as the "process of testing the agreements between behaviour of the decision support system and that of the real world system being modelled". Validation can also be defined as the process to confirm that the model behaviour is representative of the real world system in the specific problem domain.

Borenstein (1998) presents a DSS validation method that is based on a formal model to validate Expert systems. The method is based on three principles as follows:

a. Formal validation. Validation occurs within the DSS development phase.
b. Prescriptive validation process. The validation is designed to be performed under research constraints.
c. Qualitative-based validation. This principle is based on the subjective comparison of performance.

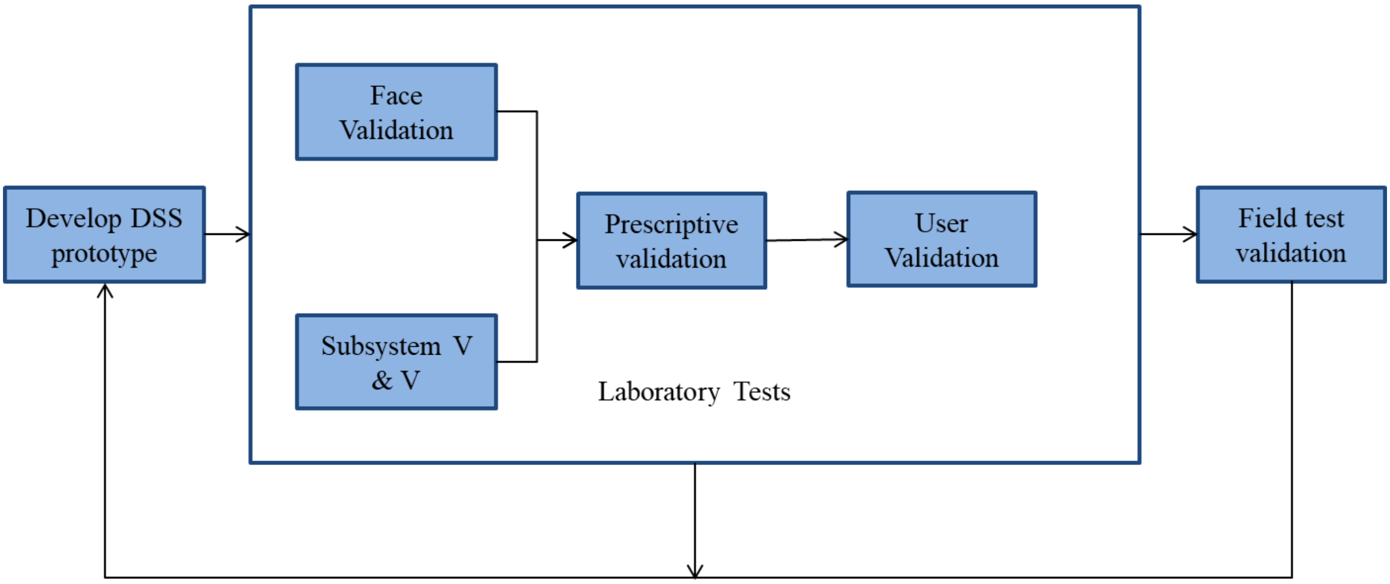


Figure 2.13 DSS Validation Process (Adopted from Borenstein, 1998)

The process starts off with the prototype development of the decision support system. This is followed by face validation. In this stage the objective is to achieve consistency between the developer's view and the potential user's view of the problem in a timely and cost-effective way. It provides feedback to the developer to assist with DSS refinement.

As described in Figure 2.13 the subsystem verification and validation stage occurs in parallel with face validation. This stage consists of testing, verifying and/or validating the DSS modules one at a time as it is developed. The objective of this phase is to ensure quality of each model in the sub-model component of the DSS. Both the face validation and subsystem verification and validation focus on the internal validity of the system.

Predictive validation is concerned with validating the system against known case studies. Past input data from previous test cases are used in DSS and compared to known results. In the user assessment phase, users who were not part of the concept, development or implementation phase, determine whether the results of the DSS can be used in decision-making. The main objective is (1) to ascertain the applicability of the system by possible users and (2) to assess the impact of the computational system assumptions, simplifications, methods and structure from an independent source. Field test validation happens in the real-world environment.

2.3. Maintenance Budgeting

Mathiba (2011) notes that trends in financial management reform indicate that budget reforms have been driven by the need to restrain expenditure for macroeconomic reasons and the need for financial performance improvement.

The second need specifically concerns the type of budgeting and financial management that could stimulate greater efficiency, effectiveness and higher quality. “Taken together, these pressures have led to… an expansion in the scope or purpose of budgeting.

Instead of a situation where budgets were mainly a process by which annual financial allocations were incrementally adjusted… the budget has become more intimately linked with other processes – planning, operational management and performance management” (Mathiba, 2011).

2.3.1. Budget Types

Mdlazi (2000) states that budgeting systems are categorised into input-orientated systems, activity (performance) measuring systems, performance objective/goal orientated systems and the medium-term expenditure framework. He further describes the following budget types:

a. Traditional line item budgeting (LIB) is a system with a focus on control where control is defined as that process of enforcing limitations and conditions set in the budget.
b. Programme budgeting (PB) consists of hierarchy of objectives, activity schedule, resource schedule and financial schedule in terms of standard expenditure items.
c. Performance budgeting (PeB) ties workload measurement to various activities. It considers the performance benchmark which must be economical, efficient and effective in utilities.
d. Planning-Programming-Budgeting System (PPBS) is a system with an economic planning orientation.
e. Management-by-Objectives (MBO) focuses on budgetary decentralisation. The focus is on executing approved plans as efficiently and effectively as possible through participation of lower level management.
f. Zero-Base budgeting (ZBB) focus on ranking programme priorities. The focus is on justifying expenditure to continue funding activities. It also examines the effectiveness of the programme.
g. Medium-Term Expenditure Framework (MTEF) focuses on a three-year budget.

LIB, as an input-orientated system, is the oldest form of budgeting, with simple implementation, associated with administrative honesty, is rather inflexible, not aligned to any policy and fails to show what funds were used for programmes (Mdlazi, 2000).

PB allocates funds to functions or activities and not to specific items. It also indicates priority of spending on more critical functions making it difficult for budget compilers to hide money in the budget. Unfortunately this kind of budgeting does not show the level of performance that functions should have for which funds were allocated (Mdlazi, 2000).

PeB is based on cost per activity as compared to performance of a service. It allocates funds and performance standards to each activity. In financial management this budget process can ensure efficiency and effectiveness as it monitors time, cost and standards of activities. Atrill & Mclaney (1994) also impart the importance of realising the difference between fixed and flexible budgets. A fixed budget remains the same whatever the level of activity of the business. The flexible budget will change according to the level of activity which the business is expected to achieve (Atrill & McLaney, 1994). Atrill & Mclaney (1994) recommend that in the preparation of flexible budgets it is necessary to divide cost into their fix and variable elements. It can then provide estimates of future expenditure levels for each possible activity. The concern with this type of budgeting is the breakdown of work into activities in some public environments and to establish reliable measures of work output (Mdlazi, 2000).

PPBS focuses on the needs of decision-makers. In this type of budgeting process planning defines options of operational goals while programming focuses on scheduling and implementing specific programmes to meet goals effectively and efficiently (Jones & Pendlebury, 1992). Budgeting focuses on the funds required for each goal and programme. This type of approach to budgeting is regarded as highly technical and complex to implement.

"MBO focuses on budgeting and employee behaviour to achieve the goal through participation, budget performance and comparison or competition. As a process it contains objectives, action plans, progress reviews and self-control" (Mdlazi, 2000).

ZBB has been defined as "…the preparation of operating budgets from a zero base; even though the budget process might be operating more or less the same as in previous years, the budget process assumes that it is starting anew…" (Jones & Pendlebury, 1992). According to Jones & Pendlebury (1992) the core elements of ZBB are:

a. Decision Units: The lowest organisational level at which a meaningful management decision is made.
b. Formation of decision packages: Each decision unit develops its own decision package that details the description of programme objectives and the amount of resources needed to execute such a programme.
c. Ranking of decision packages: Ranking of decision packages by means of set criteria.
d. Administrative Level: Ranking of decision packages at strategic level.

"ZBB... is sophisticated and overestimates the individual's ability to calculate and look at all the other alternatives for decision making" (Mdlazi, 2000). Mdlazi further notes that ZBB tries to impose a highly formal and economical approach to budgeting on a system in the public domain that is essentially based on political choice and political control.

Hastings (2010) also states that due to the "Maintenance Iceberg" concept, ZBB is difficult to implement because of the uncertainty of cost factors such as on-job training, absenteeism, travel time, weather delays etc. The "Maintenance Iceberg" concept implies that there is always an associated cost that is unknown and very difficult to quantify in advance. It extends from the idea that the size of an iceberg is far larger than what is visible above water and that it is difficult to quantify the size of the iceberg below the surface.

MTEF budgets "…are an analysis of existing and proposed programmes, supported by quantitative calculations where possible" (Gildenhuys, 1993). The budgeting method assists with understanding future expenditure and its impact on current programmes in the longer term.

2.3.2. Budget Cutback Management Theory

Budget cutback management theory means managing organisational change toward a lower level of resource consumption and organisational activity, by the application of a rational or incremental budget model (Ibrahim, 2017). The former models express reason rather than experience as the foundation of decision-making.

Ibrahim (2017) argues that "rationalism and incrementalist models of budgeting are not diametrically opposing viewpoints". It is pointed out that the rationalist model places emphasis on the value of analysis and comprehension while the incremental model regards interaction and selectiveness in decision-making as of utmost importance. Ibrahim (2017) continues to explain that both theories share the assumption that regards decision makers as goal-oriented actors. It is however argued that incremental models assume the current base as the previous period's budget or actual performance and adds incremental amounts for the new period. This approach assumes then that the goals of the company have not been adjusted. This could be fatal to a changing fiscal environment.

Ibrahim (2017) as well as Okubena (2016) propose that incremental budgeting should be the method of choice in an environment of economic decline as it places a restriction on substantial cutbacks. This is a safe strategy to minimise conflict between programme managers and policy makers. In contrast to these, Jimenez (2014) proposes a more rational approach to budget setting and suggests that "rational analytic techniques can help local governments target cuts to expenditures". Jimenez (2014) argues that "Analysis can be used as a tool to minimise (sic) political opposition, as when performance information is used to justify targeted cuts".

Private and public companies have, in recent times, showed a renewed interest in ZBB (Hopkins, 2015). Hopkins reports that "In the public sector, this stems largely from contemporary fiscal constraints precipitated by the 2008 recession". He further provides a comparison between private and public sectors in terms of ZBB implementation which is summarised in Table 2.2 below.

Table 2.2 Advantages and disadvantages of ZBB (Adopted from Hopkins, 2015)

Public Sector	**Private Sector**
Advantages	
• Supports cost reduction by encouraging active resource allocation over automatic budget increases • Increases organisational efficiency by forcing government agencies to work together in order to actively prioritise programme • Improves alignment of resource allocations with strategic goals by forcing	• Supports cost reduction by encouraging active resource allocation over automatic budget increases • Improves operational efficiency by challenging assumptions at every level, especially for organisations that are overly complex (for example, due to a merger or acquisition)

cost centre's to identify their mission and priorities • Improves public perception through perceived increases in transparency and accountability, both internally within their organisation and externally with the public	• Supports implementation of aggressive saving strategies by identifying priorities at the department or project level
Disadvantages	
• The ZBB process is costly, complex, and time-consuming • Implementing ZBB at all can be a major challenge for public-sector organisations with limited funding, and can constitute a major risk when potential cost is high and potential savings are uncertain • Government agencies may face extreme constraints relating to their ability to complete ZBB within a budget cycle and the availability of personnel to drive the process internally • Prioritisation process may be problematic for departments with intangible outputs	• The ZBB process is costly, complex, and time-consuming • Implementing ZBB can be a risk for corporations when the potential cost is high and potential savings are uncertain • Adopting ZBB can have unintended consequences on company culture and brand in the marketplace

According to Mo (2006), ”Zero-Based Budgeting was introduced in China in the early 1990 …”. Mo (2006) further argues that the ZBB practised in the Hubei province in China morphed into a target based budgeting (TBB) method. It further describes the constraint in implementing ZBB by the fact that departments were unable to change personnel cost. In this regard wage expenditures, which can compose more than 70% of local governments' budgets, were determined outside the process of ZBB. The unique aspect of this Chinese ZBB variant is that the application is limited to budget decisions of one type of expenditure, i.e. programme expenditures. The focus of the TBB approach is therefore on the variable cost proportion of the budget.

2.3.3. Reliability and Risk-based Budget Approaches

Traditionally, reliability studies focusing on generation, transmission and distribution systems are mainly in support of system planning (Ge, 2012). Ge (2012) reports that "recently, optimisation techniques in maintenance studies have been adopted to determine optimum maintenance intervals in systems. Multi-objective optimisation, risk-based approaches and stochastic and evolutionary-based optimisation techniques have been developed for transmission and distribution maintenance optimisation". These techniques still lack economic assessments of maintenance cost and its relation to a constraint budget (Ge, 2012). Brown (2000) suggests a budget constraint planning (BCP) methodology that recognises that budgets have a fixed ceiling similar to the Chinese TBB. The BCP problem formulation states that a utility is required to select projects to maximise its benefit without exceeding its budget. Li and Brown (2004) present an extension of BCP in the distribution maintenance environment. This approach ranks distribution maintenance activities based on reliability impact. Reliability is maximised by sequentially selecting the highest ranked tasks until either reliability targets are obtained or budget constraints are reached.

Jiang (2006) presents a Risk-Based Resource Optimisation model for a transmission maintenance system. The model is applied to a large US utility system. It creates an hourly trajectory of operating conditions over a budget period of one year. The maximisation of risk reduction is assumed by the benefit gained from maintenance selection. The model uses transformer dissolved gas analysis to determine risk and assumes appropriate maintenance activities to reduce risk. The assumption becomes problematic as the probability of maintenance to reduce this preserve-risk is very low.

Maintenance optimisation techniques, evident from the literature review, often use constant hazard functions to describe power system component failure rates. Network component reliability is often characterised by bathtub curve failure rates (Ge, 2012). Optimisation techniques also generate optimum solutions over one budget period. Grid utilities normally require a period of six years to complete a cycle of maintenance on all network components. Optimisation is thus required over multiple budget periods. In periods of budget contraction there is a tendency of top-down budget ceiling setting where maintenance managers need to react fast to implement fund reduction (Ibrahim, 2017). The model, therefore, needs to be adaptive to respond to these realities.

2.4. **Chapter Summary**

In this chapter, literature of the two principle research themes of the study is reviewed. The basic principles of Asset Management are reviewed with a strong focus on Maintenance Management and decision-making techniques in the operational and maintenance environment. Literature in maintenance performance management literature is reviewed with a focus on analysing relationships between KPIs within a performance management system as well as the construction and verification of decision-making systems. Finally, budget cutback theory is reviewed to understand the effectiveness of different budget methods in a financially constraint environment.

Chapter 3

Research Design and Methodology

This chapter discusses the specific research approach, objectives, data gathering and methods to address the research problem stated in Chapter 1. Firstly, the philosophical worldview and the research approach are presented, followed by a description of the research. The chapter concludes with a discussion on research methods.

3.1. Selection of Research Approach

Research approaches are plans and procedures for research that span the steps from broad assumptions to detailed methods for data collection, analysis and interpretation (Creswell, 2014). Creswell argues that the decision as to which research approach to follow depends on the following;

a) the "philosophical assumption the researcher brings to the table",
b) the research procedure (research design) as well as,
c) the research methods of collecting, analysing and interpreting data.

The selection is further influenced by the nature of the research problem, the researcher's personal experience as well as the audience of the study.

Creswell (2014) introduces three approaches to research with the following definitions:

> **Qualitative research** is an approach for exploring and understanding the meaning individuals or groups ascribe to a social or human problem. The process of research involves emerging questions and procedures, data typically collected in the participant's setting, data analysis inductively building from particulars to general themes, and the researcher making interpretations of the meaning of the data. The final report has a flexible structure. Those who engage in this form of inquiry support a way of looking at research that honours an inductive style, focus on individual meaning and the importance of rendering the complexity of a situation.
>
> **Quantitative research** is an approach for testing objective theories by examining the relationship among variables. These variables, in turn can be measured, typically on instruments, so that numbered data can be analysed using statistical procedures. The final written report has a set structure consisting of introduction, literature and theory, methods, results and discussion. Like qualitative researchers, those who engage in this form of inquiry have assumptions about testing theories deductively, building in protection against bias, controlling for alternative explanations, and being able to generalise and replicate findings.
>
> **Mixed method research** is an approach to inquiry involving collecting both quantitative and qualitative data, integrating the two forms of data, and using distinct designs that may involve philosophical assumptions and theoretical frameworks. The core assumption of this form of inquiry is that the combination of qualitative and quantitative approaches provides an understanding of a research problem rather than either approach alone.

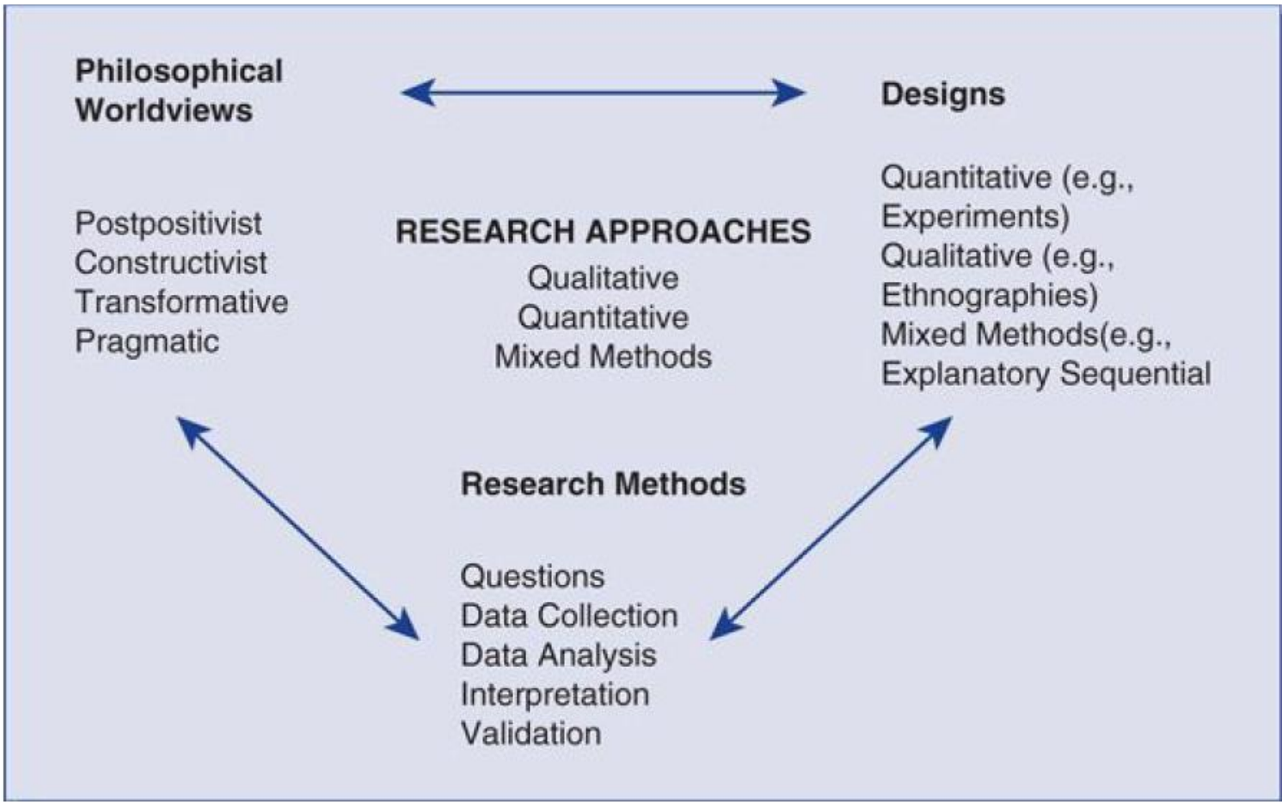


Figure 3.1 Research Framework (Adopted from Creswell, 2014)

Creswell (2014) defines Philosophical Worldviews as "a basic set of beliefs that guides the action". Bryman and Bell (2017) describes these set or cluster of beliefs as "paradigms" that dictate to researchers what to study, how research should be done and how results should be interpreted. Research paradigms can therefore be characterised through Ontology (What is reality?), Epistemology (How do you know something) and Methodology (how do you go about finding out?).

Table 3.1 Research paradigm, methods and data collection tools

Paradigm	**Methods (primarily)**	**Data collection tools (examples)**
Postpositivist	Quantitative.	Experiments, Quasi-experiments, Tests, Scales
Interpretivist/ Constructivist	Qualitative methods predominate although quantitative methods may also be utilised.	Interviews, Observations, Document reviews, Visual data analysis
Transformative	Qualitative methods with quantitative and mixed methods. Contextual and historical factors described, especially as they relate to oppression	Diverse range of tools – particular need to avoid discrimination, e.g. sexism, racism, and homophobia.
Pragmatic	Qualitative and/or quantitative methods may be employed. Methods are matched to the specific questions and purpose of the research.	May include tools from both positivist and interpretivist paradigms, e.g. interviews, observations and testing and experiments.

Creswell (2014) highlights four common paradigms in his research framework in Figure 3.1 and discusses their relationships with the different research designs and methods as indicated in Table 3.1.

3.1.1. Philosophical World View

This research will adopt a pragmatic world view and be placed within a mixed methods research approach. This is based on the assumption that collecting diverse types of data will provide for a more comprehensive understanding of the research problem than either quantitative or qualitative data alone.

3.1.2. Research Design

The proposed mixed methods design for this study is the convergent parallel mixed methods design which is applied on a single case study. The research problem defined in Chapter 1 focus on the South African Transmission Utility and the study is directed to gain insights into the underlying systematic issues pertaining relationships between maintenance planning, budget setting and TPG performance.

"Case study research is an empirical inquiry that investigate a contemporary phenomenon within its real-life context, when the boundaries between the phenomenon and context are not clearly evident…" (Yin, 2018). This type of research design allows for a more detailed focus at a micro level of the organisation as the data is researched within the context of use (Zaidah, 2007). Case study design with a mix methods approach for both data collection and analysis can assist with the understanding of the process and outcome of a particular phenomenon in a specific environment or case (Tellis, 1997). Multi source evidence, due to mix method approach, assist with depth of enquiry as well as triangulation. In addition Harris et al.(2017) categories case study designs as descriptive, exploratory, explanatory, illustrative or evaluative.

Table 3.2 Case Study advantages and disadvantages (Adapted from Yin,2018)

Advantages	**Disadvantages**
Evaluating data within the situation in which the activity takes place	Bias views could influence findings
Allow for both quantitative and qualitative collection and analysis of data	Small sample size offer little bias for scientific generalisation
Rich data corpus assist to explore, describe, explain, illustrate and evaluate phenomena	Labelled as long and difficult to conduct

This research design focus on exploring and explaining apparent and underlying themes within a real-life context as well as evaluating a DSS using a mix-method research design. An in-depth case study is performed on the South African Transmission Power Grid Utility in order to develop and validate a DSS within a budget constraint environment. The study focuses on a single utility, which is uniquely positioned as the only licensee to distribute bulk electricity at transmission-voltage levels in South Africa. Although the study can be classified as an intrinsic case, where insight is gained into a particular case, the opportunity exists to use the case to understand the broader issues. This will promote the understanding of the budget-maintenance-performance relationship phenomenon in a broader context relating to other electricity transmission utilities with fiscal constraints and a similar organisational structure.

Creswell (2014) explains that in a convergent parallel mixed method research design the researcher collects both quantitative and qualitative data, analyses them separately and then compares the results to confirm or disconfirm each other. The qualitative data collection approach will focus on gaining an in-depth perspective while the quantitative data collection approach will focus to generalise to a population. The data collection is primarily focused on a portion of the TPG where the qualitative data collections is extended to other portions of TPG. This was due to the restriction of secondary data from these areas.

The challenge in a convergent parallel mixed methods design is to merge data. This problem can be overcome by side-by-side comparison or transforming qualitative codes into quantitative variables. In the first approach the researcher makes the comparison in a discussion. In the second approach qualitative codes are transformed into quantitative variables and then the two quantitative data sets are combined. A final approach is to present both data sets graphically or in one table. The objective is to jointly display both data sets in a single visual.

As described in Chapter 1, the data collection phase of the research study will address the following research objectives:

1) Investigate relationship between maintenance planning and budget setting.
    a. Review the different types of maintenance budget methods.
    b. Study the different maintenance strategies and challenges in the TPS environment.
    c. Examine the relationship between maintenance budgets and planning.

2) Investigate relationship between power system performance and maintenance planning.
    a. Study the measurement of performance in a TPS environment.
    b. Examine how TPS performance is considered during maintenance planning activities.
    c. Investigate the comparison between transmission performance and maintenance plans

The qualitative data collection methods will include a literature review that will investigate the Asset Management knowledge base with specific reference to asset management decision-making in the operation and maintenance environment. The review will include a focus on maintenance decision-making methods as well as on budget procedures. The review concludes with an examination of the development of decision support systems and the validation of DSSs. Qualitative data collection will also include semi-structured interviews where operational maintenance and performance managers will be interviewed. Quantitative data collection methods will include secondary data collection from organisational documents, availability data, and maintenance cost and reliability information.

Data analysis will address the research objectives, (1c) and (2c) that concern the relationship between maintenance budgets, maintenance planning and system performance as well as the latent organisational reasons for these links or lack of them. The effectiveness of the DSS will depend on how maintenance planning decisions affect budget and performance outputs as well as other business objectives.

3.2. Research Methods

3.2.1. Qualitative Data Collection

An interview is a popular data collection strategy in both quantitative and qualitative research (Bryman. A., 2017). The methods that are employed under this type of strategy include structured interviews, used in quantitative research, and semi-structured and unstructured interviews used in qualitative research and focus groups. Bryman (2017) proposes that the selection of an approach to qualitative interviewing is based on: (i) the explorative or hypothesis testing nature of research; (ii) clarity of focus of the researcher; (iii) number of interviewers doing the field work; and (iv) whether the researcher is doing multi-case study research.

Kvale (2011) describes interview research as a “morale enterprise”. “Ethical problems in interview research arise particularly because of the complexities of researching private lives and placing it in the public arena” (Kvale, 2007). It is therefore critical that the interview design should include “obtaining the subjects’ informed consent to participate in the study, securing the confidentiality and considering the possible consequences of the study for the subjects” (Kvale, 2007). Bryman (2017) states that ethical principals in the research can be classified as:

a) Whether there is harm to participants;
b) Whether there is a lack of informed consent;
c) Whether there is an invasion of privacy; and
d) Whether deception is involved.

Written consent from research participants is therefore required to ensure that the interviewee will not be harmed, informed on possible consequences of study, prevent invasion of privacy and to prohibit deception (Bryman. A., 2017).

Kvale (2011) propose the following seven stages of an interview inquiry:

Thematising: Formulate the purpose of an investigation and the concept of the theme to be investigated before the interview starts. The why and what of the investigation should be clarified before the question of the how-method-is posed.

Designing: Plan the design of the study, taking into consideration all seven stages of the investigation, before interviewing. Designing the study is undertaken with regard to obtaining knowledge and taking into account the moral implications of the study

Interviewing: Conduct the interviews based on an interview guide and with a reflective approach to the knowledge sought and the interpersonal relation of the interview situation.

Transcribing: Prepare the interview material for analysis, which includes a transcription from oral speech to written text.

Analysing: Decide on the basis of the purpose and the topic of the investigation, and of the nature of the interview material, which modes of analysis are appropriate for the interviews.

Verifying: Ascertain the validity, reliability and generalisation of the interview findings. Reliability refers to how consistent the results are, and validity means whether an interview study investigates what is intended to be investigated.

Reporting: Communicate the findings of the study and the methods applied in a form that lives up to scientific criteria, takes the ethical aspects of the investigation into consideration and that results in a readable product.

(Kvale, 2007)

The research study will use semi-structured interviews as a qualitative data collection tool. This type of interview method allows for open-ended questions based on the research domain and is structured in such a way that the focus is placed on the ideas and opinions. Semi-structured interviews do not allow the interviewee the opportunity to speak unrestrictedly on the specific topic but the interviewer uses an interview guide to direct the interview with enough leeway to optimise data collection. The interviewer may use techniques such as paraphrasing, reflecting on, summarising and clarifying to assist interviewees to elaborate on their point of view. The method is well suited for an exploratory research study where the interest is in the underlying insights and perspectives of the interviewee (Bryman. A., 2017).

In this study the researcher will investigate how maintenance planning influences maintenance budget setting and how this then impacts TPG performance. The reason for using interviews as the preferred qualitative data-collection tool is to gain insight into operational maintenance and performance managers' understanding of the relationship of maintenance planning, budget setting and performance. The underlying issue of understanding these dynamics in a financially constrained TPG environment through analysing their experiences and self-understanding was a further reason for using this data-collection tool.

3.2.2. Qualitative Data Analysis

The use of qualitative descriptive data analysis research methods such as content analysis and thematic analysis is suitable for researchers who wish to employ a relatively low level of interpretation (Vaismoradi, 2013). Bryman and Bell (2017) argue that even though qualitative research often provides a great deal of descriptive detail in its report they do consider the explanations of certain perspectives and themes. In this study, it is important to understand the relations between concepts as experienced by maintenance managers. In addition to this there is a requirement, at a lower level, to understand why these relationships exist. Both content and thematic analysis approaches share the same aim of analytically examining narrative material " …by breaking the text into relatively small units of content and submitting them to descriptive treatment" (Vaismoradi, 2013). In using a content analysis approach, data can be analysed qualitatively as well as quantitatively. Thematic analysis provides for more qualitative perspective of a data set by identifying, analysing and describing themes across the data set. Thematic analysis shares some of the features of content analysis, as indicated in Table 3.3, but is more suited to investigating meaning in content (Bryman. A., 2017).

Table 3.3 Process in thematic analysis and qualitative content analysis (Adapted from Vaismoradi, 2013)

Analysis phases and their descriptions	
Thematic analysis	**Content analysis**
Familiarising with data Transcribing data, reading and rereading the data, noting down initial ideas.	**Preparation** Being immersed in the data and obtaining the sense of the whole, selecting the unit of analysis, deciding on the analysis of manifest content or latent content
Generating initial codes Coding interesting features of the data systematically across the entire data set, collating data relevant to each code.	**Organising** Open coding and creating categories, grouping codes under higher-order headings, formulating a general description of the research topic through generating categories and subcategories as abstracting.
Searching for themes Collating codes into potential themes, gathering all data relevant to each potential theme.	
Reviewing themes Checking if the themes work in relation to the coded extracts and the entire data set, generating a thematic map.	
Defining and naming themes Ongoing analysis for refining the specifics of each theme and the overall story that the analysis tells, generating clear definitions and names for each theme	
Producing the report The final opportunity for analysis. Selection of vivid, compelling extract examples, final analysis of selected extracts, relating the analysis back to the research question and literature, producing a report of the analysis	**Reporting** Reporting the analysing process and the results through models, conceptual systems, conceptual map or categories and a story line

The objective of the investigation is to identify and understand the relationships between maintenance planning, budget setting and TPG performance. The investigation also seeks to uncover latent organisational reasons for these relationships. It also investigates the levers available in maintenance planning to optimise the maintenance plan. The approach is to use the analysis in an inductive approach by developing themes from interview data.

Taking into consideration the requirements for an interpretative and inductive approach to the study, the researcher opted for a thematic analysis of the interview data set.

3.3. **Chapter Summary**

This chapter covers the research approach selected for this thesis. The research design focuses on the data collection and analysis techniques for the mixed method research study approach which is applied within a single organisation case study.

Chapter 4

Data Collection and Analysis within a Case Study

This chapter provides a detailed overview of the collection and analysis of the quantitative and qualitative data sets within a single-case case study. The case study organisation is describe as the South African Transmission Power Grid utility. It further describes the results as input into the development of the Maintenance Budget Decision Support System.

4.1. Case Study Organisation Description

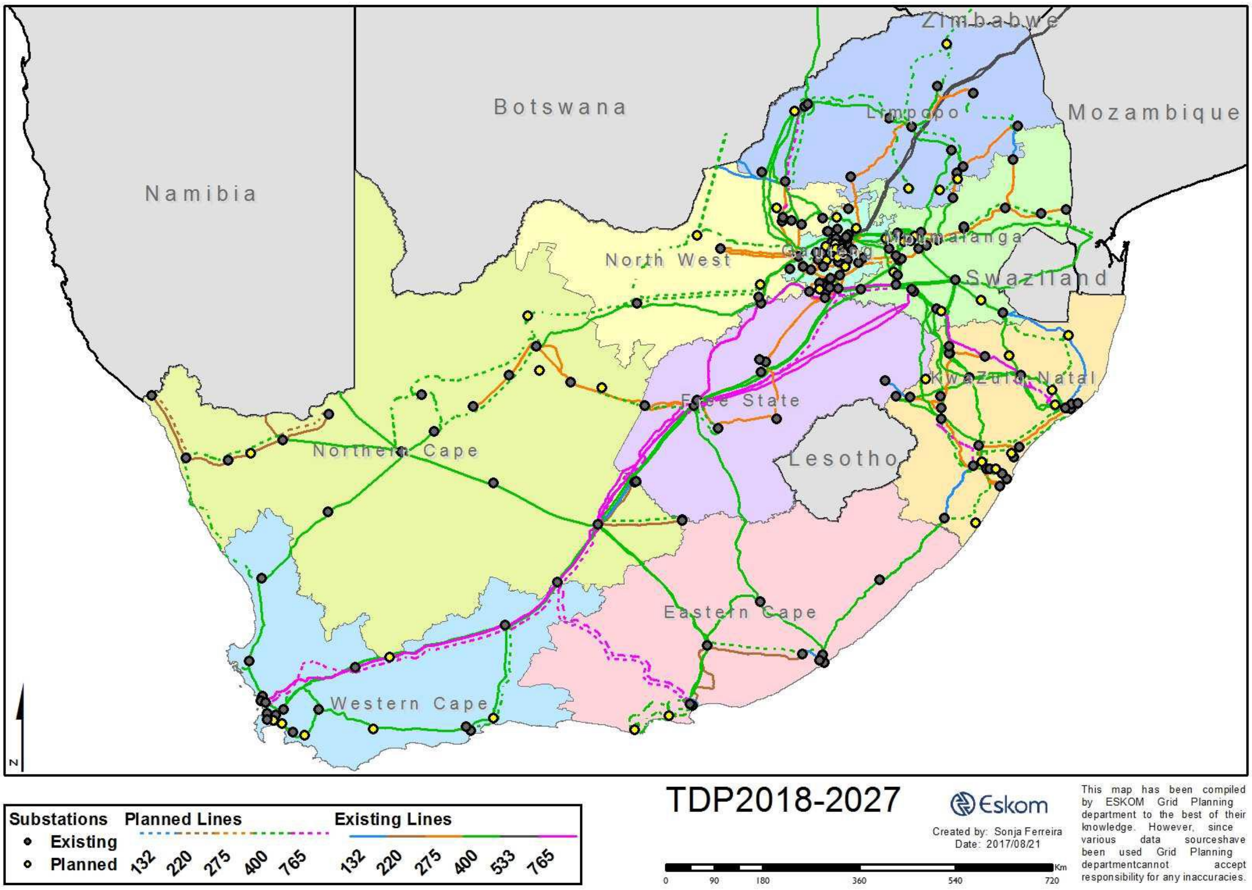


Figure 4.1 Eskom Transmission Power Grid (Adopted from Eskom Transmission Development Plan, 2018)

The South African Transmission Power Grid is divided into nine-plus 1 grids. These grids are aligned to the nine provinces of the Republic of South Africa. The (+1) grid status is assigned to Apollo substation, west of Johannesburg, which is a critical AC/DC interconnector supply point on the national grid which provides input from the Cahora Bassa hydroelectric generation plant in northern Mozambique. Each grid comprises of one grid manager and four operational maintenance managers.

Operational managers focus on different aspects of the TPG and manage the High Voltage Plant-, Secondary Voltage Plant-, Overhead Lines and Servitudes- and Performance and Works Planning departments respectively. In terms of maintenance planning and performance the grids are supported by a centralised works-planning department. This department ensures overall national compliance to maintenance strategies and measures maintenance performance.

The study focused on a portion of the Transmission Power Grid managed by the Eskom Transmission Western Grid division. The Western Grid provides backbone supply to the Western Cape province which is situated in the south-west of the Republic of South Africa. According to the Transmission Development Plan (2017–2028) the provisional load peaked at approximately 3900MW in 2017. This was approximately 9% of the total demand for that financial year.

The Western Grid is unique in that it provides grid connection to the only nuclear generation power station in the Eskom generation fleet. The Western Grid comprises of 17 major substations and 32000 km of predominately 400 kV overhead lines. The Grid also operates two 765kV overhead lines as well as one 132kV line that is designed at 400kV. This 132kV line provides the critical alternative offsite supply to Koeberg power station. The Grid also provides grid connection to one pump-storage hydroelectric generation plant and two Open Cycle Gas Turbine (OCGT) generation plants.

4.2. Qualitative Data Collection

Qualitative research is normally associated with an exploratory approach to research where certain underlying and latent perspectives and views are investigated. This type of research, in general, focuses on a bottom-up approach where the aim is to provide insight and understanding of the problem at hand. Qualitative research is inductive in nature where the study starts with observations and moves towards generalised theories.

4.2.1. Qualitative Interviewing as a Data Collection Tool

Qualitative interviewing was selected as a data collection tool to explore the understanding of the research problem as well as the relationships noted in the research questions described in Chapter 1.

The interviews were targeted at operational managers confronted with the particular research problem. The approach was less structured, in order to allow participants to express their views and perspectives. This data collection method allows for deeper exploration. It provides the opportunity to deviate from the interview schedule, permitting new questions based on interviewees' replies.

In understanding the latent concerns and issues of the research problem, the DSS can be designed to accommodate underlying matters in the work environment.

4.2.2. Ethical Considerations within the Interview Investigation

Bryman and Bell (2017) classify ethical principles in organisational research into four main areas, namely: potential harm to participants, potential lack of informed consent, potential invasion of privacy and whether deception is involved. Kvale (2007) notes that interview research involves human interaction and the knowledge created from these interactions has the potential to breach ethical considerations. Ethical issues go throughout the entire process of an interview investigation, and potential ethical concerns should be taken into account from the very start of an interview enquiry up to the final report (Kvale, 2007).

An informed consent form was developed to ensure that prospective interviewees provide voluntary and informed permission before the interview starts. The consent form highlighted the objective and the research method employed. It also highlighted risks and benefits to participants, conditions of participation and the withdrawal process. The form indicated the process of maintaining confidentiality as well as the management of data collected during the interview process.

The study was performed in accordance with Stellenbosch University ethics requirements.

4.2.3. Sampling Strategy

Qualitative interview sampling often shows very similar characteristics to sampling in ethnographic research (Bryman. A., 2017). Bryman (2017) further states that it is generally characterised by a lack of sampling strategy description. Vasileiou et al (2018) confirm this and further highlight sample saturation as a critical consideration in determining the size of the sample as well as a demographic description of the sample. They concluded that in qualitative research, sample size was normally justified "… with reference to the principle of saturation and to pragmatic considerations" (Vasileiou, 2018). Van Rooyen (2018) notes that the concept of sample saturation is vaguely defined in literature. Van Rooyen (2018) argues that the specific point of saturation can only be observed towards the latter part of the data-collection process. This requires continuous monitoring of the data being generated.

According to Bryman and Bell (2017), sampling in interview research is often a combination of convenience and snowball sampling. Access to a specific resource is often limited when organisations select interviewees rather than giving the researcher the opportunity to choose. Bryman and Bell (2017) further suggest that selection of participants is critical when employing non-probabilistic sampling techniques. The participants should find the topic relevant and they should represent the organisational grouping that has a specific interest in the topic. Bryman and Bell (2017) also argue that the sample size depends on a number of factors including time and cost. They further state that the absolute sample is more important than the relative size of the sample to the total population.

In this research study, the researcher had access to local operational managers. There was, however a limitation in terms of physical access to managers and engineers not based in the Cape Town area. Local bias was identified as a risk in identifying underlying aspects of the research problem. This risk was mitigated by recorded telephonic and MS Teams interviews with managers and specialists outside of the immediate Cape Town area. Snowball sampling provided further access to prospective candidates with specific experience and knowledge of the research matter. This was achieved through references provided by interviewees.

The number of operational managers directly involved in operational maintenance and operational management in the entire Eskom Transmission Division is approximately 50. The population considered was relative homogeneous as it comprised of individuals with identical or similar levels of authority in the organisation. Less variation was therefore expected and hence a smaller sample size was considered sufficient given the constraints in terms of availability of managers.

The participant recruitment strategy was to invite all the maintenance managers directly involved in operational and maintenance for the Eskom Transmission Western Grid as well as the senior manager overseeing this portion of the TPG. This would provide insight and understanding of local dynamics concerning the maintenance management of the specific portion of the TPG. The recruitment was extended beyond the Western Grid management team to similar levels of authority still within Transmission. Maintenance and Performance Management in Eskom Transmission is well standardised with all the Grids complying with a central maintenance management strategy and management accounting system.

The study used a sample of 10 participants out of a population of approximately 50 transmission operational maintenance managers. As indicated in Table 4.1 the 10 participants represented an average related experience of approximately 17 years per participant. The related experience referred to experience gained in maintenance and performance management in a transmission utility environment. Regarding qualifications, 90% of the participants had electrical engineering qualifications, with one manager having an applied mathematics qualification. Furthermore, 20% of the sample had relevant work experience outside the Eskom environment while 50% had relevant work experience outside an Eskom Transmission environment, predominantly in an Eskom Distribution setting. In addition to this, 40% of the sample also had direct experience in maintenance management on a national tactical level while at least 20% had experience on a strategic level.

Table 4.1 Participant demographics

Demographics	**Mean**	**Range**
Related experience in years in Eskom Transmission	17 years	6–30
Gender	Female	30%
	Male	70%
Education	Engineering	90%
	Science	10%
Level in Organisation	Operational	40%
	Tactical	40%
	Strategic level	20%
Related experience outside Eskom (additional to internal experience)		20%

The recruited participants held positions such as Senior Grid Manager, HV Plant Manager, Secondary Plant Manager, Lines and Servitude Manager, Performance and Works Planning Manager, Senior Business Consultant (Works Planning Centralised Services) and Senior Business Analyst (Works Planning Centralised Services).

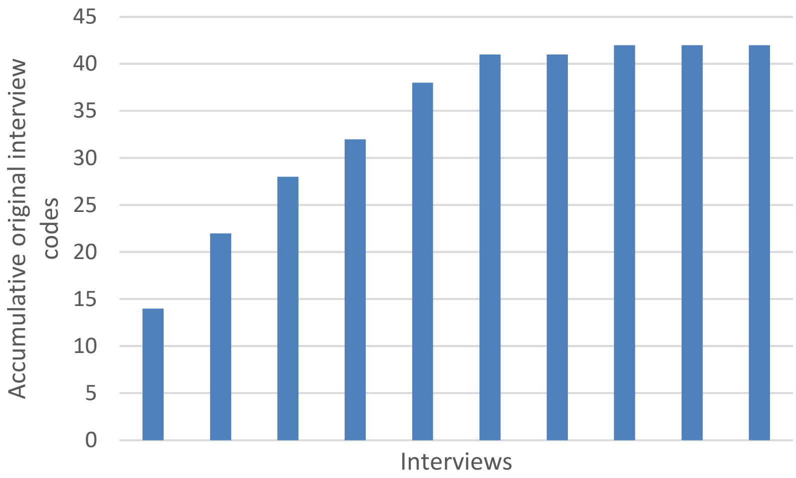


Figure 4.2 Interview code generation

Originally, 42 interview codes were identified. In Figure 4.2, data saturation occurred after the 8th interview. The graph indicates the accumulative interview codes uncovered after each interview. No new interview codes were identified after the 8th interview. This confirmed the adequacy of 10 interviews by means of the saturation principle.

4.2.4. Semi-structured Interviews

Qualitative interviewing comprises of two main types of interviews, namely: a) unstructured interviews, and b) semi-structured interviews. This research study had a very clear focus and therefore semi-structured interviews were more suited to ensuring that the specific research objectives were addressed. The objective of the investigation was to explore the latent reasons for the evident relationship between maintenance planning, budget setting and performance of the power grid. The interview objective was not to determine the strength of the relationships but rather the underlying basis for the relationships.

Invitations to prospective participants were preluded by face-to-face research introductions, phone calls or email. These introductions were followed up with a formal interview appointment on email or MS Teams which included the following documents to assist in interview effectiveness as well as ethical clarity and transparency;

- An information sheet that included information on the research-study background, problem statement and objectives. The objective of the document was to provide the prospective interviewee with the necessary references in order to prepare for the interview.
- Institutional permission letter confirming permission given to researcher to perform the study within the organisation.
- Written consent form that provided clarity on the risk and benefits to interviewee, participation and withdrawal stipulations, confidentiality as well as data management. The signoff of the consent form confirms the participant's willingness, after reviewing all the relevant information, to participate in the study.

The researcher noted and applied the following criteria for a successful interviewer proposed by Kvale (2007):

- The interviewer should be knowledgeable on the focus of the interview. The interview focused on maintenance management. The interviewer had approximately 15 years operational experience at management level in maintenance management.

- Interview guides provide structure and purpose in the interview. The development of an interview guide was used to provide purpose and direction during the interview. This guide is attached in Appendix B.

- The interview should be clear. The guide contained simple and short questions. The interviewer first asked the question and then provided context to the question.

- The interviewer should be gentle. The interviewer allowed people to finish and only interrupted when the answer drifted to far from the focus. The interviewer also allowed time to think. The interviewer gave the interviewees' the option of responding in either Afrikaans or English. Most of the interviewees chose English as this was the business language most often used and most of the terminology referred to was better expressed in English. The interviewer, however, was still critical and prepared to challenge inconsistencies in a manner so as not to cause professional offence to the interviewee's opinion.

- The interviewer should be sensitive. The interviewer listened attentively to what was said and how the interviewee responded. Acknowledgement was given throughout the interview for critical insights by verbal and non-verbal cues. These responses were also given to what the interviewee regarded as important.

- The interview should be able to steer the interview into the direction required without placing restrictions on the interviewee.

- The interviewer should listen attentively with the focus to remember even if the interview is recorded. This is to relate to what was said. After each long response the interviewer attempted to summarise the response in short and provided the interviewee to correct any misunderstanding. The key words of the summary were recorded to assist with future references in the interview.

Bryman and Bell (2017) further recommended that interviewers should be balanced in their approach and not talk too much. The interviewer should also be ethically sensitive and ensure that the participants understand the objective of the research as well as the associated confidentially concerning their responses. The interviewer started all the interviews by asking the interviewee to share their related experience in maintenance management. The question was twofold in collecting demographic detail on the sample as well as putting the interviewee at ease by asking them to share something about themselves.

Bryman and Bell (2017) proposed that the interview questions be formulated to assist with answering the research questions. The interview guide was structured by linking the interview questions with the qualitative data-collecting research objectives. This was done to provide focus during the interview as well as to assist with analysis at a later stage. Bryman and Bell further proposed that the sequence of questions should allow for a flow but cautioned the interviewer to be prepared to change this order if the interview required it.

Kvale (2007) proposed that in qualitative interviewing nine types of questions can be utilised. Introduction questions open the interview and are normally a follow-on question from a brief description of the research. Kvale (2007) argues that, depending on the type of research the brief on the objective of the research could also happen at the end of the interview. It was deemed important to provide a brief description of the research before the interview started. This would provide context to the questions and prepare the interviewee as to what the objective of the interview was. The introductory question was also used to put the interviewee at ease with the interview process.

Kvale (2007) further described follow-up questions as invitations to the interviewee to continue with a specific theme to gain more clarity. This is not necessarily a question and could be a notion or repeat of a specific word or phrase. Follow-up questions required the interviewer to listen attentively in order to recognise subjects in the reply, that could unlock further relevant themes.

The interviewer uses probing questions to probe the answers given without stating what dimensions were to be taken into account (Kvale, 2007). These questions will typically ask for more examples of a specific event or more detail on what happened.

In a discussion with many generic statements, Kvale (2007) also suggested that the interviewer use specifying questions to follow-up and ask for a more detailed description. This also assisted to provide focus on the interview and to lead an interviewee in a specific direction.

According to Kvale (2007) direct questions are used to introduce new topics for discussion. He further suggests that direct questions can also be held back until later in the interview. This will provide the interviewee to proceed with a more spontaneous and unrestricted reply on the topic of discussion. In this approach, the interviewer can use direct questions to focus on the aspects more central to the research.

Indirect questions are described as projective questions such as “How would other TPGs optimise maintenance to improve cost efficiencies?”. Kvale (2007) argued that this may well be an indirect statement of the interviewee’s own preference to a certain challenge.

Structuring questions allow the interviewer to lead the interview in the required direction. These questions are used to directly and politely break off long-winded answers that are irrelevant to the interview.

Kvale (2017) recommends silence in the interview to give the interviewee a change to associate and reflect. This can provide the opportunity for more meaningful information than continuously bombarding them with questions. Kvale (2007) describes interpreting questions as merely rephrasing an answer in an attempt to clarify or confirm a particular response. It could also be a more direct interpretation of what the interviewee is actually saying. Kvale (2007) notes that interviewing experts and individuals in management positions is different from interviewing children. Experts and people in authority are used to being asked their opinion and thoughts. It is important that the interviewer shows knowledge on the topic under discussion and uses the technical language associated with the environment.

The interview guide focused on six research themes. The research themes were aligned to the data-collecting research objectives of the study as stated in Chapter 1. The following themes were noted in the guide:

- **Relationship between maintenance planning and budget setting** – Investigate how maintenance planning influences the budget-setting process and how the budget influences maintenance planning. Explore what the latent reasons are for this relationship. It was important to understand these associations in developing the DSS.

- **Budget-setting strategy** – Investigate the budget-setting strategy and the limitations and opportunities within the strategy that are being employed. In addition, explore the reasons for the particular strategy. It was deemed important to understand this process as it will determine where to optimally position the DDS and what outcome is required.

- **Maintenance strategy** – Investigate the maintenance strategy being employed and what the potential opportunities are in terms of optimisation.

- **Relationship between maintenance planning and performance** – Investigate how maintenance planning and the power system performance influence each other and what the underlying reasons for this are.

- **Maintenance optimisation** – Investigate how maintenance is currently optimised and what kind of variables are considered.

- **Maintenance DDS criteria** – Request the interviewer's opinion on what criteria would be critical for a Decision Support System and why this would be important. Also, explore the availability of information.

4.3. Thematic Data Analysis

Thematic data analysis revealed 42 codes after ten interviews. Data saturation was achieved after the 8th interview as indicated in Figure 4.2. The codes are described in the interview-coding sheet in Appendix E . During the thematic coding process, described in Chapter 3, consideration was given to both the latent as well as apparent content. Emerging codes were then clustered and classified into basic themes. The analysis revealed 18 basic themes. The basic themes were further aligned to six research themes described in 4.2.4.

4.3.1. Research Theme 1: The Relationship between Maintenance Planning and Budget Setting

The interview process revealed three basic themes associated with the relationship between maintenance planning and budget setting. The themes were built out of eight codes as indicated in Table 4.2.

The interviews revealed a consensus that maintenance planning does not influence budget setting at a corporate level. Respondents agreed that planned maintenance requirements are adjusted to the provisions in the maintenance budget rather than the budgets being influence by the maintenance required. It was further suggested that maintenance plans be optimised over a longer planning period to ensure a consistent maintenance execution rate. This will ensure that resources are evenly spread out over a multi-year planning period without extreme peaks and low demands on financial and human resources. This should also be matched with the maintenance capability of the organisation in terms of available skills and physical resources to execute maintenance.

Table 4.2 Basic themes related to relationship between maintenance planning and budget setting

Research Theme	Basic Theme	Code Description
Relationship between maintenance planning and budget setting	Maintenance planning does not impact budget setting	Maintenance planning does not impact on budget setting
		The maintenance plan is fitted into the budget that is provided
		Budget and resources influence the maintenance plan
		Although budget is fixed there is flexibility in terms of moving funds around within operational budget to address critical unplanned events
	Requirement for rationalised approach	There is a requirement for ZBB approach to budget setting
		Incremental budget setting promotes spending of entire budget
	Difficult to quantify maintenance cost per asset within MMS	Quantification of maintenance cost is problematic
		Operational units cannot justify maintenance plan financially

The maintenance plan is fitted into the maintenance budget by moving funds within the budget from non-critical projects to more critical maintenance work. The criticality is normally based on the short-term impact on the actual network with a key consideration on the System Minute (SM) loss potential. SM is an international network index where one SM is equivalent to an interruption of the total system load for one minute at the time of the annual system peak.

$$SM = \frac{Load\ interruption\ (MW)\ x\ duration\ \ (minutes)}{Eskom\ Transmission\ Network\ Annual\ Peak\ (MW)} \qquad 4.1$$

SM is further defined in (NERSA, 2016) as the aggregate of unsupplied energy over the system annual peak demand and is referenced in the Multi-Year Price Determination methodology as a Transmission Service Quality Incentive/Penalty. Furthermore, NERSA further states that, if allowed cost for system reliability is underspent and SM targets are not achieved they are entitled to a clawback of the underspent funds (NERSA, 2016).

Respondents also suggested a more rationalised approach to budget setting. According to the respondents, the current incremental budget-setting strategy promotes spending. ZBB could potentially ratify maintenance budget requirements.

It was further recognised that a rationalised approach is restricted by difficulties in quantifying maintenance costs at asset level due to the configuration of the accounting system. Cost centres are only defined up to substation location level. Labour cost is not necessarily booked to the substation where maintenance was done while maintenance spares costs cannot be linked to the asset they were used on. Labour time and associated travel time is booked on work orders but these are not consistent and accurate enough to analyse and predict. Respondents find it difficult to justify maintenance allocation at asset level. This further restricts the ability of quantifying maintenance planning in financial terms.

4.3.2. Research Theme 2: Budget-Setting Strategy

There was a consistent view, across the interview sample, that the current budget-setting strategy is based on an incremental budget-setting philosophy. The maintenance budget is further apportioned between the operational grids, as described in Table 4.3, based on the population of employees and network assets.

Table 4.3 Basic themes related to budget-setting strategy

Research Theme	**Basic Theme**	**Code Description**
Budget-setting strategy	Predominately incremental budget setting using population count to assign budget to different grids	Incremental budget setting
		Incremental budget setting in combination with equipment population count used to apportion funds between operational areas
	ZBB strategy employed as required	Limited ZBB as required by business during cost-cutting budget reviews
	Budget structure	Budget structure with high employee salary portion

According to the respondents, the budget structure is characterised by a high employee benefit portion. This limits possible savings due to a possible reduction in maintenance execution reduction that could be realised by maintenance optimisation. Employee benefit cost is largely classified as a fixed cost. It is not dependent on the amount of maintenance work done in a financial year. This excludes travel and subsistence (T&S) costs as well as overtime costs.

Effective maintenance resource planning could increase employee productivity. The notion of centralised maintenance resource planning was suggested to utilise resources more efficiently in order to support the maintenance plan.

The ratio between the variable maintenance cost allowance and total maintenance budget is perceived to be low as the employee benefit costs absorb a substantial proportion of the budget. Maintenance activities that have a substantial impact on the variable component of the budget are identified as:

- Vegetation management under overhead lines and substations (planned activity);
- Transformer intrusive maintenance i.e. tap changer maintenance and corrosion protection (planned activity);
- Major building maintenance (unplanned activity);
- Circuit breaker maintenance kit (planned activity);
- Aerial overhead line inspections (planned activity);
- Activities requiring T&S cost (planned and unplanned);
- Activities requiring overtime expenditure (planned and unplanned);
- Infrastructure repairs i.e. overhead towers, breaker mechanism replacements etc. (unplanned activity).

The interview process revealed that limited ZBB philosophy is employed. This is only utilised as required by business during cost-cutting reviews.

4.3.3. Research Theme 3: Maintenance Strategy

In this research focus area, five basic themes were identified. There was a unanimous response that the organisation has a mixture of time- and condition-based maintenance approach. Although the current approach is still largely time-based, respondents reported on a change in strategy towards a more condition-based approach. It was recognised that equipment with high-maintenance cost-intensive activities is normally equipment that exhibits wear-and-tear failure characteristics. Equipment types such as power transformers and high voltage breakers would normally fall into this class. This failure characteristic normally aligned well with a time-based approach as described in Figure 2.3 where the risk of failure increases with time. Equipment types with low-maintenance cost-intensive activities, such as newer generation protection scheme control panels, are often self-monitored as it exhibited a more random failure characteristic.

Table 4.4 Basic themes related to maintenance strategies

Research Theme	Basic Theme	Code Description
Maintenance strategy	Mixture of TBM, CBM and plant performance	Mixture of TBM and CBM
		Performance of equipment impacts maintenance planning
		Predominant time-based maintenance strategy
	Planned outage optimisation	Maintenance cluster to optimise plant outages
	Evolving maintenance strategy	Require condition-based approach to maintenance Strategy
	Maintenance strategy influenced by the Regulator	Maintenance strategy influenced by Electricity regulator
	Challenges in executing maintenance strategy	Constraint in spending maintenance budget due to procurement and resource challenges

These equipment types are well suited to a CBM approach. It was recognised that the strategy will fundamentally still be based on a TBM approach to ensure alignment with budget provisions and a more equalised work distributions over a longer planning period.

The maintenance strategy is largely of a preventive nature where the focus is rather on preventing a failure than implementing a more corrective-based maintenance approach.

Equipment performance influences maintenance planning by reviewing critical functional failure modes and addressing risk by appropriate maintenance actions through a RCM review. This would include environmental, duty cycle and network criticality factors that will determine localised frequency of maintenance tasks.

In addition to this, maintenance activities are clustered to reduce outages on plant. The objective is to increase plant availability and thereby increase system reliability. Equipment affected by a single outage on the network is grouped and offline-maintenance is performed as required. The maintenance plans for the individual equipment affected are aligned to ensure that all maintenance is performed in the single outage.

Maintenance clustering also reduces the amount of operating resources required. This is due to a reduction of outages and switching out of plant.

In determining the allowable revenue stream the National Electricity Regulator of South Africa (NERSA), largely determines the long-term organisational budget through the application of its Multi-Year Price Determination (MYPD) methodology. One of aspects under consideration is the amount of maintenance required for the specific MYDP period. NERSA (2016) defines the calculation of the allowable revenue as:

$$AR = (RAB \times WACC) + E + PE + D + R\&D + IDM \pm SQI + L\&T \pm RCA \qquad 4.2$$

where AR = Allowable Revenue, RAB = Regulatory Asset Base, $WACC$ = Weighted Average Cost of Capital, E = Expenses (operating and maintenance costs), $P\ E$ = Primary Energy costs (inclusive of non-Eskom generation), D = Depreciation, $R\&D$ = Costs related to research and development programmes/projects, IDM = Integrated Demand Management costs, SQI = Service Quality Incentives related costs, $L\&T$ = Government imposed levies or taxes (not direct income taxes) and RCA = The balance in the Regulatory Clearing Account (risk management devices of the MYPD).

The respondents argue that NERSA requires a reliable predictable forecast, based on actual cost, to determine the maintenance allowance required over the MYPD period. A TBM approach naturally lends itself to such a forecasting model. Maintenance on condition potentially demands maintenance within a shorter planning period as variability in equipment duty cycle and weather patterns could result in low confidence in maintenance forecasting.

Respondents highlighted the impact of procurement and human resource availability on executing maintenance strategies. In a financial constraint environment, the scrutiny on the procurement of maintenance spares and services results in long lead times. The organisation is also faced with skills lost due to natural employee-base attrition and initiatives to manage a high employee-base. This forces the buy-in of skills through contracts to maintain the TPG. The maintenance demand growth, due to new commissioned plant and older equipment, already challenges internal maintenance capabilities in strategic areas.

4.3.4. Research Theme 4: The Relationship between Maintenance Planning and System Performance

In this research theme, two basic themes were uncovered. This resulted from five codes as described in Table 4.5. This research theme focuses on the relationship between maintenance planning and system performance. The thematic analysis also looks at the underlying themes that describe the reasons for the relationship.

Table 4.5 Basic themes related to the relationship between maintenance planning and system performance

Research Theme	Basic Theme	Code description
Relationship between Maintenance Planning and Performance	Indifferent relationship between performance and maintenance planning	Performance of equipment impacts maintenance planning
		Maintenance planning does impact performance of equipment
		Maintenance planning does not impact performance of equipment
		Performance does not impact budget/maintenance funding
	Maintenance planning impact on performance	Maintenance planning impacts reliability of network by removing redundancy when equipment is taken out of service for maintenance

In line with the common thread of an incremental budget-setting philosophy it was indicated that performance does not impact the budget setting at a strategic level. As indicated in section 4.3.2 funds within the budget are often realigned to current operational focus areas at the expense of other less-critical maintenance activities. The impact of performance on the maintenance plan is discussed in section 4.3.3.

In some circumstances maintenance planning does not have an impact on the performance of equipment. This is largely due to critical failure modes that cannot be mitigated with a time-based or condition-based maintenance action. These failure modes require a design-out maintenance mitigation. The design-out maintenance approach focuses on the removal of a functional component from the base. This can be at subcomponent, component or asset level. Asset replacements are normally managed in the capital expenditure environment and are often associated with long lead times to replace. NERSA regards full asset replacements as refurbishment and requires these costs to be capitalised. Major capital refurbishment project delays due to financial constraints result in network performance with a low correlation to maintenance planning. Replacements of components and subcomponents are also dependent on Original Equipment Manufacturer (OEM) support and are often associated with enormous cost. OEM support on older equipment is also limited as such technology is declared as obsolete.

The South African Transmission Grid Code requires the TPG to be *n-1* compliant for networks operated at and above a voltage of 66kV (V_{LL}). This essentially requires the grid to provide supply to the entire load, under all credible system operating conditions, with one overhead line or power transformer or reactive compensation device out of service. According to respondents this design requirement sometimes masks performance-related issues as one transformer failure would not necessarily have an SM impact as described in section 4.3.1. It is, however, suggested that maintenance planning potentially has an impact on system reliability due to the fact that a failure of a transformer, while the other transformer is out on maintenance, will result in supply loss. The management of planned system unavailability is thus critical in mitigating the potential impact of planning maintenance activities on system performance. This is in line with the maintenance clustering strategy mentioned in section 4.3.3.

4.3.5. Research Theme 5: Maintenance Optimisation

The maintenance optimisation research-theme has three basic themes as illustrated in Table 4.6, built on five distinctive interview codes.

Table 4.6 Basic themes related to maintenance optimisation

Research Theme	Basic Theme	Description
Maintenance Optimisation	Optimisation of maintenance based on resources available	Optimisation of maintenance based on resources available
		Maintenance load should be equalised over a long-term planning period in order to provide an equally distributed maintenance resource requirement.
		Leverage of cost of maintenance/refurbishment against income generated
	Requirement for optimisation based on organisation value proposition	Maintenance optimisation should recognise impact on organisation value proposition
	Optimisation of maintenance based on equipment condition	Optimisation of maintenance based on equipment condition
	Suggested maintenance DDS optimisation criteria	Type of load, equipment with high replacement cost, equipment critical to network, resource capability, performance of equipment, budget available, equipment condition, equipment availability, duty cycle, SM and maintenance cost

The maintenance plan is based on a FMECA study per equipment group and locality analysis based on network criticality, usages and environmental conditions. The maintenance plan is further optimised by grouping maintenance activities as described in section 4.3.3. In addition to this, the plan is also adjusted to match the maintenance capability of the specific grid over a longer planning period. In the scenario where the grid is equipped to perform n x breaker maintenance the demand for breaker maintenance is spread equally over a maintenance period to meet that capability of n breakers per annum. The maintenance period equals the inverse of the maintenance frequency of the specific equipment type. In a changing maintenance strategy environment, mentioned in section 4.3.3, there is an increased focus on equipment condition to optimise maintenance plans. This focus is also driven due to a constrained fiscal environment resulting in CAPEX-driven refurbishment projects being restrained. This results in equipment being operated beyond original planned replacement time frames. Power plant equipment normally characterised wear-and-tear failure modes and is associated with a bathtub-type failure curve.

Respondents further suggested that maintenance optimisation should be cognisant of the organisational value realisation generated when investing in maintenance. The organisation uses a standardised maintenance approach to all equipment on the TPG and maintenance should rather reflect that certain nodes or corridors are of higher/lower value. The respondents argue that budget allocation should be done on a more rational basis rather than basing it on history. This relates to themes identified in section 4.3.2 where a more rationalised approach to budget setting was proposed.

Table 4.7 Proposed DDS Criteria

Code	**Description**
M_cost	Maintenance Cost
SM	System Minute
D-cycle	Duty Cycle of Equipment (work rate)
E-avail	Equipment Availability
E-Cond	Equipment
Budg_Avail	Budget Availibility
Perf	Performance
R_capab	Resource capability
E maj-Cond	Major Equipment Condition (Only critical equipment with major impact)
Type-L	Type of Load

Respondents were asked what typical criteria they would propose having in a DSS. They proposed 10 critical criteria as noted in Table 4.7 and Figure 4.3.

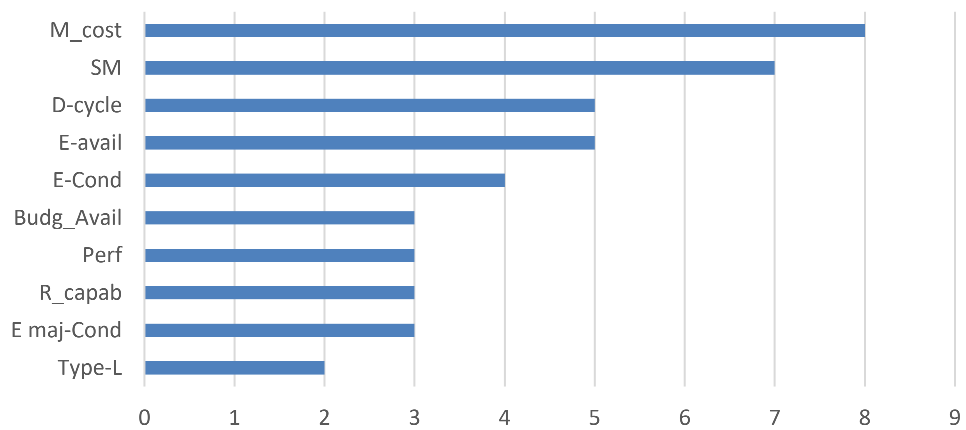


Figure 4.3 Count on proposed criteria

The counts reflected in Figure 4.3 do not reflect the strength of the criteria compared to the others listed. It rather gives an indication of what the respondents viewed as should be included in the DSS. Frequent occurrence could indicate importance, but it might simply reflect greater willingness or ability to talk at length about that topic (Vaismoradi, 2013). The high proposal rate of maintenance cost and SM corresponds to the theme of ensuring adequate system reliability by efficient maintenance spending. SM is also recognised in the MYPD modelling. Equipment availability was identified by five respondents as a critical criteria and is also linked to the reliability of the network as described in section 4.3.4.

The duty cycle of the equipment shared the same proposal rate as equipment availability and is related to the usage of the equipment. The rate of usage of equipment normally provides an indication of the condition of equipment, especially in mechanical wear. Breaker mechanisms are rated as normal or high-duty cycle mechanisms and would require maintenance based on the number of breaker operations. The condition of the breaker interrupter can also be monitored on the usage rate in conjunction with the magnitude of the fault current that needs to be interrupted. The equipment condition criteria proposed by four respondents includes the environmental impact on plant and the need to maintain it in order to prevent failures. This could also include condition-monitoring activities that are done on a time-based frequency.

Budget availability, equipment performance and resource capability were identified by three respondents. Equipment performance relates to the failure rate of the equipment and thus the reliability of the network. It does not necessarily translate into a supply loss incident due to the N-1 design criteria mentioned in section 4.3.4. Equipment performance could be captured as forced equipment unavailability and is thus a subsection of the equipment availability criteria. The budget availability criteria proposed speaks to the limitation of funds and the motivation to optimise and rank in order to execute the most important maintenance tasks available.

Respondents also suggested a Pareto-approach to focus on equipment that is more critical to the network and having a high replacement cost. The identification of replacement cost speaks to the potential risk to the budget in terms of catastrophic failure of equipment.

Respondents also identified the type of load that is served by the equipment. The type of load reflects on the severity potential. Typical loads that could be listed as critical are nuclear power stations, hospitals and national key points (as declared by the National Key Point Act 102 of 1980).

4.3.6. Thematic Analysis Summary

The theme map depicted in Figure 4.4 presents the associations between interview codes identified across the data corpus. Each code is tagged with the heading reference of the research theme in which it resides. Interview codes associated with the first two research themes are clustered to the left of the map whereas the balance of the basic themes are evenly distributed towards the right of the map.

The codes associated with sections 4.3.1 and 4.3.2 describe the latent content supporting the relationship between maintenance planning and the budget-setting process as well as the particular budget-setting strategy that is employed. Codes associated with sections 4.3.3 to 4.3.5 describe the underlying content supporting the maintenance strategy employed, the relationship between maintenance planning and performance, current maintenance optimisation as well as how optimisation could be enhanced with a DDS.

The dominant apparent themes identified during the interview process were:

a) Budget setting is not influenced by maintenance planning;
b) Budget setting is based on an incremental/decremental setting philosophy;
c) The employed preventive maintenance strategy is based on time and there is a definite migration to a more condition-based approach;
d) Indifferent relationship between system performance and maintenance planning.

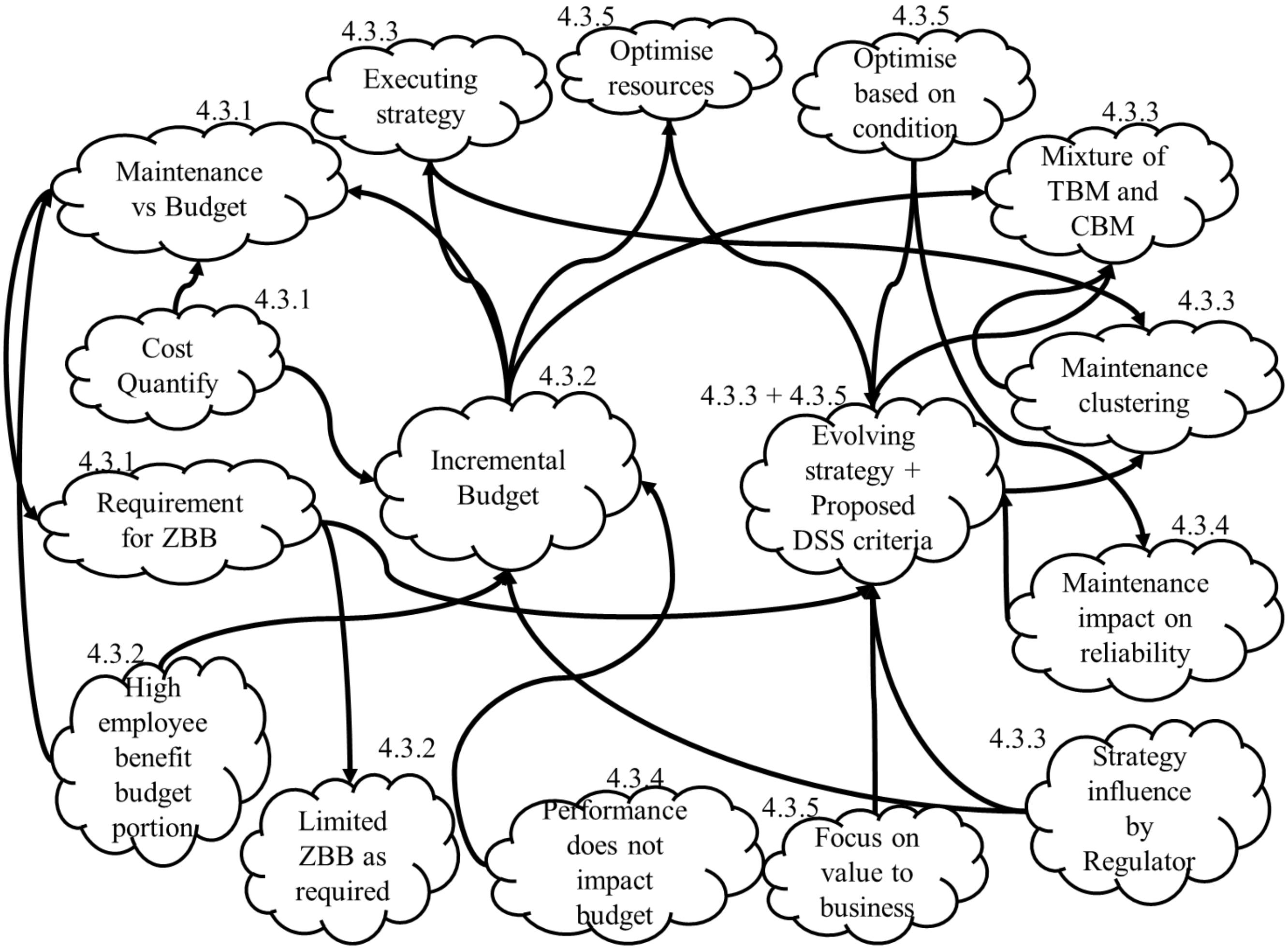


Figure 4.4 Thematic map

NERSA determines the Eskom allowable revenue based on the multi-year-price-determination. The maintenance and performance related variables influencing this model are: (i) the regulatory asset base (RAB); (ii) Operating and Maintenance cost; and (iii) Service Quality Incentives/Penalty-related costs. The operating and maintenance cost component carries a large employee benefit portion. This is regarded as a fixed cost and does not vary with the maintenance demand of a specific year. The Transmission asset base is largely constant due to slow progress in CAPEX network expansion programmes. This also does not reflect maintenance demand fluctuations on a year-to-year basis. Cost centres, in the ERP system, are only defined up to substation location level. This limits the cost accrual to substation level and not to asset level. Labour time and associated travel time is booked on work orders but is not consistent and accurate enough to analyse and predict. The budget setting is predominantly a top-down approach securing OPEX funding in line with the expenditure of the previous year.

Critical failure modes in plant reaching the end of its life cycle is difficult to mitigate with time-based and condition-based maintenance activities. Plant associated with large replacement cost often exhibits wear and tear failure profiles and requires large overhauls or refurbishment to assist with life extension programmes. The transmission network is characterised by redundancy to protect the system against the next worst contingency. This trait prevents major supply events due to single contingencies and contributes to the indifferent relationship between maintenance planning and system performance.

4.4. **Secondary Data Analysis**

The objective of the quantitative data analysis was to confirm the apparent relationships identified in the qualitative study analysis and to ascertain the strength and direction of the analysis. The objective was not to construct a model developed through multivariate regression analysis to predict an outcome or multiple outcomes based on various independent variables.

A sample is a subset of a population that allows the researcher the opportunity to draw inferences on the larger population. Appropriate sample size is therefore critical in reducing the possible sample error and improving the validity of the analysis. Austin (2015) argues that literature described various rule-of thumb to estimate the number of observations to execute linear regression analysis. Broadly, these rules of thumb can be divided into two categories. The first category defines a fixed number of observations irrespective of the number of predictive variables while the second takes into account the number of predictive variables in establishing the number of observations (Austin, 2015). Austin (2005) further concludes that although Peduzzi(1996) suggested a minimum of 10 observations per predictive variable to successfully predict linear regression models, his analysis indicated that under certain conditions the number of observations can be limited to two observations per variable. Tabachnick & Fidell (2019) recommend that observations should be limited to between 5 and 20 per independent variable.

The test of statistical significance is a measure to evaluate the confidence with which the results of a study on a sample can be extended to the large population. The level of statistical significance is the level of risk the researcher is willing to accept by assuming that the relationship between two variables in the population, from which the sample was taken exists, when in fact no such relationship exists. Traditionally, the level of risk in business and managerial research is set at 5% that it is concluded falsely that a relationship exists in the population (Bryman. A., 2017).

The analysis required the correlation between maintenance cost data, maintenance work-order and performance data. This was required to investigate the relationships between:

a) Maintenance Planning and Maintenance Budget
b) Maintenance Planning and Performance

The secondary data was retrieved from the accounting, maintenance management and performance systems. In addition, data was also retrieved from organisational Equipment Life Cycle Plan documentation. Apart from costing data all other data sets were retrieved quarterly over a period of seven years. This resulted in 28 observations per relevant aspect. Costing data was only available on a yearly basis.

The specific Transmission MMS system was introduced about 10 years ago and although the raw historic data is available, the specific maintenance performance measurements captured in the performance database only started in 2013. Similarly, the specific performance KPIs were only consistently being reported on over the last six to eight years.

The numerical variables identified during the interview process for each aspect were:

a) Budget annual spend;
b) Maintenance completion rate;
c) System minute loss, unplanned unavailability of plant, equipment failure rate.

The qualitative interview analysis, discussed in section 4.3.6, suggested that the quantitative data analysis should focus on the variable maintenance cost budget due to the relative large fixed employee benefit portion of the budget. The interview analysis further indicated that performance and cost of high-value items should be considered in the Maintenance Budget DSS as it had a more direct relationship on maintenance execution.

Bivariate analysis concerns the analysis of two variables at a time to determine if they are related (Bryman. A., 2017). The first objective was to correlate the number of work orders completed to the budget spend. The maintenance planning and budget spend aspects are described by one variable respectively which lent it itself to bivariate analysis. The most common bivariate analysis techniques are:

a) Pearson's correlation coefficient (r),
b) Spearman's rho (ρ) and
c) Phi coefficient (ϕ)

Pearson's correlation coefficient is a technique to determine the strength of a linear relationship between two interval or ratio variables. If it is established that the relationship is broadly linear the direction of the relationship can also be determined (Bryman. A., 2017). The *r*-coefficient will lie between 0 (no relation) and 1 (full relation) and the closer it is to 1, the stronger the relationship. In the event of a positive (+) *r*-coefficient the direction of the relationship is positive, i.e. an increase in one variable will lead to an increase in the other. The coefficient of determination ,square value of Pearson's *r,* express the degree of variation in one variable is due to the other.

Spearman's *rho* calculates the correlation between pairs of ordinal variables between an ordinal variable and interval/ratio variable. It is not as sensitive to the normal distribution of data as the Pearson correlation coefficient is and it is based on the rank order of variable values. The *Phi*-coefficient is normally used to determine the correlation between two dichotomous variables. Dichotomous variables have only two categories, i.e. yes/no response.

The variables in the secondary data set are considered to be ratio variables as the distance between categories is considered to be equal and absolute zero is included as part of the data set. Bryman

(2017) recommended that a Pearson correlation coefficient be used to determine the relationship between interval/ratio variables.

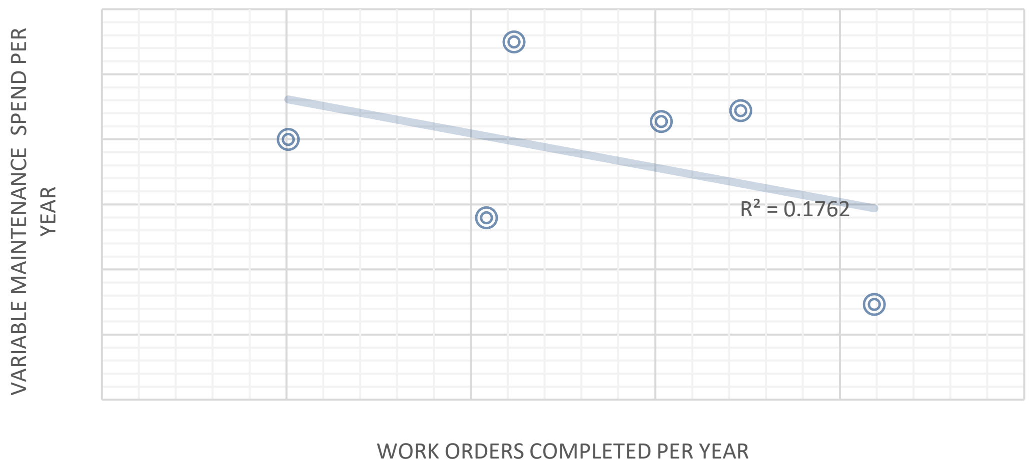


Figure 4.5 Correlation between work-orders completed and variable budget spend

The correlation in Figure 4.5 between the total variable maintenance cost and the maintenance work-order completion yielded a Pearson correlation coefficient of r = -0.4198 and a statistical significance of ρ = 0.41. This related to a moderate negative correlation with high probability that the relationship will not exist in the larger population. The *coefficient of determination* also indicates that work-order completion only accounts for 17.6% of the variation in variable maintenance spending. The analysis was restricted to six observations, limited by the availability of costing data.

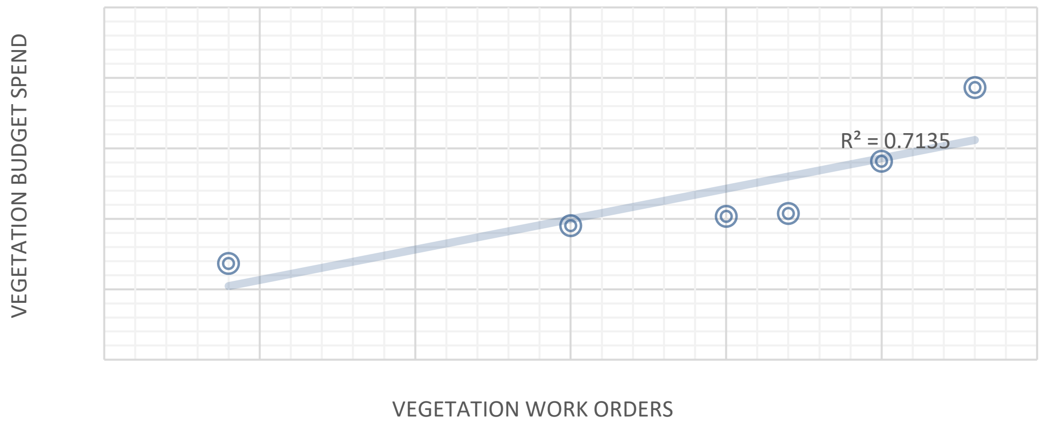


Figure 4.6 Correlation between vegetation maintenance complete vs variable budget spend

The correlation in Figure 4.6 between the total variable maintenance cost and the maintenance work-order completion yielded a Pearson correlation coefficient of r = 0.844 and a statistical significance of ρ = 0.034. This related to a strong positive correlation with low probability that the relationship will not exist in the larger population. The level of statistical significance is set at ρ = 0.05 and therefore the null hypothesis, that the two variables are not related in the population, is rejected.

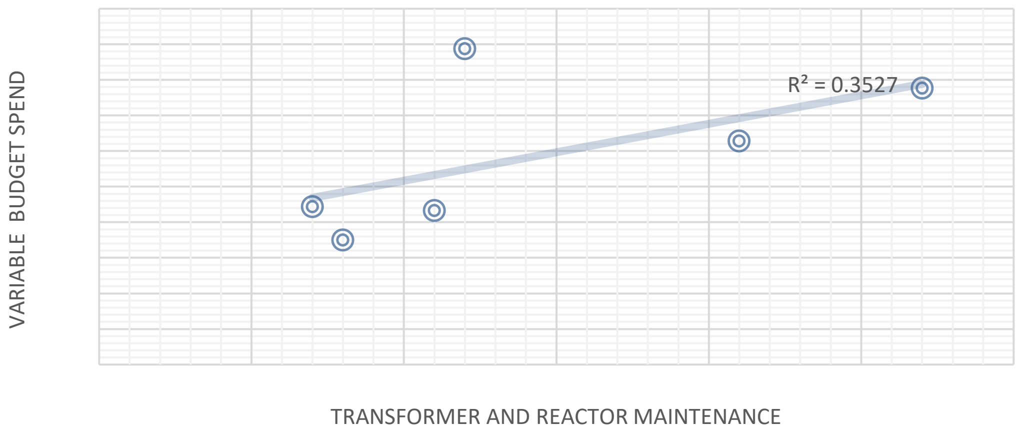


Figure 4.7 Correlation between transformer and reactor maintenance completed vs variable budget spend

The correlation in Figure 4.7 between the total variable maintenance cost and the maintenance work-order completion yielded a Pearson correlation coefficient of $r = 0.594$ and a statistical significance of $\rho = 0.21$. This related to a moderate to strong positive correlation with a 21% probability that the relationship will not exist in the larger population. The level of statistical significance is set at $\rho = 0.05$ and therefore the null hypothesis, that the two variables are not related in the population, is accepted.

The weak relationship between the transformer and reactor planned maintenance completed and budget spend is ascribed to the fact that this budget provision is also used for corrective maintenance on transformer and reactors. The budget is further also utilised for other major unplanned maintenance activities. This correlates well with the $r^2 = 0.3527$ that explains that planned transformer and reactor maintenance accounts for 35.27 % of the variation in the budget spend.

The interview analysis isolated planned vegetation-, transformer and reactor-, breaker- and aerial line inspection maintenance as activities that have a large impact on the variable maintenance budget allocation. It was difficult to isolate breaker kit costs as it is not normally accounted to the asset. The aerial inspection cost also resides under a different cost centre and was not available to include in the study.

The bivariate study confirmed the relationship between vegetation- and transformer/reactor cost as moderate-to-strong. This is in line with the findings in the qualitative analysis.

Multivariable regression analysis involves deriving a mathematical equation that predicts a dependable variable (DV) with the use of more than one independent variable (IVs). The mathematical equation will use a linear relationship between the IVs with a DV-intercept that will represent an error term. The second objective lends itself to multivariable regression analysis as the relationship between maintenance completion (DV) and multi-performance KPIs (IVs) is investigated. The performance variables identified in the interview process are not totally independent and could potentially pose a challenge in terms of multicollinearity. This challenge arises when one IV can be predicted from the other variables.

$$M_T = a_0 + a_1 \times SM_T + a_2 \times PPI_T + a_3 \times UCU_T \qquad 4.3$$

where M_T = Total Maintenance Completed, SM_T = Total System Minutes, PPI_T = Plant Performance Index and UCU_T = Unplanned Circuit Unavailability.

The multivariable regression equation includes the performance variables identified in the interview process, as input variables and maintenance completion as the dependent output variable. The data was collected on a quarterly basis over a period of seven years. This amounted to 28 observation points per variable.

The total system minutes represent the time measured, in minutes, of unsupplied energy over the system annual peak demand as described in section 4.3.1. This variable is associated with a supply loss event on the TPG. The Plant Performance Index (PPI) is an aggregate performance indicator that measures the equipment performance over the spectrum of transmission assets. This KPI is indicative of equipment failures as well as protection bus-zone and bus-trip operations. These protection operations normally affect unavailability of critical nodes in the substation and can potentially lead to loss of supply events. The Eskom Transmission Grid Code requires an *n-1* design philosophy, as noted in 4.3.4, and therefore ensures that supply is not interrupted in the event of a single failure contingency. Unplanned circuit unavailability measures the aggregate time that plant or equipment is out of service due to an unplanned event such as a failure or short notice unplanned outage to correct a performance deviation. The unavailability of circuit removed the *n-1* network condition and put the system at a higher risk of potential supply loss. The magnitude of the potential supply loss will be determined by the load at risk and the reaction time to restore the load.

Table 4.8 Correlation matrix for SM, PPI and UCU performance parameters

	SM	**PPI**	**UCU**
SM	1	0.095	0.238
PPI	0.095	1	-0.194
UCU	0.238	-0.194	1

The correlation matrix, described in Table 4.8, indicates weak relationships between the input variables. The highest correlation of $r_{SMvsUCU}$ = 0.238 is measured between SM and UCU. The correlation between PPI and UCU is measured as slightly negative. A high PPI is indicative of good equipment performance and potentially fewer circuits forced to be unavailable.

$$M_T = 223.82 + 159.16 \times SM_T + 6.31 \times PPI_T - 246.4 \times UCU_T \qquad 4.4$$

The results of the multivariable regression analysis is described in Appendix D. The analysis resulted in r = 0.49 and is indicative of a moderate relationship between the outcome variable and the predictive outcome variable, based on the calculated IV's and intercept coefficients. The R^2 = 0.243 describes that 24.3% of the variance in maintenance completion can be described by the three performance variables. The statistical significance of the relationship is calculated as ρ = 0.07 and is above the 5% statistical significance level.

The multivariable regression analysis described the impact performance has on maintenance. The impact of maintenance and performance can be investigated with the use of bivariate analysis calculating the correlation between maintenance and the three performance variables.

Table 4.9 Pearson correlation and statistical significant calculations between maintenance and performance variables

	Maintenance vs SM	**Maintenance vs PPI**	**Maintenance vs UCU**
R	0.3259	0.3202	-0.2021
r^2	0.1062	0.1025	0.041
P	0.0905	0.0967	0.3022

The individual relationships between maintenance and the three performance variables are described in Table 4.9. The correlation statistics are indicative of weak to moderate relationships between the variables. The maintenance variables only have a 10% contribution to the variance of SM and PPI and less than 5% impact on the variance of UCU.

The statistical description of the strength of relationship between maintenance and performance varies pending the aspect under consideration. This is in line with the observation from the qualitative analysis, which described the relationship as indifferent.

4.5. **Data Analysis Impact on DDS development**

Thematic analysis on the interview data corps revealed that budget setting is predominately based on an incremental/decremental philosophy. The underlying themes that contributed to this apparent theme were identified as (i) high employee benefit budget, (ii) cost quantification within the ERP, (iii) need for stable forecasting model and (iv) the performance of the network does not have a profound impact on the planned maintenance. The latter latent theme corresponds to the use of time-based maintenance as the predominated maintenance approach as well the theme of an aging fleet which requires major component refurbishment or replacement. The findings highlighted possible limitations of a maintenance DDS.

The indifferent relationship between system performance and total maintenance planned, per planning period, was confirm by the secondary data analysis with reports of weak to moderate correlation. The secondary data analysis did reveal stronger relationships between budget spending and maintenance executed for specific asset classes maintenance activities i.e servitude vegetation management, transformer and reactor maintenance . The focus of the analysis was on the variable budget portion that defined the funds required for executing these activities. This is normally directed at external services providers, production equipment and maintenance spares. The data confirm the probable impact of deferring non-critical maintenance activities where funds are sourced from the variable budget portion.

The thematic analysis further suggested ten possible decision-making criteria. These criteria are divided into probability and severity criteria and is listed in Table 4.10.

Table 4.10 Proposed DDS criteria apportioned

Probability Criteria	**Severity Criteria**
Equipment Performance (Failure rate)	Maintenance Cost
Equipment Condition (Asset Health Indicator)	System Minute
Duty Cycle (Equipment work rate)	Type of load
	Equipment Availability

The suggested indices are measured as part of the organisation balanced scorecard and annual assessment reporting system. This made the datasets available for implementation in a DDS environment.

4.6. **Chapter Summary**

This chapter described the qualitative data collection process as well as both the qualitative and quantitative data analysis processes to investigate the relationships between maintenance planning, budget setting and TPG performance.

Qualitative data was collected through semi-structured interviews. The raw data was transcribed and thematic analysis was used to identify codes and themes that aligned to the research objectives of the study. This enabled the identification of apparent as well as latent characteristics of the relationships described earlier. The chapter also described the quantitative data analysis on secondary data. This analysis investigated the strengths of relationships and confirmed the latent aspects identified through the interview process.

The data analysis on both sets of data identified critical input variables of the decision support system that will be developed in the next chapter.

Chapter 5

Decision-making Model Construction and Validation

This chapter describes the development process of a maintenance budget decision support model (MBDSS) as well as the DSS validation process.

It starts off with an overview of the system design parameters and boundaries. It continues with a detailed description of the scope of the field study. This is followed by a description of the model development process and preventive-maintenance task (PMT) criticality analysis with reference to a constrained maintenance budget.

Lastly the model is validated with the use of the Borenstein (1998) DSS validation process.

5.1. System Design and Boundaries

The focus of the study is on the alignment of business objectives and priorities to maintenance strategies during periods of fiscal constraints. Maintenance strategies are developed during the asset design phase and define the maintenance requirements of the specific asset. This includes the identification of spares, maintenance tasks, training and facilities. Preventive maintenance tasks are produced through RCM processes and use Failure Mode Effects and Criticality Analysis (FMECA) maintenance engineering techniques. Failure-modes criticality analysis is largely based on equipment reliability and does not, necessarily, focus on the current business objectives and priorities that, potentially, fluctuate over the operational life of the asset.

Recent financial and environmental challenges in the Power Electricity Utility sector have highlighted the need for continuous reviews of maintenance strategies. Maintenance managers are often confronted with budget cutbacks. This requires quick operational responses to ensure that infrastructure is adequately managed to ensure acceptable levels of safety and reliability within the financial and environmental constraints.

Marquez *et al*. (2015) suggest that, while the FMECA process focuses on the prioritisation of failure modes, the prioritisation of assets with a maintenance programme promotes a business focus ensuring a more sustainable asset management outcome. The focus on critical assets has become a business need in order to maximise availability during asset operation phase (Marquez, *et al*., 2015). Marquez *et al*. (2015) describe a rational working process and model that provides a ranked assets list based on business objectives. This process is described as supplementary to Root Cause Failure Analysis and Reliability Centred Maintenance. The model has a strong focus on asset-intensive industries such as electrical power plants, network utilities and transportation systems.

Tam & Price (2008) developed a maintenance optimisation framework that prioritises maintenance work in terms of maximising the return on maintenance investment. Maintenance activities are ranked based on three criteria; Time Index, Maintenance Investment Index and a Budget Index. The fundamental research question is; “What best maintenance to do in terms of return on investment given that there are time and budget constraints” (Tam & Price, 2008). The framework is focused on a manufacturing and production environment with a strong reliance on structured reliability and cost data. The model uses an AHP MCDM methodology to assign weights to the criteria. AHP suffers rank reversal of alternatives and pairwise uncertainties when the number of alternatives increases exponentially. Swart (2015) improved the TAMS & Price model by introducing an ELECTRE and Promethee MCDM methodology to the process.

In this study the proposed Maintenance Budget Decision Support System exhibits the following design requirements.

a. The model should be applicable to a large scale of in-service assets spread over a geographically large area. Assets installed across a wide geographical area are exposed to diverse environmental, operating and maintenance cost conditions. Similar asset designs react differently, due to location conditions and demands, and have diverse impacts on business priorities;
b. The model should review the current Preventive Maintenance (PM) programme against current business objectives. It should also accommodate for business priority fluctuations over the operational life of assets in terms of dynamic social -economic pressures;
c. The model should utilise a criticality analysis ranking elements of the maintenance plan based on probability of a failure event, the preventive maintenance task (PMT) is deemed to protect against, and severity impact on business objectives and priorities with the associated functional loss. The maintenance plan element, that needs to be ranked, is defined by the location-asset-failure mode- PMT combination;
d. The analysis should support dynamic changes in the scale for severity as well as probability effects to promote model flexibility in a dynamic business environment;
e. The model should be used in conjunction with Root Cause Analysis and RCM process in identifying new failure modes and mitigation;
f. Simple implementation in the enterprise asset management system of the company in order to automatically replicate criticality studies; and
g. The model should be supported by a process to configure the model algorithm and retrieve the relevant in-service operational data and analysis results to influence maintenance strategies.

The proposed Maintenance Budget Decision Support System (MBDSS) is modelled on both the Marquez *et al.* (2015) and Tam & Price (2008) maintenance prioritisation models. The Marquez model finds application in very similar network utility industries, which is characterised by large-scale complex in-service engineering assets that are located over a geographically large area. It also is cognisant of factors relating to data availability and change in business objectives though the operational life of the asset. The process is easily implementable in the enterprise asset management system of the company and analysis can be automatically reproduced.

The MBDSS is based on a RPN approach, similar to that of Marquez, that calculates criticality attaching the probability of a functional loss with the severity potential associated with the functional loss. The MBDSS focuses on the ranking of maintenance plan elements which is the combination of location, asset, failure mode and PMT. This is different to the Marquez model that focuses on the probability of failure of the asset against the severity associated with the functional loss of the asset. The failure of an asset is due to a probable occurrence of more than one failure mode. Each of these failure modes is associated with different preventive maintenance activities, which in turn represent a cost impact on the budget. The MBDSS not only evaluates the criticality at asset level but also determines the criticality of the execution of a specific maintenance activity associated with that asset in the specific location. This is similar to the Tam & Price model which prioritised maintenance activities based on a time, maintenance, investment and budget index. The MBDSS recognises that the risk of two identical assets in two different locations on the TPG is different and potentially requires different PM strategies to ensure alignment to maintenance objectives. In a similar fashion, identical PM activities, and then failure modes, potentially also present different risks to the stated objectives due to the location of the asset.

The focus of the MBDSS is on the variable portion of the maintenance budget as proposed by the data analysis in Chapter 4. It recognises that labour cost is a function of the number of employees and only accommodates for probable T&S cost incurred due to the relative position of work sites with reference to maintenance operation centres. Certain specialised maintenance activities are executed from a centralised location.

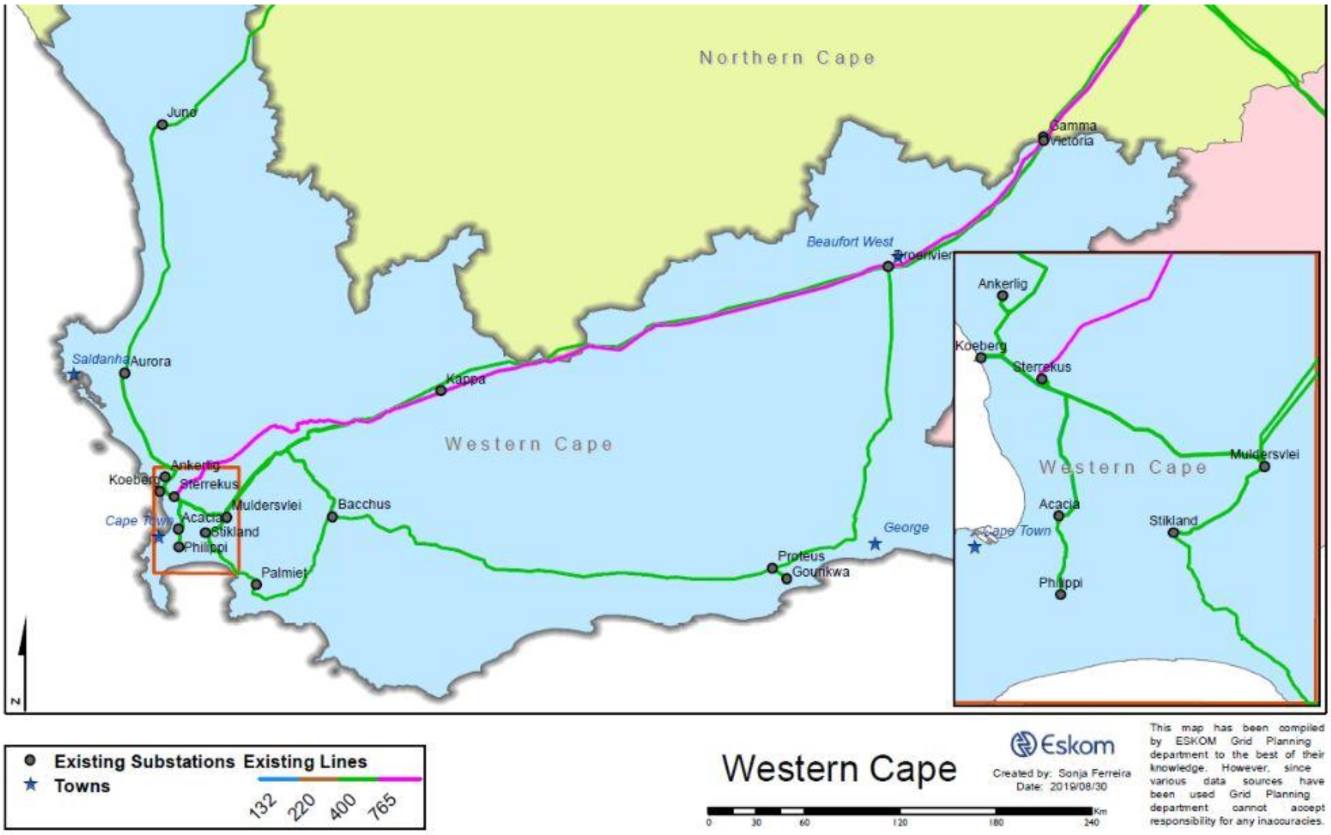


Figure 5.1 Western Grid Transmission network (Adopted from Eskom Transmission Development Plan, 2018)

The model is applied on a section of the national transmission power grid. The section includes seven transmission 400 kV substations and nine overhead lines. The portion of the network is described in the bottom right-hand corner of Figure 5.1.

The section of network includes the most critical Koeberg Nuclear Power Station (KNPS) load. Acacia substation provides the critical off-site supply to KNPS to support the critical nuclear safety systems. The portion also provides supply to the large City of Cape Town load which represents a very significant system minute risk. The section includes the following substations:

- Acacia substation
- Ankerlig substation
- Koeberg substation
- Muldersvlei substation
- Phillipi substation
- Sterrekus substation
- Stikland substation

The section also provides critical transmission connection to power generators at Ankerlig, Koeberg and Acacia substations. The generators at Koeberg are considered base generation while the generation at Ankerlig and Acacia are considered peak generation stations. The grid connection requirements of Koeberg Power Station are further viewed as critical due the impact on the nuclear licence in terms of reliable grid supply to the nuclear safety systems.

The PM programme for this section of the network under evaluation is for one financial year. The model is scalable in both network size and maintenance planning period.

5.2. **Model Development Process Description**

The model is adapted from the Marquez *et al*. (2015) model. The objective is to provide for a consistent criticality analysis with the use of the RPN method in conjunction with the AHP MCDM method that will determine weights for the probability and severity factors.

The Marquez model only utilises failure frequencies of assets to determine the probability of a loss of the functionality event for the specific asset. The proposed MBDSS uses three criteria to determine the probability of loss of functionality of an element, r. This element, r represent the asset type, asset location and maintenance activity linked to the specific failure mode. The additional probability criteria accommodate for the environmental and operational stress impact due to the location of the asset on the TPG. The failure frequency factor is denoted as ff_z in Figure 5.2 and represents the first probability criterion. The second probability criterion is the asset health index (AHI) that affects the asset in element r. The duty cycle (DC) of the asset linked to the location-asset-failure mode-PMT combination is the third probability criterion displayed in Figure 5.2.

In Figure 5.2 the probability of functional loss due to the failure mode is determined by the duty cycle of the asset (how hard the equipment is working), asset health index of the asset and the failure frequency of the asset linked to the specific maintenance element, *r*. In a similar process, the severity

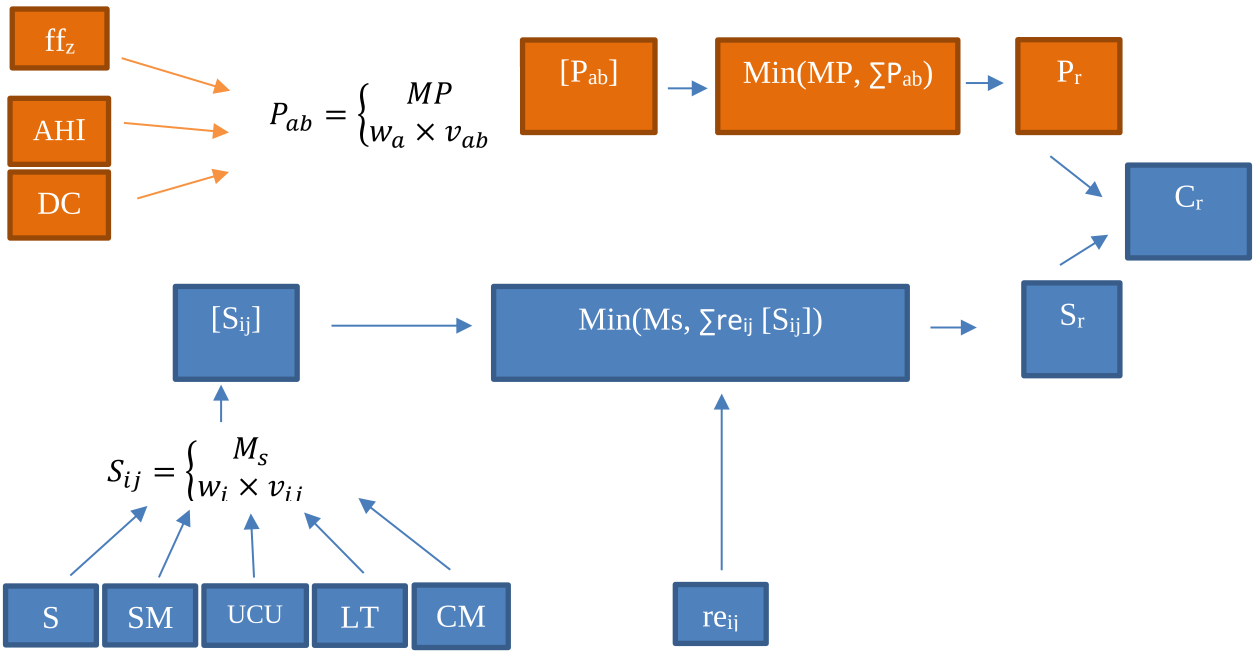


Figure 5.2 Maintenance Budget Decision Support System logic diagram

of the functional loss of an asset due to failure mode of element, *r* is determined by five severity criteria namely:

a. Safety (S);
b. System Minutes (SM);
c. Unplanned circuit unavailability (UCU);
d. Type of load supplied (LT); and
e. Corrective maintenance cost (CM).

These criteria, with the exception of safety, were proposed by the thematic analysis in Chapter 4. The addition of safety is due to the organisation's business focus on "Zero Harm" as one of its core values.

The criticality of the combination of location-asset-failure mode-PMT is thus calculated using eight criteria. The maintenance plan elements, for a specific planning period and network, are ranked accordingly. In doing so it assists maintenance managers to decide what PMTs could be deferred with minimal impact on the network. The eight criteria were identified during the analysis of the qualitative interview data as well as the organisational literature study. These criteria are also measured as part of the company balanced scorecard. The red logic blocks in Figure 5.2 are indicative of the modifications to the Marquez model and also represent the process to calculate the probability of the functional loss created by the failure mode in element, *r*. The blue logic blocks describe the process to determine the severity of the functional loss due to the failure mode in element, *r*.

The development of the model was achieved with the support of a critical review team of three maintenance managers that oversee the operation and maintenance execution of different grid equipment types. These managers were also involved with the initial qualitative data collection and understood the research objective. This critical review team assists with the criteria effects classification, AHP modelling and data retrieval concerning real element functional loss effects which is discussed later in the chapter. This also supported the internal validation requirement as stated in Borenstein (1998).

The process of developing the model consisted of the following steps and was adapted from Marquez *et al.* (2015). The process is enhanced with the introduction of the asset health and duty cycle criteria effects levels as well as the calculation of the probability level for each maintenance activity linked to a specific asset in a specific location. The model highlights that a specific maintenance activity on two identical asset types could have different criticality ratings, due to their location, and that two maintenance activities, on the same asset, could have different criticality ratings, as the activity mitigates different failure modes. The process is as follows:

1. Determining the frequency levels and frequency factors for the failure modes linked to PM-tasks;
2. Determining the asset health index criteria effect levels;
3. Determining the asset duty cycle criteria effect levels;
4. Calculating the weight of each probability criterion;
5. Determining the probability categories, or levels, per criterion effect;
6. Determining the functional loss severity criteria and criteria levels;
7. Defining the non-admissible severity functional loss effect;
8. Calculating the weight of each severity criterion;
9. Determining the severity categories, or levels, per criterion effect;
10. Retrieving data for maximum possible effects per criterion;
11. Calculating the probability level for maintenance plan element r;
12. Determining the potential maintenance plan element criticality at probability level;
13. Retrieving data for the real effects per criterion;
14. Determining the observed maintenance plan element r criticality at observed probability level; and
15. Determining the results and guidelines for budget decision-making.

The first nine steps in the above process assist with the configuring of the model algorithm. The model is then used in conjunction with in-service data retrieved from the enterprise asset management system to rank the maintenance plan elements, which include the location-asset-failure mode-PMT combination.

The critical review team is used to determine the weighting of the probability and severity criteria in steps (4) and (8), retrieving data for steps (10) and (13) to calculate the potential failure mode criticality, as well as the probable failure mode criticality. Step (15) evaluates these two observations to assist with the review of PM activities described in the current maintenance strategy.

The mathematical model that is developed uses the following notations:

a: 1,..,n criteria to determine probability of asset functional loss

b: 1,…,m levels of possible effects of a functional loss for any probability criteria

i: 1,..,n criteria to determine severity of an asset functional loss

j: 1,…,m levels of possible effects of a functional loss for any severity criteria z: $1,\ldots,l$ levels of functional loss frequency

e_{ab}: effect b of the probability criterion a

e_{ij}: effect j of the severity criterion i

w_a: weight given to the probability criterion a by experts, with $\sum_{a=1}^{a=n} w_a = 1$

w_i: weight given to the severity criterion i by experts, with $\sum_{i=1}^{i=n} w_i = 1$

MP_a: maximum level of admissible effect for probable criterion a, with $MP_a \leq m$, $\forall$ a

MP: maximum probability level

MS_i: maximum level of admissible effect for severity criterion i, with $MS_i \leq m$ $\forall$ i

MS: maximum severity level

v_{ab} : fractional value of effect b for the probability criterion a

v_{ij} : fractional value of effect j for the severity criterion i

P_{ab}: probability of effect b for the probability criterion a

ap_{rab}: actual probability effect b of criteria a for the functional loss due to failure mode r

S_{ij}: severity of effect j for the severity criterion b

pe_{rij}: potential effect j of criterion i for the functional loss due to failure mode r

P_r: value of the probability of the functional loss due to failure mode r

ff_z: frequency factor for frequency level z

af_z: average frequency of functional loss for frequency level z

S_r: severity of functional loss due to failure mode r

C_r: Criticality of failure mode r and the associated PM activity

re_{rij}: current probability of effect j of criterion i for the failure mode r

S'_r: current observed severity of the functional loss due to failure mode r

C'_r: current observed criticality of failure mode r and the associated PM activity

5.2.1. Determining the Frequency Levels and Factors for Failure Modes

The determination of the frequency levels of the asset functional loss due to the different failure modes is based on a Pareto analysis where failure modes are grouped into z frequency categories according to its frequency loss rate. The critical review team chose four categories (z=4) representing very high (VH), high (H), medium (M) and low (L) functional loss frequency categories. This is in line with organisational equipment life cycle documentation that reports on failure rate frequencies for specific equipment types.

The percentage of the failure modes that will fall into each frequency category was estimated according to business practices and experience by the review team. The category split between VH:H:M:L functional loss frequency factors was estimated at 15:20:30:35. The maintenance plan, under review, represented a hundred-and-ninety two PM activities assigned to assets on the TPG described above. Each PM activity is linked to a failure mode through the RCM process. The failure modes, or PM activity, are ranked from highest failure rate (number of failures linked to specific failure mode/year/number of assets) to lowest. The top 15% of the failure modes were assigned a "VH" classification, followed by the next 20% that were assigned by a "H" class, with the next 30% assigned an "M" class and the last 35% an "L" classification.

Table 5.1 Calculation of frequency factors per selected functional level

Category (z)	**Number of PM**	**% of total plan**	**af_z**	**ff_z**
Very High	27	14.06	0.0232	5.8125
High	41	21.35	0.0129	3.2207
Medium	61	31.77	0.0052	1.3101
Low	63	32.81	0.0040	1.0000
Total	192	100		

The best fit for the failure-mode failure-rate data produced a 14.06 %: 21.35%: 31.77%: 32.81% split between categories. The average failure rate for PMs in each category was calculated and reflected in column 4 in Table 5.1, labelled af_z. Marquez (2015) define the frequency factor vector as:

$$ff_z = \frac{af_z}{af_1}\text{, } for\ z = 1, \ldots, l\ levels\ of\ functional\ loss\ frequncy \qquad 5.1$$

The frequency factor represented the average failure rate for each category with reference to the category with the lowest average failure rate. The frequency factor for the four failure rate levels is given in Table 5.1. Each PM that is associated with a failure mode classified as "VH" will be allocated a ff_z of 5.8125. This will represent the value of the first probability criterion for that specific PM. Similarly, ff_z allocation will proceed for the rest of the PM activity listed.

5.2.2. Determination of AHI and DC Probability Criteria Effect Levels

Asset health studies and duty cycle studies are built into the current maintenance strategies and are used as inputs into asset refurbishment and maintenance execution programmes. The AHI levels used in the business reflect the following:

a. Very Poor – Extremely urgent replacement required and presents an imminent threat to the network;
b. Poor – Identified as a potential threat and to be targeted for replacement at the next planned outage;

c. Fair – These units are to be monitored for reliability and need to be incorporated into the planned maintenance or refurbishment schedule such that they do not exceed 40 years of service; and
d. Good – These units are to be monitored for reliability and failure trends. Normal maintenance to be undertaken.

Asset duty cycle reflects the operating stress the asset is exposed to at that point on the network. Typically, this relates to circuit-breaker operating events, transformer tap-changer cycle events or circuit-breaker fault-current exposure. This is a design parameter where primary plant equipment is characterised by a wear-out failure pattern. These equipment types exhibit a large probability when operating close to their design parameters. The critical review team applied the same probability level definition for the duty cycle probability criteria as the AHI probability criteria. The critical review team further recognised the worst level, very poor, as a non-admissible condition that would force the probability of the failure mode to a maximum. This is defined as the maximum value for overall probability MP.

Table 5.2 Probability effects category description for each probability criterion

Failure Frequency	**Asset health Index**	**Duty cycle**
Very High	Very Poor	Very Poor
High	Poor	Poor
Medium	Fair	Fair
Low	Good	Good

Assets that are assigned a very poor AHI or DC effect level will be regarded as assets in a condition that cannot be tolerated from a reliability perspective and require immediate replacement. These levels are represented by the shaded cells of Table 5.2.

The model will allocate a maximum value for the overall probability (PS) to the PM activity for functional loss that produces a non-admissible effect for any probability criteria. The maximum value for overall probability is 1.

The model uses the following notation:

MP_a: maximum level of admissible effect for criteria a, with $MP_a \leq m, \forall a$

MP: maximum value for overall probability

This produced a

[a] = failure rate, AHI, DC with, *5.2*

$[MP_a]$= 4,3,3 as maximum levels of admissible effects for each criterion and *5.3*

MP = 1 *5.4*

5.2.3. Calculating Weights for Probability and Severity Criteria

The MBDSS uses the AHP MCDM method to determine the weighting of the probability as well as the severity criterion. Marquez *et al*. (2015) state that although various business performance KPIs, financial pressures, brand and corporate and safety considerations can determine these weights, it still remains a relative subjective judgement from the experts that are used.

The Analytical Hierarchy Process (AHP) is considered a popular outranking method but has two disadvantages. Swart (2015) identifies the first issue as a rank reversal problem should the alternatives become sizeable. The second problem that could arise is uncertainties when determining the pairwise comparisons. The Marquez *et al*. (2015) model recognised this and limited the alternatives to be evaluated to the probability and severity criteria levels respectively and not to the PM criticality classification level. The reader is referred to section 2.2.2.3 for a detailed description of the AHP process. The process description is supplemented by an example illustrating the use of AHP documented in Appendix A.

In the development of MBDSS the weights given by subject matter experts resulting from the AHP analysis are proposed as:

$[w_a] = 60; 20; 20$ for a = failure rate, AHI, DC and *5.5*

$[w_i] = 20; 30; 10; 10; 30$ for i = safety, SM, UCU, TL, CM *5.6*

This probability-criteria weight distribution illustrated that the failure rate of the asset due to specific failure mode is three times more important than that of the asset health index and duty cycle associated with the asset and associated failure mode. The importance of the asset health and duty cycle aspects are regarded as equal. The severity-criteria weight distribution reflects that the SM and CM criteria is 1.5 times more important than safety. The safety criteria is twice as important as the UCU and TL safety factors.

Marquez *et al*. (2015) note that although the use of AHP is regarded as subjective it is a consistent judgement of the review team.

5.2.4. Determine Probability Categories per Criteria Effect

In the MBDSS, an effects probability matrix is defined, for any element, r included in the analysis, as follows:

$$P_{ab} = \begin{cases} MP, & for\ MP_a < b \leq m, \forall\, a \\ w_a v_{ab}, & for\ 1 \leq b \leq P_a \end{cases} \qquad 5.7$$

where

$$v_{ab} = \frac{e_{ab}}{e_{ak}}\ with\ k = MP_a\ and\ b \leq MP_a \qquad 5.8$$

and

$$v_{ab} = 1\ for\ b = MP_a\ and\ \forall\, a \qquad 5.9$$

where e_{ab} is the effect b of probability criterion *a* and v_{ab} is the fractional value of effect *b* for criterion *a*.

Table 5.3 Probability effects (e_{ab}) matrix per functional loss

	Failure Frequency	**Asset health Index**	**Duty cycle**
Very High	5.8125	Max	Max
High	3.2206	1.5	1.5
Medium	1.3101	1	1
Low	1	0	0

The probability effects matrix, in Table 5.3, is developed from the information in sections 5.2.1 and 5.2.2 where the probability criteria levels and factors were defined. The frequency factors calculated in section 5.2.1 represent the effects at the four levels of the failure frequency criterion.

As an example the effect of b=4 of probability criterion 2 (AHI), is calculated as P_{24}= MP = 1 because MP_2=3 (in equation 5-3) and the number of effects are m=4 . This then satisfies the top of equation 5.7. In a similar manner the effects b=4,3,2,1 of probability criterion 1 (failure rate) are calculated as

$$P_{14} = w_1 \times v_{14} = 0.6 \times 1 = 0.6 \qquad 5.10$$

and

$$P_{13} = w_1 \times v_{13} = 0.6 \times \frac{3.22}{5.81} = 0.332 \qquad 5.11$$

and

$$P_{12} = w_1 \times v_{12} = 0.6 \times \frac{1.31}{5.81} = 0.135 \qquad 5.12$$

and

$$P_{11} = w_1 \times v_{11} = 0.6 \times \frac{1}{5.81} = 0.103 \qquad 5.13$$

The full probability effects matrix, P_{ab}, describing probability effects for each probability criteria are noted in Table 5.4.

Table 5.4 Probability effects matrix (P_{ab})

	Failure rate	**AHI**	**DC**
Weight	**60%**	**20%**	**20%**
Very High	0.6	1	1
High	0.3325	0.2	0.2
Medium	0.1352	0.13	0.13
Low	0.1032	0	0

The interpretation of the probability effect matrix (P_{ab}) is as follows: an asset failure mode that is linked to a very high failure rate is allocated a 0.6 score. If the asset under consideration was assessed and assigned a very high AHI, the failure mode for that asset will automatically get the maximum probability score of 1 irrespective of the effects of the other criteria.

5.2.5. Determination of Severity Criteria and Criteria Effects Levels

The severity associated with the PM activity should be aligned to the business plan objectives that are determined by the management and shareholders. The Transmission business plan focuses strongly on safety, network reliability and cost as strategic objectives. These objectives are reflected in the criteria for this MBDSS. The MBDSS adopts similar safety criteria levels described in Marquez *et al.* (2015) with criteria level descriptions aligned to the utility business safety definition:

- Fatality;
- Permanent disability;
- Minor injury; and
- Negligible.

The reliability severity criteria are composed of a System Minute (SM), Unplanned Circuit Unavailability (UCU) and Type of load (TL) criterion. SM is defined by NERSA (2016) as the aggregate of unsupplied energy over the system annual peak demand and is referenced in the Multi-Year Price Determination methodology as a Transmission Service Quality Incentive/Penalty. UCU reflects circuit unavailability due to unplanned events i.e. equipment failures. This KPI is indicative that the system is degraded from its *n-1* design where the next worst contingency could lead to a supply loss event and an SM impact. The business further recognises the importance of a nuclear safety load as well as other loads deemed critical for the supply to loads with critical processes.

Table 5.5 Calculation of SM factors for SM severity criteria

Category (z)	Number of PM	% of total plan	aSM_z	SMf_z
Very High	17	8.8542	1.2070	663.8824
High	11	5.7292	0.3086	129.7273
Medium	9	4.6875	0.0253	13.8889
Low	155	80.7292	0.0018	1.000
Total	192	100		

The SM criteria effects were determined by a similar process described in section 5.2.1. The asset was evaluated at the point of connection on the TPG and the SM threat was calculated using the load at risk at that position using an average 60 minute reaction time. The reaction time was deemed as acceptable by the critical review team due to the location of the substations relative to the closest response team. The PM activities linked to the asset were then ranked from highest to lowest. The critical review team set the following criteria for the SM criteria effects levels:

- $SM \geq 1$ Very High
- $0.2 \leq SM < 1$ High
- $0.002 \leq SM < 0.2$ Medium
- $SM < 0.002$ Low

This resulted in the SM severity factors reflected in Table 5.5. The business regards any SM above 1 as a non-admissible event on its balanced score card. This requires the model to assign the maximum value for severity when the functional loss element is assigned a VH classification for the SM criterion.

UCU ten-year historical data, retrieved from the enterprise asset database, reflect the average duration for failure modes as reported in Table 5.6. The table described the PM tasks that are assigned to the assets on the TPG for the duration of a year, as declared in section 5.1. The critical task team assigned the minimum duration as one day.

The UCU average durations, in Table 5.6, are assigned to the 192 PM activities declared in the maintenance plan for the specified grid and ranked from longest duration to shortest duration. The critical review team assigned the following criteria, in line with business drivers, to the PM activities to establish the four UCU criteria effect levels:

- UCU ≥ 2 years — Very High
- 4 months ≤ UCU < 2 years — High
- 28 days ≤ UCU < 4 months — Medium
- UCU < 28 days — Low

Table 5.6 Average UCU durations linked to asset failure modes and maintenance tasks

Planned Maintenance Task	**Assets – failure mode**	**Average UCU duration in days**
Tap Changer Maintenance	Transformer/tap-changer internal failure	732
Bushing Tan Delta Test	Bushing failure	732
Breaker PMT and Mechanism Maintenance	Breaker internal failure	441
Breaker PMT	Breaker internal failure	441
CT Care	CT failure	133
Protection Scheme Maintenance	Protection failure	68
Transformer Maintenance	External Transformer failure	28
Aux Transformer Maintenance	External Aux Transformer failure	1
Isolator PMT	Isolator failure	1
Earth Switch Maintenance	Isolator failure	1
Aux Transformer Painting	External Aux Transformer failure	1
Transformer Painting	External Transformer failure	1
Pole Top Inspection-Conductors & Hardware	Line failure due to hardware/conductor	5
Conventional Live Line Maintenance	Line failure due to hardware/conductor	5
Pole Top Inspection	Line failure due to hardware/conductor	5
Inspection for Porcelain Insulators	Line failure due to hardware/conductor	5
Hydrophobicity Test on Coated Insulation	Insulation flashover failure	1
Localized ESDD on Coated Insulation	Insulation flashover failure	1
NEC/NER Painting	External Aux Transformer failure	1
NEC Maintenance	External Aux Transformer failure	1
NEC/NER Maintenance	External Aux Transformer failure	1
Spray Washing of Coated Insulation	Insulation flashover failure	1

The resultant UCU factors are declared in Table 5.7 and describe the factors that are assigned to PM activities aligned to the different UCU severity criteria effects. Unplanned circuit unavailability presents risk to the total reliability of the network as the circuit unavailability removes redundancy from the network. UCU thus have a potential loss of supply impact and not a direct impact. Operational contingency plans mitigate the risk of unplanned unavailability.

Table 5.7 Calculation of UCU factors for UCU severity criteria

Category (z)	Number of PM	% of total plan	$aUCU_z$	$UCUf_z$
Very High	11	5.7292	732	417.0182
High	37	19.2708	349.4324	199.0706
Medium	64	26.0417	64	36.4606
Low	94	48.9583	1.7553	1
Total	192	100		

The type of load supplied was identified by the critical review team, as well as the interview respondents, as a critical criterion in deciding what planned maintenance activities to proceed with. The critical review team proposed the following four categories for this severity criteria:

- Nuclear safety load — Very High
- Generation connections to grid — High
- Critical load — Medium
- Normal load — Low

The corrective maintenance (CM) cost is considered an unplanned additional cost to the budget and will get preference in terms of budget allocation, depending the critical nature of failure mode. The CM cost represent a risk to the budget should specific preventive planned maintenance activity, linked to a particular failure mode, not occur increasing the risk of failure. The critical review team benchmarked costs to current business risk indices and proposed the following CM effects categories:

- Cost ≥ R10M — Very high
- R1M < Cost < 10M — High
- R100k < Cost ≤ R1M — Medium
- R10k < Cost ≤R100k — Low

The quoted actual values will vary depending on market and business risk appetite but the critical review team considered the ratio balance between categories acceptable. The definition of the categories for the different severity criteria are summarised in Table 5.8.

Table 5.8 Summary of the effects linked to failure mode/PM activity

Safety Criteria	Operational Reliability			Cost Criteria
S	**SM**	**UCU**	**LT**	**CM**
non-admissible	*non-admissible*	417.02	*non-admissible*	10,000,000
1.5	169.73	199.07	1.5	1,000,000
1	13.89	36.46	1	100,000
0	1	1	0	10,000

The summary indicates three non-admissible functional loss effects, one each in safety, system minute and load type. The model will assign the maximum value of overall severity to those failure-modes/PM activities where the non-admissible effect is assigned to a functional loss. The maximum value for overall severity is chosen as 100. The model uses the following notation:

M_i: maximum level of admissible effect for criteria i, with $M_i \leq m, \forall i$

MS: maximum value for overall severity

This produced a

[i] = S, SM, UCU, LT, CM

[M_i]= 3,3,4,3 as maximum levels of admissible effects for each criterion and

MS = 100

5.2.6. Determine Severity Categories per Criteria Effect

Similar to the development of effects probability matrix in section 5.1.4, the effects severity matrix is defined for any element included in the analysis r, as follows:

$$S_{ij} = \begin{cases} MS, & for\ M_i < j \leq m, \forall\, i \\ w_i v_{ij}, & for\ 1 \leq j \leq M_i \end{cases} \qquad 5.14$$

where $$v_{ij} = \frac{e_{ij}}{e_{ik}}\ with\ k = M_i\ and\ j \leq M_i \qquad 5.15$$

and $$v_{ij} = 1\ for\ j = M_i\ and\ \forall\, i \qquad 5.16$$

where e_{ij} is the effect *j* of severity criterion *i* and v_{ij} is the fractional value of effect *j* for severity criterion *i*.

The Effects matrix per functional loss, defined in Table 5.8, is converted to severity effects matrix (S_{ij}), defined in Table 5.9, with the use of equations 5.14 – 5.16 as well as the severity criteria weighting factors w_i calculated in section 5.2.3.

Table 5.9 Severity effects matrix (S_{ij})

Severity Criteria	**Safety Criteria**	**Operational Reliability**			**Cost Criteria**
	S	**SM**	**UCU**	**LT**	**CM**
Weight	**20%**	**30%**	**10%**	**10%**	**30%**
Very High	100	100	10	100	30
High	20	30	4.77	10	3
Medium	13.33	2.46	0.87	6.67	0.3
Low	0	0.18	0.02	0	0.03

The severity effects matrix (S_{ij}) reflects that an asset failure mode with a very high safety classification will score the maximum value (MS= 100) irrespective of the effect in any other criteria. In the event where the corrective cost linked the functional loss of the asset due to the specific failure mode is regarded as high it will score a 3.

5.2.7. Retrieving Data for Actual Probability Functional Loss

Actual data for probability effects, with regards to the functional loss of an element, can be retrieved from the enterprise asset database and captured in the variables ap_{rab}. These variables conform for each failure mode, *r*, a matrix of *n x m* elements, where *a* = 1,…,*n* criteria to measure the probability of each element and b =1,…,b levels of effects of the functional loss for any criteria. It is therefore noted that ap_{rab} are Boolean variables with the following values:

$$ap_{rab} = \begin{cases} 1, when\ b\ is\ the\ level\ of\ probability\ effect\ of\ the\ functional\ loss \\ 0, otherwise, \end{cases}$$

An example for this data retrieval and capturing process follows that for a certain failure mode "*b*" the criticality review team retrieves its probability effects which are represented in the following probability effects matrix:

$$[ap_{bab}] = \begin{bmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}$$

This failure mode on the specific asset represents a high failure rate, very poor AHI and medium duty cycle. The following model is used to calculate the actual probability of the functional loss due to the failure mode on specific asset:

$$P_r = Min(MP, \sum_{a=1}^{a=n} \sum_{b=1}^{b=m} ap_{rab} P_{ab})$$

The probability of the failure mode occurring on the specific asset, in the assign location, is calculated, using the information in Table 17, as:

$$P_r = Min\ (1, 0.3325 + 1 + 0.13) = 1$$

Marquez *et al*. (2015) argue that this equation represents a weighted average algorithm. The weights were introduced during the construction of P_{ab} and provide consistency in the probability calculation of one element with respect to the other. Marquez (2015) also highlights that the assigning of inadmissible effects to the different role actors (i.e. asset health inspectors) in the review team are safeguarded and consensus is easily reached.

5.2.8. Retrieving Data for Maximum Possible Effects per Severity Criterion

In a similar fashion data concerning maximum potential effects per severity criterion is retrieved and captured in variables pe_{rij} where these variables represent, for each failure mode *r*, a *n x m* matrix with *i* = 1,…*n* criteria to measuring severity and *j* = 1,…m levels of possible effects of the functional loss for any criteria. Again, the pe_{rij} are Boolean variables, with the following values;

$$pe_{rij} = \begin{cases} 1, when\ j\ is\ the\ level\ of\ \max potential\ effect\ of\ the\ functional\ loss \\ 0, otherwise \end{cases}$$

Following the example in section 5.2.7 the effects severity matrix defined in Table 5.9 is used to retrieve data to populate the following potential effects matrix for the failure mode b linked to the specific asset:

$$[pe_{bij}] = \begin{bmatrix} 0 & 0 & 1 & 0 & 1 \\ 1 & 1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

The potential effects matrix define the specific failure mode as having the potential of having a high safety, SM and LT effect as well as a very high UCU and corrective maintenance cost effect associated to the failure mode b.

The potential effect matrix is used to calculate the potential severity of failure mode b related to the specific asset with,

$$S_r = Min(MS, \sum_{i=1}^{i=n} \sum_{j=1}^{j=m} pe_{ri} S_{ij})$$

$$= (100,20 + 30 + 10 + 10 + 30)$$

$$= 100$$

5.2.9. Calculating Potential Criticality at Current Probability

The potential criticality of failure mode r on the specific asset can be calculated as the product of the probability P_r and severity S_r,

$$C_r = P_r \times S_r$$

Where the potential criticality for the failure mode in the examples above can be calculated as

$$C_b = 1 \times 100$$

5.2.10. Data Retrieval for Real Effects per Severity Criterion

The real severity effects, per severity criterion, can be calculated by retrieving and capturing the actual data for the element *r* from the enterprise asset database. The data is captured in variables re_{rij}. These variables, as with the potential severity effects, are presented as a *n x m* matrix with *i*=1,…n severity criteria and *j*=1,…m levels of possible severity effects of a functional loss for any criteria.

Marquez *et al*., (2005) describe the matrix as,

re_{rij} = current probability of the effect j of criteria I for the functional loss due to failure mode r

with $\sum_{j=1}^{j=m} re_{ij} = 1$

As an example the potential effect matrix developed in section 5.2.8 is re-evaluated with the extraction of actual data on the failure mode b. The critical review team used this data to construct the real effects matrix as :

$$[re_{bij}] = \begin{bmatrix} 0.0 & 0.0 & 0.8 & 0.0 & 0.1 \\ 0.3 & 0.7 & 0.2 & 1.0 & 0.0 \\ 0.0 & 0.3 & 0.0 & 0.0 & 0.9 \\ 0.7 & 0.0 & 0.0 & 0.0 & 0.0 \end{bmatrix}$$

The evaluation of the real effects matrix reveals than although the safety potential effect is regarded as high, the data reveals that it only has a 30% probability of having a permanent disability safety effect and that 70% of the time it has a minor incident safety effect. Likewise, the probability of a high system minute impact is only 70%. The location of the asset remains the same and thus the type of load effect remained at high. The corrective cost also only has a 10% possibility of a very high effect. The revised severity is then calculated by using,

$$S`_r \ = Min(MS, \sum_{i=1}^{i=n} \sum_{j=1}^{j=m} re_{rij} S_{ij}$$

This results in the calculation of the severity of element b as,

$S`_b$ = Min[100, (0.3x20) + (0.7x30 + 0.3x2.46) + (0.8x10 + 0.2x4.77) + (1x10) + (0.1x30+0.9x0.3)]

= 47.26

5.2.11. Calculating the Observed Criticality at the Current Probability

The real criticality can be calculated as

$$C`_r = P_r \times S`_r$$

The real criticality for the example can be calculated as

$$C`_r = 1 \times 47.26 \ = 47.26$$

5.3. Maintenance Activity Criticality Analysis

The MBDSS model is required to be a simple, fast and automated system to be implemented in order to react to the dynamic operational environment. The following steps are followed to achieve easy data entry to support fast data analysis.

a) The maintenance plan, for the specific area and time period, is retrieved from the maintenance management system and should include the asset location, asset description and PM activities linked to the asset in that specific location. The PM activity is linked to specific failure modes through an RCM process at the development phase of PM plans.

Table 5.10 Example of actual probability and potential severity effects qualitative matrix

Maintenance Plan data				**Probability Criteria**			**Severity Criteria**				
Element	**Location**	**Asset**	**PM activity**	**Failure**	**AHI**	**DC**	**Safety**	**SM**	**UCU**	**LT**	**CM**
A	Alpha	A	PM1	M	L	M	VH	M	M	H	M
B	Alpha	A	PM2	H	VH	M	H	H	VH	H	VH
C	Alpha	A	PM3	VH	M	L	L	M	M	H	L
D	Alpha	B	PM1	L	H	L	VH	M	L	H	M
E	Alpha	B	PM2	L	M	L	H	VH	VH	H	VH
F	Alpha	B	PM3	H	L	M	L	M	L	H	L
G	Beta	C	PM1	L	H	M	H	L	H	M	M
H	Beta	C	PM2	M	L	L	H	H	VH	M	VH
I	Beta	C	PM3	L	M	M	L	M	M	M	L
J	Beta	D	PM1	M	H	M	VH	H	M	M	H

b) Retrieve the actual probability and potential severity data for each failure mode linked to a PM activity as shown in the example in Table 5.10. Use the definitions of probability and severity effects levels in Table 5.2 and section 5.2.5 to qualitatively define the risk. This process can be automated within the enterprise asset management system environment or outside.

c) The qualitative data, from b, is converted into the quantitative matrix defined in Table 5.11. This matrix is built from Table 5.10 using the P_{ab} and S_{ij} described in equation 5.7 and equation 5.14 respectively. This matrix describes the potential criticality risk of each element in the maintenance plan.

Table 5.11 Example of current actual probability and potential severity effects quantitative matrix

Maintenance Plan data				**Probability Criteria**			**Severity Criteria**					**Probability**	**Severity**	**Criticality**	**Level**
Element	**Location**	**Asset**	**PM activity**	**Failure**	**AHI**	**DC**	**Safety**	**SM**	**UCU**	**LT**	**CM**				
A	Alpha	A	PM1	0.13	0	0.13	100	2.46	0.87	10	0.3	0.26	100	26	H
B	Alpha	A	PM2	0.33	1	0.13	20	30	10	10	30	1	100	100	VH
C	Alpha	A	PM3	0.6	0.13	0	0	2.46	0.87	10	0.03	0.73	13.36	9.75	L
D	Alpha	B	PM1	0.10	1	0	100	2.46	0.02	10	0.3	1	100	100	VH
E	Alpha	B	PM2	0.10	0.13	0	20	100	10	10	30	0.23	100	23	H
F	Alpha	B	PM3	0.33	0	0.13	0	2.46	0.02	10	0.03	0.46	12.51	5.75	L
G	Beta	C	PM1	0.10	0.2	0.13	20	0.18	4.77	6.67	0.3	0.43	31.92	13.92	M
H	Beta	C	PM2	0.13	0	0	20	30	10	6.67	30	0.13	96.67	12.57	M
I	Beta	C	PM3	0.10	0.13	0.13	0	2.46	0.87	6.67	0.03	0.36	10.03	3.61	L
J	Beta	D	PM1	0.13	0,2	0.13	100	30	0.87	6.67	3	0.46	100	46	H

d) The critical review team can now, with input from the medium- to long-term business plan set the criteria for low, medium, high and very high criticality. This will enable business to manage the different categories optimally. In this example the criticality category split was defined as 20%:30%:20%:30% and the assignment is included in Table 5.12. The criticality definition is defined in Table 5.11.

e) The data set can now be plotted on a two-dimensional criticality map by categorising the probability and severity scale in 10 bins. If more sensitivity is required the bins can be increased. The two dimensional criticality map, Figure 26, describes the potential criticality matrix for the 10 PMT defined as the maintenance plan in the example provided.

The observed criticality data from in Appendix G Table G1 is included in the criticality map. The observed criticality of each element is noted with a hyphen.

Table 5.12 Criticality level definition

Criticality level	**Distribution %**	**Elements**	**Colour Coding**
VH	20	b , d	Dark grey
H	30	a , e , j	Mild grey
M	20	g , h	Light grey
L	30	c , f , i	None

f) The criticality map demonstrates the "space" between the potential and the observed criticality for each PMT. In the example the potential criticality of PMT *b* was calculated at C_b= 100 while the observed criticality was calculated at $C`_b$= 47.26. The observed criticality was due to the observed actual severity level definition, S_{bij}, calculated in 5.2.10. The interpretation is that the potential criticality of this PMT is 100 while the observed criticality is 47.26. The user can use this information to support a decision to move or keep a particular PMT based on the potential effect.

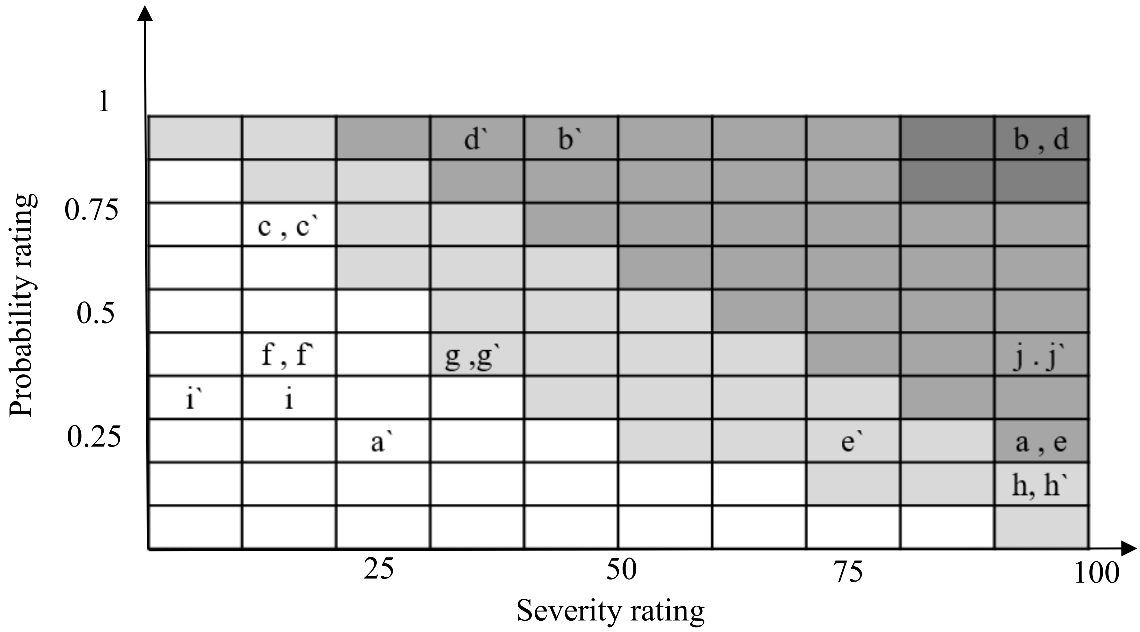


Figure 5.3 Criticality Map

In evaluating the potential savings on the maintenance budget all the low risk PMTs are identified as PMTs with a criticality rating of C_r<10. This would include PMT = {a,c,f,i}. In

Figure 5.3 PMT "a" has a low current observed criticality but the potential severity effect is high. Maintenance managers could view a delay or removal of the PMT, from the current plan, as a risk and rather decide to keep to it due its potential impact.

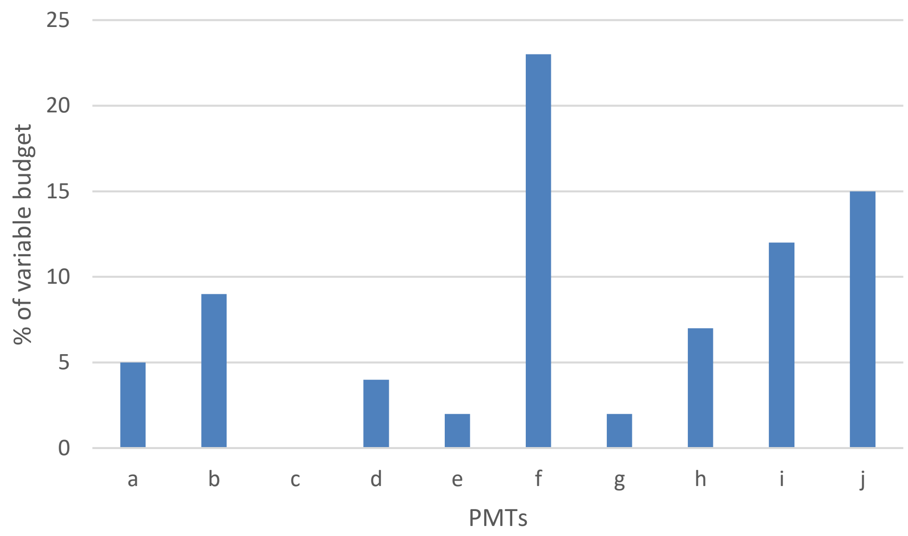


Figure 5.4 Example of PMT impact on Budget

g) In evaluating the low critical PMTs against their impact on the variable budget the maintenance manager can decide on which PMTs have the highest potential to be removed. In the example PMT "f" has a low actual and potential criticality with a high impact on the budget. PMT "c" has a very low impact on the budget but could be removed due to other constraints i.e. human resources or outage availability.

Marquez *et al.* (2015) warn that, although PMTs in the low criticality range might be ideal to be discarded, decision-makers must be cautioned against removing PMTs avoiding early equipment deterioration as this could lead to an increase in corrective maintenance and hence to an increase in failure probability. Marquez *et al.* (2015) further suggest that the severity of the failure should be under control before the PMT is removed. This could potentially relate to equipment design changes to decrease the safety severity impact in case of a functional failure.

5.4. **Model Field Results**

The MBDSS model was applied on real world maintenance data in preparation for the field evaluation. The sample space contained 192 maintenance plans assigned to nine overhead lines and equipment in seven substations. The results of the MBDSS assessment is discussed through Figure 5.5 and 5.6 respectively. The sample space as well as the results are presented to potential users in support of the field validation.

The model results are displayed in Figure 5.5 as a distribution of PMT criticality. This indicates that 80% of the total PMTs listed have a criticality number of less than 20. This could indicate the potential of cost savings but Marquez *et al.* (2015) caution against the removal of PMTs on equipment that scores a high severity loss potential but low probability loss. The Resnikoff conundrum (Marquez, et al., 2015) states that in order to collect failure data there must be equipment failures, but failures of very critical assets are considered unacceptable and therefore the maintenance programme for such assets must be designed without failure data. In Annex H Table H1, an extract of the top 40 critical PMTs assessed by the MBDSS, assets with the maximum severity functional loss potential score low on criticality due to the low probability functional loss of asset.

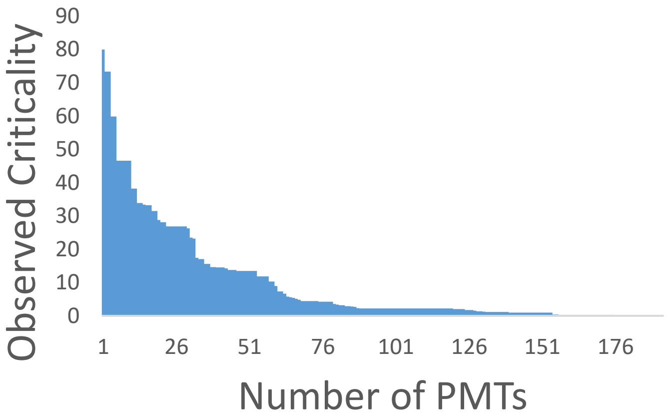


Figure 5.5 Observed criticality distribution for PMTs in maintenance plan

The removal or delay of PMTs on assets with high severity functional potential increase the likelihood of failure on assets with non-admissible criteria levels assigned to them. In this particular case the testing of transformer bushings has a very high safety severity effect associated with a failure of a bushing and it would therefore not be advised to remove this activity.

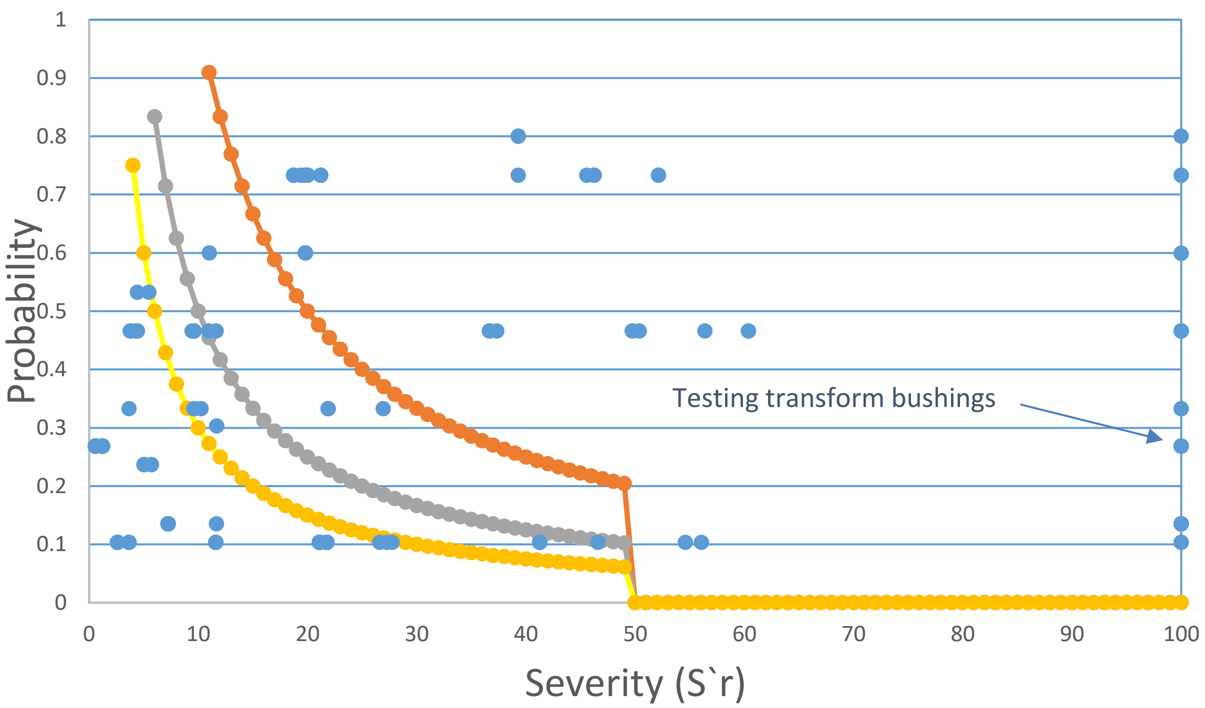


Figure 5.6 Criticality map for MBDSS PMT output

In Figure 5.6 the criticality of the preventive maintenance tasks, listed in the maintenance plan, is displayed on a criticality map. Approximately 70% of the PMTs are found under the orange limit line that represents

$$P_r = \begin{cases} \frac{C`_r}{S`_r} \, for \, S`_r < 50 \\ 0 \, otherwise \end{cases}$$

with $C`_r = 10$,

The grey and yellow limit lines represent $C`_r=5$ and $C`_r = 3$ with approximately 65% and 56% of PMTs under each of them respectively. The limit line will depend on the risk appetite of the business and in particular the maintenance managers. In the above data set the critical review team proposed a $C`_r = 1.5$ limit line that produced approximately 56 PMTs rated as very low. Out of this the review identified transformer corrosion treatment as a PMT that could potentially be delayed, which would have a substantial impact on the variable portion of the budget.

5.5. **Model Validation**

The validation of the MBDSS is based on the Borenstein (1998) DSS validation process. Validation is the process of proving whether the model behaviour represents the real-world system in the defined problem domain (Finlay, 1994). Borenstein (1998) further describes validation as having two dimensions of verification and substantiation. Verification is regarded as testing the model against what it was developed for while substantiation is viewed to examine if the model has produced a satisfactory outcome, within the boundaries of the design application.

The Borenstein (1998) DSS validation process, described in Figure 15 in Chapter 2, is based on three principals:

(i) Formal validation – internal validation within the DSS development stage
(ii) Prescriptive validation – performance measured against a standard laboratory outcome
(iii) Qualitative validation – validation based on qualitative input from a user perspective

The MBDSS, based on the Marquez *et al.* (2015) criticality model, was developed up to a conceptual level and the objective was to prove the concept and examine if the model, in its basic format, could produce a satisfactory outcome. The model was developed in a MS-Excel environment for easy implementation.

5.5.1. Formal Validation

The main objective of face validation is to achieve alignment and consistency between the model developer view and the potential users' view of the problem. The problem statement defined in the study was to ensure and maintain business objective and maintenance objective alignment within a fiscal constraint environment.

During the qualitative data collection stage maintenance managers confirmed the difficulty of operating and maintaining the TPG within a budget constrained environment. The budget-setting procedure was also perceived not to be aligned to the maintenance plan on a year-on-year basis as it was based on a predominantly incremental budget-setting philosophy.

The interviewees concurred on an optimisation model with stated input variables to prioritise maintenance activities based on cost, network reliability and safety. Managers highlighted that the model should be a decision support system and not an automated process of adjusting the maintenance plan. The model should provide an objective view that can be evaluated by maintenance managers in order to assist in decision-making.

Borenstein (1998) states that subsystem verification and validation is concerned with testing, verifying and validating DSS sub-modules. The objective is to ensure the quality of each subsystem. This process is an iterative process as it focuses on the prototype details and further development. The first step of this sub-process is to divide the MBDSS into independent subsystems with clear input and output variables.

The MBDSS was divided into two subsystems as described in Figure 5.2 and section 5.2. The first subsystem produced the probability value of the functional loss as the subsystem output. This output is based on the input probability variables namely, failure frequency, AHI and DC. The second subsystem calculated the potential and observed severity due to a functional failure and is based on five severity input variables.

The TPG consists of overhead lines and substations operating at various voltage levels. These substations are built up from different bays that are characterised by their function and equipment they contain. The substations, as basic building blocks, consist of different types of bays such as transformer bays, capacitor bank bays, feeder bays, bus-section bays and bus-coupler bays. Each bay consists of specific equipment linked to its functionality and forms the most basic location building block.

The development of the severity subsystem started with developing a system to calculate the frequency factors of assets in a transformer bay. The development included the support of a critical review team that assisted with the classification definition of the frequency levels as stated in section 5.2. The second prototype focused on the maintenance plan for a substation to calculate the frequency factors of all the equipment in the substation as well as defining the severity criteria effect levels. The critical review team assisted with the classification of the frequency levels as well as the weighting of the severity criteria. The third prototype focused on the maintenance plan of the TPG defined in section 5.1. This section consisted of seven substations and nine overhead lines. The objective of this phase was to include the development of the real severity effects matrix (re_{rij}). This enabled the calculation of the observed severity index. The critical review team assisted with the retrieval and capturing of data to establish the real effects matrix. The objective of the final model was to develop the additional probability criteria namely, AHI and DC. This enabled the calculation of the actual probability of the functional loss and thus the observed criticality C_r.

Throughout this iterative process the critical review team ensured that design assumptions are valid and consistent with the real world.

5.5.2. Prescriptive Validation

Prescriptive validation refers to the validating of the model by comparing the results of test input data to the results achieved from a proven test case.

The MBDSS was loaded with test data from Marquez *et al*. (2015). Although the model application was different, the objective of ranking alternatives according to their criticality was in principle the same. The alternatives in the case of Marquez *et al*. (2015) were defined as the assets in a train transport system while the MBDSS focused on the combination elements of location-asset-failure mode-PMT found in the maintenance plan. The Marquez *et al*. (2015) model expressed all the severity criteria as cost factors while the MBDSS used the business KPIs as severity input variables.

The MBDSS used more input variables, linked to the TPG PMTs ranking problem, and the criteria effects levels was differently defined. The MBDSS utilised three probability variables while the Marquez model only utilised one variable to calculate the probability of the functional loss.

The Marquez *et al*. (2015) model potential-criteria effect input data was used as input data to the MBDSS. The comfort criteria data, from the Marquez *et al*. (2015) model, was excluded as no related variable in the MBDSS could be found.

Table 5.13 Marquez et al. (2015) frequency and potential effects input data in MBDSs model

Maintenance Plan data				**Probability Criteria**			**Severity Criteria**				
Element	**Location**	**Asset**	**PM activity**	**Failure**	**AHI**	**DC**	**Safety**	**SM**	**UCU**	**LT**	**CM**
		A		L			L	M			H
		B		L			VH	H			M
		C		M			L	M			H
		D		H			H	H			M
		E		M			L	M			L
		F		L			L	L			M
		G		L			M	VH			L
		H		H			H	L			L
		I		VH			L	VH			L
		J		L			L	L			L

Table 5.13 reflects the Marquez *et al.* (2015) input data. This data is converted into a current frequency and potential effects quantitative matrix with the use of MBDSs. The ranking achieved is reported in Table 5.14:

Table 5.14 Prescriptive validation results

	Asset criticality rank comparisons from highest (left) to lowest right									
Marquez	I	G	D	H	B	C	A	E	F	J
MBDSs	I	D	B	G	H	C	A	E	F	J

The alpha numbering of assets was converted into numerical numbering to facilitate the quantitative comparison of the outputs. A bivariate analysis indicated a strong positive correlation between the ranking of the two models with r = 0.69, where r is the Pearson correlation coefficient.

5.5.3. Field Validation

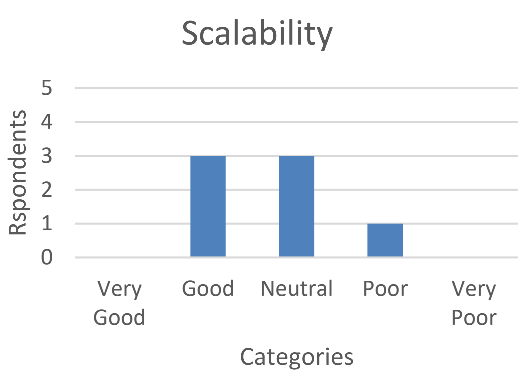
The objective of user assessment, as defined by Borenstein (1998), is to determine whether potential users, who were not part of the development and implementation process, find the model outcome acceptable as a means to support decision-making in the real world. The first objective is to examine if the potential user finds the model applicable to the stated field environment and secondly to assess the impact of the design assumptions and model structure on the required support required.

The researcher used three managers as the critical review team. They made up part of the ten respondents in the qualitative data collection phase. This team assisted with the development of critical parameters in the model to align to business objectives. All of the ten interview respondents were potential users of the MBDS. The researcher developed the following questionnaire to support the user and field validation with a qualitative approach. The questionnaire is based on the stated requirements in section 5.1 as well as the ease of implementation. Seven managers that were part of the ten interview responders but not part of the development, were invited to complete the following questionnaire.

Table 5.15 Face validation on field test

Questionnaire	**Very Good**	**Good**	**Neutral**	**Poor**	**Very Poor**
How scalable is the model and process to accommodate for large and small maintenance plans ?					
How good does the model outcome align to stated business objectives ?					
How flexible is the model in terms of adjusting weightings to align to new business focus ?					
How good does the criticality analysis align with own expectations?					
How easy is model implementation?					
What are the possible disadvantages of the model ?					

The results of the model were presented to each participant and the process of model development described. The results of the face validation are captured in Figure 5.7.



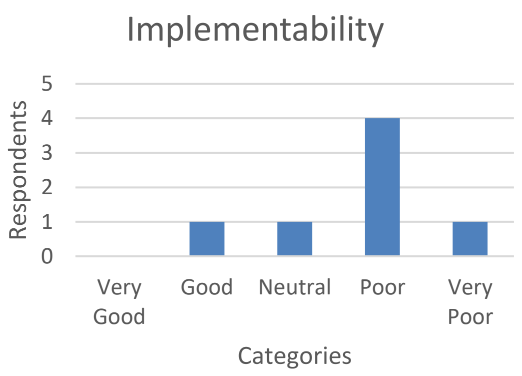


Figure 5.7 Face validation of field results and model construction

Although the high percentage of the respondents indicated that the model is scalable an equally high percentage of the respondents gave a neutral response due to the limited number of field studies as well as the sample size of the field studies that were performed. The current platform of the model was also mentioned as a possible limitation to increase the number of location-asset-PMT combinations it can handle and the automated scalability that is required.

The model was perceived to have a fairly good business objective alignment with two respondents giving it a poor rating due to a lower than expected focus on cost variables. The concern was raised that while the PMT criticality is to adequately address the PMT, the cost impact could be undervalued if the overtime and travel-and-subsistence cost per activity is neglected. The field study did not consider the effect of distance from maintenance centres that could influence expenditure. The model ranking highlighted a strong focus on nuclear safety and general safety as well as SM severity potentials. It also addressed the probability criteria efficiently with the introduction of asset condition and duty cycle as modifiers to the failure rate criteria.

Only five managers had integral knowledge of the network that was evaluated and four of them rated the response of the model as good in alignment with their own expectations. The grid's unique exposure to nuclear safety was adequately addressed as well as known supply loss risks on the network. The UCU impact also correlated well with current experiences with current long-time outages on certain plants. The was a view, however, that the model undervalues the importance of maintenance activities on secondary plant equipment because single failures of this type of equipment do not directly impact the network. It does, however, put the total network under pressure due to the impact of the next primary plant failure.

In general, the respondents rated the implementability of the model as poor due to the perceived time and resources required to generate all the real criteria severity effects for the different PMTs. The recommendation was to build the model into the existing enterprise asset management database in order to automate the model. The lack of a sufficient number of field tests contributed to the high number of neutral responses.

5.6. **Chapter Summary**

This chapter describes the development process of the maintenance budget decision support system as well as the DSS validation process.

The DSS system is based on a proven asset criticality system that was designed by Marquez et al. (2015) with the focus of prioritising assets to assist with the alignment of maintenance strategies to business priorities. The MBDSS was applied on PMTs linked to assets in a specific location in order to prioritise the specific PMT. The argument put forward was that critical assets could have less critical PMTs assigned to them that could potentially have large impact on the available budget.

The DSS validation was based on the Borenstein (1998) DDS validation process and provided insight on the possible challenges with regards to full model implementation. These challenges are discussed in Chapter 6.

Chapter 6

Conclusions and Recommendations

This chapter examines to what extent the research objectives were achieved. It focuses on the research review, the results and value added to the specific research field.

The chapter includes recommendations for future research.

6.1. Research Review

Jahed (2017) reported that financial and environmental challenges in the electrical utility environment are placing pressure on working capital management. Utilities are continuously revising capital structure strategies in order to maintain the business as a going concern. Budget plans are continuously revised to accommodate for unstable revenue streams and increasing expense accounts driven by high-input energy costs, high non-technical losses and inflated employment bills.

Recent experiences in the public utility environment, demonstrated multiple budget cutbacks within a single budget period. This placed pressure on maintenance managers to react appropriately and still comply with stated maintenance objectives. It is often difficult to quantify and qualify maintenance plan cuts without the knowledge of how it will impact the performance and reliability of the TPG in the long run.

The challenge with the South African power utility's power system maintenance budget is that current procedures do not relate to the operational maintenance objectives in terms of ensuring adequate levels of reliability and availability in a budget-constrained environment. This places the focus on maintenance managers to optimise maintenance plans, in line with maintenance objectives, to ensure that the network as well as financial performances are maintained.

In following a mixed method research approach (Chapter 3), qualitative as well as quantitative data collection and analysis tools were employed to investigate and analyse research questions (Chapter 4) in order to assist with the development of a maintenance decision support system (Chapter 5). Semi-structured interviews were conducted and secondary data extracted from maintenance databases to collect data.

Qualitative interview data was analysed by developing interview codes and themes linked to the research questions. The objective was to investigate the latent and apparent reasons for relationships between maintenance plans, performance and budget plans. Quantitative data was analysed by employing multivariable analysis to confirm strength and direction of relationships. The analysis lead to the identification of input variables of the DSS and understanding what type of limitations could be expected.

The review of the research was examined through evaluating the answers to the stated research question (Chapter 1).

What is the relationship between maintenance planning and budget setting?

1. Maintenance planning does not influence budget setting.
2. Maintenance spending forecast is based in an incremental budget-setting philosophy as the budget structure has a high employee benefit component and the philosophy is simple to implement.
3. Revenue stream is determined by the Multi-Year-Price-Determination model administrated by NERSA and the model takes into account, amongst others, the size of the fleet and certain reliability indices i.e. System Minutes. It uses the incremental spending forecast for the multi-year period to calculate allowable revenue.
4. The budget plan does influence maintenance plans as cutbacks are normally administrated across departments.
5. Less critical maintenance plans can be deferred due to working capital shortage to accommodate for more critical work.
6. The budget spending is apportioned between an employee-benefit account and a variable maintenance account. The employee-benefit account is based on the number of staff and is closely aligned to salary negotiations. The maintenance account is structured according to business requirements and deals with maintenance issues such as spares, service contracts, fleet cost and production equipment. There is a good relationship between specific maintenance-account cost-buckets and corresponding maintenance activities.

What is the relationship between maintenance planning and power system performance?

1. Indifferent relationship between performance and maintenance planning.
    a. In circumstances where critical end-of-life failure modes cannot be mitigated by preventive maintenance measures, maintenance planning does not have an impact on performance.
    b. The (n-1) Transmission Grid Code can potentially mask major performance-related issues.
    c. The quantitative secondary data analysis confirmed a moderate relationship between maintenance planning and critical performance criteria with an r=49 and statistical significance of ρ=0.07.
2. Maintenance planning impacts the reliability of the network by removing redundancy when equipment is taken out of service for maintenance
    a. Long duration planned outage on critical plant removes (n-1) system redundancy exposing the network to large SM risks.

How can maintenance plans be optimised to ensure maintenance objectives are met in a financially constrained environment?

1. Optimisation of maintenance plan based on resource availability. The maintenance resource load is equalised over a long-term planning period in order to adequately distribute workload.
2. Interviewees recognised the need to optimise maintenance more aggressively based on current business objectives and suggested the following criteria:
    a. Type of load
    b. Equipment with high replacement cost
    c. Equipment critical to network
    d. Budget availability
    e. Equipment condition
    f. Equipment availability
    g. Duty cycle of equipment (work rate of equipment)
    h. System Minute impact
    i. Maintenance cost

How can a maintenance management decision support model be constructed and validated for improving maintenance planning and budget compliance?

A literature study revealed various decision support models in the maintenance environment. The most common approach in the maintenance environment is the use of discrete multi-criteria decision-making models. This is due to the finite nature of reasonable options that could be ranked or aggregated by using multi-criteria weighted in terms of its importance. Other factors that promote the use of discrete MCDM methods are the limited amount of information available to make decisions as well as the ease of use.

Tsang *et al.* (2000) identified cost, capacity and compliance as constraints in developing a maintenance optimisation framework. TAM and Price (2008) further developed this maintenance optimisation framework to integrate business priorities in order to optimise maintenance investments. This framework was based on AHP methodology to evaluate the different options.

Swart (2015) improved on this by introducing ELECTRA and PROMETHEE ranking models to assist in developing a shutdown priority framework. This was done to accommodate for the evaluation of a larger amount of alternatives without comprising the accuracy.

Marques *et al.* (2015) proposed an asset criticality model based on risk- and cost-benefit analysis. The model is designed to prioritise assets in terms of them fulfilling business objectives and used RPN analysis in combination with AHP to assign weights to severity criteria.

Borenstein (1998) proposed a very practical DSS validation process that includes internal prescriptive validation as well as qualitative field test validation.

6.2. Research Contributions

The contribution made to the Physical Asset Management (PAM), and specifically the utility maintenance-decision research field and industry are:

a. Examination of latent and apparent reasons for the prevalent relationships between operational maintenance management, network performance and maintenance spending patterns in a financially constrained electricity transmission utility environment. This understanding is used to formulate the critical input variables for the DSS and to ensure reasonable and expected outcomes through participative development from a critical review team. Thematic analysis revealed the following apparently dominant themes:
    i. Budget setting is not influenced by maintenance planning.
    ii. Budget setting is based on an incremental/decremental setting philosophy with limited concern for the actual maintenance programme.
    iii. The current preventive maintenance strategy is time-based with a definite migration to a more condition-based approach.
    iv. There is an indifferent relationship between system performance and maintenance planning. This is due to aging plant exhibiting end-of-life failure modes that are not catered for in PMTs. The actual network performance, from an MYPD model perspective, is also possibly skewed due to the n-1 design specification of Transmission networks.

   Budget-setting principles are regulated by macroeconomics and financial performance objectives. This underlying theme promoted the requirement for an optimisation model at operational level ensuring that assigned funds are appropriately aligned to critical maintenance tasks. The research provided for a simple risk-based methodology to establish a model that ranks preventive maintenance tasks with reference to a failure mode and location of asset on the network.

b. DSS to support operational maintenance managers in making quantified operational decisions in line with strategic business objectives. Recent financial and environmental challenges in the power utility section have highlighted the need for continuous reviews of maintenance strategies. RCM and FMECA methods have a strong focus on plant reliability and to a lesser extent financial considerations that are linked to external macroeconomic factors. Although various models exist, the MBDSS is based on criteria identified as critical in a transmission utility environment. The Marquez model has been validated in numerous large-scale utility industries, including electricity transmission, but focused solely on asset criticality without recognising non-critical high-cost PMTs linked to it. The MBDSS model is refined to focus on PMTs linked to specific assets, in specific locations on the network. In addition to this, it includes a more dynamic probability analysis with the introduction of asset health and work-rate criteria.

The research comes at a time when the South African Electricity Utility industry is embarking on new business models in order to optimise and realign business priorities to deliver on its core mandate.

6.3. Recommendations on Future Work and Conclusion

Maintenance decision-making in Physical Asset Management is a well-developed research domain based on the fundamental principles of asset management. According to the GFMAM maintenance framework, maintenance management is defined as the decision-making process that aligns maintenance delivery activities with corporate objectives and strategies (GFMAM, 2016). This research study focused on the specific relationships between business objectives and performance through maintenance decision-making in the fiscally constrained transmission utility environment. The DSS aligns with IAM (2015) that states that it should consider the cost of planned interventions as well as the risk and the cost of failure.

It is however, recommended that the model expand on the cost of preventive maintenance tasks by including the variable T&S and overtime cost, especially at sites that are far from maintenance centres. Overtime is not a planned activity but the probability of incurring overtime can be determined by linking staff skills to certain sites.

The probability of a failure event is currently based on constant failure modes curves. These failure modes are modified with the introduction of asset health and equipment work rate determinations to replicate wear-and-tear failure mode curves. Protection and control equipment exhibits a more random failure mode and should be treated differently as opposed to large primary plant equipment with dominant mechanical-related failures.

In addition, the validation process revealed that the model should be exposed to a larger data set to test the scalability and ease of implementation. The model only focused on outage-related PMTs because of the perceived larger impact on the variable cost component. The inclusion of employment cost could test the PMT programme against the required resource compliment.

The aforementioned recommendations will potentially enhance and further the research study as well as the Maintenance Budget Decision Model. The fundamentals of the model could also be applied in similar industries with large-scale asset PMT programmes.

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Appendix A: Example A Demonstrating AHP Method:

A Section of a Transmission system has six 400 kV overhead high voltage lines. These lines are critical in the supply of electricity in this area. A health and criticality assessments is conducted on these overhead lines using four independent criteria. The maintenance planner requires understanding of the criticality of the system to adequately plan maintenance. Table A1 describes the four different criteria that will be used to assess the lines.

Table A1: Criteria assessments

Judgement Ratio Scale				
Level	**Functional Importance**	**Loading**	**Health**	**Environment**
5	Critical	High	Very Poor	Harsh
4			Poor	
3	Significant		Fair	
2		Low	Good	
1	Economic		Very Good	Mild

Table A1 depicts the comparison matrix where

FL = Functionality Location

L = Loading

H = Health

E = Environment

Table A2: Comparison Matrix

aij	**FL**	**L**	**H**	**E**
FL	1.00	2.00	2.00	3.00
L	0.50	1.00	1.00	2.00
H	0.50	1.00	1.00	2.00
E	0.33	0.50	0.50	1.00

The comparison matrix defines that the functional location of the line is twice as important as the load on the line and the health of the line. In addition it is three times more important than the environmental conditions. The loading on the line and the health of the line is of equal importance but is twice as important as the environment but only half as important as the functional location. The environment in which the line operates is regarded as a third of the importance of the functional location half the importance of the other two criteria. In determining the eigenvalues and corresponding eigenvectors of the comparison matrix the following steps is followed:

a. First multiply the 4 x 4 identity matrix with the scalar λ

$$\lambda \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \lambda & 0 & 0 & 0 \\ 0 & \lambda & 0 & 0 \\ 0 & 0 & \lambda & 0 \\ 0 & 0 & 0 & \lambda \end{bmatrix} \qquad A1$$

b. Second, subtract the multiple of the identity matrix from the comparison matrix

$$\boldsymbol{A} - \lambda \boldsymbol{I} = \begin{bmatrix} 1.0 & 2.0 & 2.0 & 3.0 \\ 0.5 & 1.0 & 1.0 & 2.0 \\ 0.5 & 1.0 & 1.0 & 2.0 \\ 0.3 & 0.5 & 0.5 & 1.0 \end{bmatrix} - \begin{bmatrix} \lambda & 0 & 0 & 0 \\ 0 & \lambda & 0 & 0 \\ 0 & 0 & \lambda & 0 \\ 0 & 0 & 0 & \lambda \end{bmatrix} \qquad A2$$

$$= \begin{bmatrix} 1-\lambda & 2.0 & 2.0 & 3.0 \\ 0.5 & 1-\lambda & 1.0 & 2.0 \\ 0.5 & 1.0 & 1-\lambda & 2.0 \\ 0.3 & 0.5 & 0.5 & 1-\lambda \end{bmatrix}$$

c. Find the determinant of the difference matrix and solve for all λ_n where det(**A**-λ**I**)= 0

Where λ_1= 4.01, λ_2= -0.103, λ_3= 0.09, λ_4= 4.48 x 10^{-18}

d. Solve the eigenvectors by back substituting the maximum eigenvalue
For λ_{max}= 4.01

$$\mathbf{X} = \begin{bmatrix} 0.77 \\ 0.41 \\ 0.41 \\ 0.22 \end{bmatrix}$$

e. The CR =0.00345 is regarded as very consistent.

Table A3: Criticality analysis for overhead lines

Overhead line	Functional Locality	Duty Cycle	Health	Environment	Feeder
BAC-PRO	5	5	3	5	4.543358946
ACA-KOE2	5	2	4	5	4.086717892
ANK-KOE1	5	2	4	5	4.086717892
ACA-MUL	5	2	3	5	3.858397366
ACA-PHI1	5	2	3	5	3.858397366
ACA-PHI2	5	2	3	5	3.858397366

In Table A3 the weighting is applied to the individual criteria to determine the most important overhead lines in the section of the transmission power grid.

Appendix B: Example B Demonstrating ELECTRE II Method:

A RCM study on a 500 MVA 400 kV/132 kV transformer bay reveals the following maintenance activities linked to certain failure modes. The maintenance planner requires a criticality analysis for ranking the maintenance activities according to the following criteria:

a) Probability of failure mode, linked to activity, occurring
b) Load and availability consequence, linked to failure mode (System Minutes).
c) Condition of equipment linked to maintenance activity
d) Cost of maintenance activity and
e) Replacement Cost of item that is maintained

The following table depicts the alternatives and the criteria ratings:

Table B1: Maintenance Activities in Transformer bay

Maintenance activity		C_1	C_2	C_3	C_4	C_5
Insulator maintenance	A_1	0.02	0.05	4	R14,400	R1,000,000
Breaker maintenance	A_2	0.03	0.7	3	R33,900	R4,000,000
Protection maintenance	A_3	0.01	0.7	3	R3,500	R1,500,000
Transformer corrosion	A_4	0.001	0.01	2	R600,000	R15,000,000
Transformer OLTC	A_5	0.01	0.01	2	R400,000	R50,000,000

In the problem above C1 and C2 are considered benefit criteria and C3 and C4 are considered cost criteria. The normalised decision matrix A is calculated as

$$A = \begin{bmatrix} 0.5162 & 0.0196 & 0.2601 & 0.3248 & 0.0190 \\ 0.7743 & 0.9800 & 0.5202 & 0.1379 & 0.0763 \\ 0.2581 & 0.1960 & 0.3468 & 0.9355 & 0.0286 \\ 0.0258 & 0.0196 & 0.5202 & 0.0077 & 0.2863 \\ 0.2581 & 0.0196 & 0.5202 & 0.0116 & 0.9544 \end{bmatrix} \qquad B1$$

and the weighted normalised matrix **Y = A * W** as:

$$\mathbf{Y} = \begin{bmatrix} 0.1032 & 0.0058 & 0.0260 & 0.0649 & 0.0038 \\ 0.1548 & 0.2940 & 0.0520 & 0.0275 & 0.0152 \\ 0.5162 & 0.0588 & 0.0346 & 0.1871 & 0.0057 \\ 0.0051 & 0.0058 & 0.0520 & 0.0015 & 0.0572 \\ 0.0516 & 0.0058 & 0.0520 & 0.0023 & 0.1908 \end{bmatrix} \qquad B2$$

with the weight matrix defined as

$$\mathbf{W} = \begin{bmatrix} 0.20 & 0.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.30 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.10 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.20 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.20 \end{bmatrix} \qquad B3$$

In determining the concordance and discordances sets the following is observed*:*

Table B2 Concordance sets for Example

$C_{12} = \{4\}$	$C_{21} = \{1,2,3,5\}$	$C_{31} = \{2,3,4,5\}$	$C_{41} = \{2,3,5\}$	$C_{51} = \{2,3,5\}$
$C_{13} = \{1\}$	$C_{23} = \{1,2,3,5\}$	$C_{32} = \{4\}$	$C_{42} = \{3,5\}$	$C_{52} = \{3,5\}$
$C_{14} = \{1,2,4\}$	$C_{24} = \{1,2,3,4\}$	$C_{34} = \{1,2,4\}$	$C_{43} = \{3,5\}$	$C_{53} = \{1,2,3,5\}$
$C_{15} = \{1,2,4\}$	$C_{25} = \{1,2,3,4\}$	$C_{35} = \{1,2,4\}$	$C_{45} = \{2,3\}$	$C_{54} = \{1,2,3,4,5\}$

and

Table B3 Discordance sets for Example

$D_{12} = \{1,2,3,5\}$	$D_{21} = \{4\}$	$D_{31} = \{1,5\}$	$D_{41} = \{1,2,4\}$	$D_{51} = \{1,2,4\}$
$D_{13} = \{2,3,4,5\}$	$D_{23} = \{4\}$	$D_{32} = \{1,5\}$	$D_{42} = \{1,2,4\}$	$D_{52} = \{1,2,4\}$
$D_{14} = \{3,5\}$	$D_{24} = \{3,5\}$	$D_{34} = \{3,5\}$	$D_{43} = \{1,2,4\}$	$D_{53} = \{2,4\}$
$D_{15} = \{3,5\}$	$D_{25} = \{3,5\}$	$D_{35} = \{3,5\}$	$D_{45} = \{1,4,5\}$	$D_{54} = \{\}$

These sets, described above, are used to construct the following concordance and discordance matrices.

$$\mathbf{C} = \begin{bmatrix} -- & 0.20 & 0.20 & 0.70 & 0.70 \\ 0.80 & -- & 0.80 & 0.80 & 0.80 \\ 0.80 & 0.20 & -- & 0.70 & 0.70 \\ 0.60 & 0.30 & 0.30 & -- & 0.40 \\ 0.60 & 0.30 & 0.80 & 1.00 & - \end{bmatrix} \qquad \textit{B4}$$

and

$$\mathbf{D} = \begin{bmatrix} --- & 1.0000 & 1.0000 & 0.5449 & 1.0000 \\ 0.1297 & --- & 0.6781 & 0.1457 & 0.6095 \\ 0.4226 & 0.4389 & --- & 0.2777 & 1.0000 \\ 1.0000 & 1.0000 & 1.0000 & --- & 1.0000 \\ 1.0000 & 1.0000 & 1.0000 & 1.0000 & --- \end{bmatrix} \qquad \textit{B5}$$

The concordance and discordance matrices are used to calculate the pure concordance and discordance indices. This then calculates the ranking of the maintenance activities in a transformer bay as:

Table B4: Example: Ranking as per ELECTRE II

Maintenance activity	**C_1 Failure**	**C_2 Load**	**C_3 Plant Health**	**C_4 Maintenance Cost**	**C_5 Replacement Cost**	**C**	**D**	**Ave**	**Final Rank**
Insulator maintenance	0.02	0.01	4	R14,400	R1,000,000	4	4	4	4
Breaker maintenance	0.03	0.50	2	R33,900	R4,000,000	1	1	1	1
Protection maintenance	0.01	0.10	3	R5,00	R1,500,000	2	2	2	2
Transformer corrosion	0.001	0.01	2	R600,00	R15,000,000	5	5	5	5
Transformer OLTC	0.01	0.01	2	R400,00	R50,000,000	3	3	3	3
Weighting	0.2	0.30	0.10						

Appendix C: Example C Demonstrating PROMETHEE II Method:

This example will use the same weighted normalised decision matrix to calculate the ranking of maintenance activities for a typical 500 MVA 400/132 kV transformer bay. The preference functions for the pairs of maintenance activity alternatives is calculated, using the simplified approach as stated in Swart (2015).

Table C1: Preference functions for PROMETHEE II

Preference Function		**C_1**	**C_2**	**C_3**	**C_4**	**C_5**
$P(A_1,A_2)$		0	0	0	0.037371	0
$P(A_1,A_3)$		0.051623	0	0	0	0
$P(A_1,A_4)$		0.098083	0	0	0.063409	0
$P(A_1,A_5)$		0.051623	0	0	0.062629	0
$P(A_2,A_1)$		0.051623	0.288125	0.026013	0	0.011454
$P(A_2,A_3)$		0.103245	0.235204	0.017342	0	0.009545
$P(A_2,A_4)$		0.149705	0.288125	0	0.026038	0
$P(A_2,A_5)$		0.103245	0.288125	0	0.025258	0
$P(A_3,A_1)$		0	0.052921	0.008671	0.12214	0.001909
$P(A_3,A_2)$		0	0	0	0.159511	0
$P(A_3,A_4)$		0.04646	0.052921	0	0.185549	0
$P(A_3,A_5)$		0	0.052921	0	0.18477	0
$P(A_4,A_1)$		0	0	0.026013	0	0.05345
$P(A_4,A_2)$		0	0	0	0	0.041996
$P(A_4,A_3)$		0	0	0.017342	0	0.051541
$P(A_4,A_5)$		0	0	0	0	0
$P(A_5,A_1)$		0	0	0.026013	0	0.187074
$P(A_5,A_2)$		0	0	0	0	0.175621
$P(A_5,A_3)$		0	0	0.017342	0	0.185165
$P(A_5,A_4)$		0.04646	0	0	0.00078	0.133625

The results are used to calculate the multi-criteria preference indices as reported in

Table C2: Multi-criteria preference index

Alternative	**A1**	**A2**	**A3**	**A4**	**A5**
A1	-	0.007474	0.010325	0.032298	0.02285
A2	0.101654	-	0.094853	0.121586	0.112138
A3	0.041553	0.031902	-	0.062278	0.05283
A4	0.013291	0.008399	0.012042	-	0
A5	0.040016	0.035124	0.038767	0.036173	-

The ranking of the maintenance alternatives according to the PROMETHEE II method is presented in the last column of Table C3

Table C3: PROMETHEE Ranking for maintenance alternatives

Maintenance activity alternatives	**Ai**	**Leaving flow**	**Entering flow**	**Net flow**	**Rank**
Insulator maintenance	A1	0.015105409	0.049128654	-0.03402	4
Breaker maintenance	A2	0.10755782	0.020724983	0.086833	1
Protection maintenance	A3	0.047140969	0.038996875	0.008144	2
Transformer corrosion	A4	0.008433237	0.063083873	-0.05465	5
Transformer OLTC	A5	0.03752014	0.043823189	-0.0063	3

Appendix D: Semi-Structured Interview Guide

Introduction

Share topic of study, reason for research.

Open Questions

- What is the relationship between maintenance planning and operational budget setting?
- Explain the operational budget structure and budget-setting method that is employed in the utility environment?
- What maintenance strategies is employed and what is the typical maintenance planning challenges?
- Explain the relationship between maintenance planning and power system performance?
- How is the performance of the power system measured?
- How is maintenance planning influenced by the power system performance?
- How is the maintenance plan optimised on a year-to-year basis (What criteria is utilised)?
- Could you benefit from a Maintenance Budget Decision Support System to assist with maintenance plan optimisation (Explain)

Post Discussion Questions

Do you have anything that you want to add to the topic discussed?

Appendix E: Interview Data

Table E1 Interview Data Collection: Coding Schedule

Research Theme	**Code**	**Description of Theme/code**
Relationship between Maintenance Planning and Budget setting	MP≠BS	No relationship between maintenance planning and budget setting
	Cost_Quant	Quantification of maintenance cost is problematic
	BS»MP	The maintenance plan is fit into the budget that is provided
	(BS+Res)»MP	Budget and resources influence the maintenance plan
	Req-ZBB	There is a requirement for ZBB approach to budget setting
	ΔBS»Spend	Incremental budget setting promotes spending of entire budget to preserve safety margin
	Bud_flex	Although budget is fix there is flexibility ito moving funds around within operational budget to address critical unplanned events
	Costing≠MP	Operational units cannot justify MP financially
Budget Setting Strategy	ΔBS	Incremental budget setting
	(ΔBS+pop)_ √	Incremental budget setting in combination with equipment population count use to apportion funds between operational areas
	LimZBB	Limited ZBB as required by Business during cost cutting budget reviews
	SalvsMain	Budget-structure with high employee benefit portion
Maintenance Strategy	Time_Cond_B	Mixture of Time based and Condition based Maintenance
	MS_OEM	Maintenance Strategy based on OEM requirements
	Time_B	Time Based Maintenance Strategy
	M_Reg	Maintenance Strategy influenced by Electricity regulator
	RiskB	Require Risk based approach to Maintenance Strategy
	M_cluster	Maintenance cluster to optimise Plant Outages
	Const_Spend	Constraint in spending maintenance budget due to procurement and resource challenges
Relationship between Maintenance Planning and Performance	Pref»MP	Performance of equipment impacts maintenance planning
	MP≠Perf	Maintenance planning does not impact performance of equipment
	MP»Perf	Maintenance planning does impact performance of equipment

Research Theme	Code	Description of Theme/code
	Maint»R	Maintenance planning impacts reliability of network by removing redundancy when equipment is taken out of service for maintenance
	Perf≠Funding	Performance does not impact budget/maintenance funding
Maintenance Optimisation	R_optim	Optimisation of maintenance based on resources available
	Eq_optim	Optimisation of maintenance based on equipment condition
	Inc_vs_Cost	Leverage of cost of maintenance/refurbishment against income generated
	Val_add	Maintenance optimisation should recognised impact on organisation value proposition
	Main_Equal	Maintenance load should be equalised over a long-term planning period in order to provide an equally distributed maintenance resource requirement.
Maintenance DDS Criteria	E-avail	Equipment availability
	SM	System Minute = (Load loss * duration of loss)/ System base load
	E-Cond	Equipment condition
	M_cost	Maintenance activity cost
	E maj-Cond	High replacement cost/ Critical equipment performance
	R_capab	Resource capability
	Perf	Performance of equipment
	Budg_Avail	Maintenance budget available
	Type-L	Type of load. Nuclear , Hospital, Mines , Residential, office etc.
	D-cycle	Duty Cycle of equipment. Example breaker cyclo count, Transformer tap-changer count etc
Add Info	Move_CBM	Move to CBM approach
	Pareto_opt	Optimisation focusing on only high maintenance cost items
	Dat_Anal	Data analytics
	FrameW	Framework to support maintenance strategy

Table E2 Interview 1 Coding

Research theme	**Interview theme**	**Code**
Relationship between MP and BS	There should be a relationship but there is not	MP≠BS
	Budget is fixed and maintenance is fitted in budget	BS»MP
	Apart from budget resources are also limited	(BS+Res)»MP
	Resources = manpower and time	
	This compromise performance	Req-ZBB
	Spending of total budget encourage without consideration of maintenance required	ΔBS»Spend
Budget Setting Strategy	Top down approach	ΔBS
	Historical view on what was spend + 10%	
	Risk of having an inflated budget over time because maintenance requirement (# of plant and type of maintenance) might not increase at same rate. Operationally mangers would want to cover any unplanned eventuality with fat in budget	
Maintenance Strategies	Preventive strategy	Time_Cond_B
	Inspections and CM both time based and synchronised 6 months apart	
	Quality of inspections an issue and could impact line availability	Maint»R
Relationship between MP and Performance	Defects, that could have an impact on performance of line, are cleared by corrective maintenance	Pref»MP
	Based on ground and Arial inspections to identify defects. This impacts the performance	MP»Perf
Maintenance Optimisation	Long term planning (6 Y) is possible but inaccurate	
	Require more short term and continuous optimisation due to environmental and financial variances as well as condition	Eq_optim
	People reluctant to change and prefer to keep with existing	
Maintenance DDS criteria	Money	M_cost
	People	R_capab
	Equipment	Equipment condition
	Performance	Perf
Additional information	Optimising not only money but resources meaning people, tools and equipment.	Tot_Opt

Table E3 Interview 2 Coding

Research theme	**Interview theme**	**Code**
Relationship between MP and BS	Total disconnect between Maintenance Planning and Budget setting	MP≠BS
	Maintenance adjusted to fix budget	BS»MP
	Budget and resources influence the maintenance plan	(BS+Res)»MP
	Can motivate additional funds but these funds come from other cost centres within maintenance budget	Bud_flex
Budget Setting Strategy	Historical trend and increase based on price increases, salary increase etc.	ΔBS
	Budget also based on asset numbers	(ΔBS+pop)_ √
Maintenance Strategies	Time based Maintenance	Time_Cond_B
	Condition based Maintenance	
	RCM	
	Available resource and Procurement constraints to spend budget	Const_Spend
Relationship between MP and Performance	Bad performing year could unlock funding for following year	Pref»MP
	More Maintenance does not guarantee better performance	MP≠Perf
Maintenance Optimisation	Optimisation of maintenance based on resources available	R_optim
Maintenance DDS criteria	Performance	Perf
	Budget Availability	Budg_Avail
	Cost of Maintenance	M_cost
Additional information	DSS can support with motivating for additional funds	FrameW
	Performance measured based on historical trends and targets varies according to history. Consecutive good weather lead to good performance than leads to tighten of targets. Than one bad weather leads to bad performance and exceeding of target	

Table E4 Interview 3 Coding

Research theme	**Interview theme**	**Code**
Relationship between MP and BS	Disassociation between MP and BS	MP≠BS
	Budget and resources influence the maintenance plan	(BS+Res)»MP
	Operational units cannot justify MP financially	Costing≠MP
	Maintenance cost not itemised sufficiently to account for manpower, spares, transport etc.	Cost_Quant
Budget Setting Strategy	Historical view on what was spend + 10%	∆BS
	MP does not influence budget	
	BS does not recognise fluctuation of number of plant to be maintain over 6 year cycle	
Maintenance Strategies	Time based	Time_Cond_B
	Condition based	
	RCM	
	Maintenance work clustering to optimised plant outages	M_Cluster
Relationship between MP and Performance	One way relationship	Pref»MP
		MP≠Perf
Maintenance Optimisation	Resources balance with work required in year	R_optim
Maintenance DDS criteria	Network risk	E-avail
	Performance	SM
	Condition	E-Cond
	Cost	M_cost
Additional information	Stringent alignment of maintenance to OEM requirements is cost intensive	

Table E5 Interview 4 Coding

Research theme	**Interview theme**	**Code**
Relationship between MP and BS	Total disconnect between Maintenance Planning and Budget setting	MP≠BS
	Maintenance adjusted to fix budget	BS»MP
	Although budget is fix there is flexibility ito moving funds around within operational budget to address critical unplanned events	Bud_flex
Budget Setting Strategy	Historical trend and increase based on price increases, salary increase etc.	ΔBS
	No relationship between budget acquired and maintenance required and that is correct	
Maintenance Strategies	Combination of Time based and CBM with limited RCM	Time_Cond_B
	Require Risk based approach to Maintenance Strategy	RiskB
	MS also depended on network design as it impacts plant availability and network integrity	
Relationship between MP and Performance	There is a relationship between power system reliability and maintenance philosophy	Pref»MP
	Maintenance planning has an influence on system reliability in that redundancy is removed when equipment is out of service for maintenance	Maint»R
	Maintenance planning has an influence on system performance	MP»Perf
Maintenance Optimisation	Maintenance optimisation should happen over a longer planning period and bigger operational area according to resource and budget availability	Main_Equal
	Optimisation of maintenance based on equipment condition, duty cycle and environment	Eq_optim
	Work equalised over longer planning period	R_optim
Maintenance DDS criteria	Size of load at risk	SM
	Type of load	Type-L
	Availability of funds	Budg_Avail
	Resource capability	R_capab
	Duty Cycle	D-cycle
	Environmental conditions	Enviro
Additional information	Maintenance planning to ensure an equal maintenance load spread over long period	

Table E6 Interview 5 Coding

Research theme	**Interview theme**	**Code**
Relationship between MP and BS	Total disconnect between Maintenance Planning and Budget setting	MP≠BS
	There was a connection before changeover to new MMS	Req-ZBB
	Incremental budget setting promotes spending of entire budget to preserve safety margin	ΔBS»Spend
	Maintenance adjusted to fix budget	BS»MP
Budget Setting Strategy	Budget apportioned on emotion	
	Budget increased by 5 %– 10%	ΔBS
Maintenance Strategies	Time based Maintenance	Time_B
	Maintenance based on international benchmarking	
	Maintenance verify functionality of equipment	
	Regulatory impact on Maintenance approach requires preventivemaintenance	M_Reg
Relationship between MP and Performance	Changes from 1Y to 3Y frequency little impact on performance	Pref»MP
	Environment and duty cycle could change maintenance approach	MP≠Perf
	OEM has no experience on aging process in field and relies on users feedback	
	Market forces have high impact on maintenance approach in deregulated environment	Val_add
Maintenance Optimisation	Leverage cost of maintenance and refurbishing against the income generated	Inc_vs_Cost
	ROI criteria	RoI
	Asset Management approach – what value is added to business	Val_add
Maintenance DDS criteria	Quality of supply	
	Interruptions and size of customer base (SM)	SM
	Maintenance Outage durations	E-avail
	Ranking of maintenance activities by cost	M_cost
Additional information	Proposed to move to a total CBM	Move_CBM
	Focus should be on quantifying value of maintenance	Dat_Anal
	Require a framework to support these advances in analysis	FrameW

Table E7 Interview 6 Coding

Research theme	**Interview theme**	**Code**
Relationship between MP and BS	Maintenance adjusted to fix budget	BS»MP
Budget Setting Strategy	Historical trend and increase based on price increases, salary increase etc.	∆BS
	Huge proportion of budget is focus on employment benefit (salary, overtime etc)	SalvsMain
Maintenance Strategies	Limited RCM	Time_Cond_B
	Risk based approach to Maintenance Strategy	RiskB
Relationship between MP and Performance	Maintenance planning has an influence on system reliability in that redundancy is removed when equipment is out of service for maintenance	Maint»R
Maintenance Optimisation	Optimisation of maintenance based on equipment condition, duty cycle and environment	EqR_optim
Maintenance DDS criteria	High replacement cost equipment performance	E maj-Cond
	Maintenance cost	M_cost
	Duty Cycle of equipment. Example breaker cyclo count, Transformer tap-changer count etc	D-cycle
	Maintenance Outage durations	E-avail
	Interruptions and size of customer base (SM)	SM
Additional information	DDS should focus on high maintenance cost items ito optimisation and not on entire plan	Pareto_optim

Table E8 Interview 7 Coding

Research theme	Interview theme	Code
Relationship between MP and BS	No relationship between maintenance planning and budget setting	MP≠BS
	Grids cannot defend maintenance plan financially	Costing≠MP
Budget Setting Strategy	Incremental/ decremental budget setting philosophy	ΔBS
	Incremental budget setting in combination with equipment population count use to apportion funds between operational areas	(ΔBS+pop)_ √
Maintenance Strategies	Preventive maintenance approach	Time_Cond_B
	Predominate Time based approach	
	Maintenance strategy influence by Electricity regulator	M_Reg
Relationship between MP and Performance	Maintenance is about preventing failures that will cost you. (replacement)	Maint»Perf
	Performance does not impact budget/maintenance funding	Perf≠Funding
Maintenance Optimisation	Maintenance optimisation should recognised the impact on organisation value proposition	Val_add
	Leverage of cost of maintenance against income generated	Inc_vs_Cost
Maintenance DDS criteria	Maintenance cost	M_cost
	Duty Cycle of equipment. Example breaker cyclo count, Transformer tap-changer count etc	D-cycle
	High replacement cost equipment performance	E maj-Cond
Additional information	Optimisation focusing on only high maintenance cost items	Pareto_opt

Table E9 Interview 8 Coding

Research theme	**Interview theme**	**Code**
Relationship between MP and BS	No correlation between maintenance planning and budget setting	MP≠BS
	Actual direct cost of maintenance is not captured (only time and T&S)	Cost_Quant
	Budget and resources influence the maintenance plan	(BS+Res)»MP
Budget Setting Strategy	Incremental budget setting	ΔBS
	Limited ZBB as required by Business during cost cutting budget reviews	LimZBB
Maintenance Strategies	Time based maintenance	Time_B
	Maintenance clustering to optimise outages	M_cluster
Relationship between MP and Performance	Maintenance planning impacts performance	MP»Perf
	Maintenance planning impacts reliability	Maint»R
Maintenance Optimisation	Optimisation based on resource availability	R_optim
Maintenance DDS criteria	Equipment availability	E-avail
	System minute loss	SM
	Equipment Condition	E-Cond
	Maintenance cost	M_cost
	Duty cycle of equipment	D-cycle
Additional information	Move to risk based	Move_CBM
	Data analytics	Dat_Anal
	Framework to support maintenance strategy	FrameW

Table E10 Interview 9 Coding

Research theme	Interview theme	Code
Relationship between MP and BS	No relationship between MP and BS	MP≠BS
	Cost quantification problematic	Cost_Quant
	Maintenance plan fitted into Budget	BS»MP
	Budget and resources influence the maintenance plan	(BS+Res)»MP
	Operational units cannot justify MP financially	Costing≠MP
	Bud flexibility	Bud_flex
	Incremental budget setting promotes entire budget to preserve safety margin	ΔBS»Spend
Budget Setting Strategy	Incremental budget setting	ΔBS
Maintenance Strategies	Mixture between Time based and CBM	Time_Cond_B
	Maintenance activity clustering	M_cluster
	Constraint in spending maintenance budget due to procurement and resource challenges	Const_Spend
Relationship between MP and Performance	Maintenance Big impact on performance	MP»Perf
	Performance limited impact on maintenance	
Maintenance Optimisation	Optimisation based on resources	R_optim
Maintenance DDS criteria	System minute	SM
	Equipment condition	E-Cond
	Maintenance cost	M_cost
	Duty cycle of equipment	D-cycle
	Performance	Perf
Additional information	Move towards risk based maintenance	Move_CBM
	Frame work to support maintenance strategy	FrameW

Table E11 Interview 10 Coding

Research theme	**Interview theme**	**Code**
Relationship between MP and BS	Budget and resource influence the maintenance planning	(BS+Res)»MP
	Cost quantification problematic	Cost_Quant
	Maintenance plan fitted into Budget	BS»MP
	Require some ZBB at times of budget review	Req-ZBB
Budget Setting Strategy	Incremental budget setting	ΔBS
	Limited ZBB as required by business during cost cutting budget reviews	LimZBB
	Budget-structure with high employee benefit portion	SalvsMain
	Incremental budget setting in combination with equipment population count use to apportion funds between operational areas	(ΔBS+pop)_ √
Maintenance Strategies	Mixture between Time based and CBM	Time_Cond_B
	Maintenance activity clustering	M_cluster
Relationship between MP and Performance	Maintenance Big impact on performance	MP»Perf
	Performance impacts maintenance	Pref»MP
	Maintenance Planning impacts Reliability	Maint»R
Maintenance Optimisation	Optimisation based on resources	R_optim
	Equipment condition	Eq_optim
Maintenance DDS criteria	System minute	SM
	Equipment availability	E-avail
	Budget availability	Budg_Avail
	Type of load	Type-L
	Critical plant	E maj-Cond
	Resource capability	R_capab
Additional information	Move towards risk based maintenance	Move_CBM
	Frame work to support maintenance strategy	FrameW

Appendix F: Quantitative Data

$$M_T = a_0 + a_1 \times SM_T + a_2 \times PPI_T + a_3 \times UCU_T$$

Multivariable Regression Analysis

OVERALL FIT	
Multiple R	0.492878
R Square	0.242929
Adjusted R Square	0.148295
Standard Error	135.9229
Observations	28

AIC	278.7607
AICc	281.488
SBC	284.0895

ANOVA				**Alpha**	**0.05**	
	df	*SS*	*MS*	*F*	*p-value*	*sig*
Regression	3	142278.1	47426.04	2.567036	0.078113	no
Residual	24	443400.6	18475.02			
Total	27	585678.7				

	coeff	***std err***	***t stat***	***p-value***	***lower***	***upper***	***vif***
a_0	223.819	510.1653	0.438719	0.66479	-829.11	1276.748	
a_1	159.1646	81.60553	1.950414	0.062899	-9.26095	327.5901	1.083782
a_2	6.307548	4.830643	1.305737	0.20402	-3.66241	16.27751	1.062428
a_3	-246.396	191.3406	-1.28773	0.210118	-641.303	148.512	1.115923

Appendix G :Actual Probability and Current Observed Severity Effects Quantified Matrix

Table G1 Observed criticality using real severity effects

		RE1 (safety)				RE2(SM)				RE3 (UCU)				RE4 (LT)				RE5(CM				S`r	C`r	Level
r	**Pr**	**L**	**M**	**H**	**VH**	**L**	**M**	**H**	**VH**	**L**	**M**	**H**	**VH**	**L**	**M**	**H**	**VH**	**L**	**M**	**H**	**VH**			
a	0.26	0.7	0.2		0.1	0.7	0.3				1.0					1.0			0.7	0.3		29.91	7.25	L
b	1	0.7		0.3			0.3	0.7				0.2	0.8			1.0			0.9		0.1	47.26	47.26	H
c	0.73	1.0				0.3	0.7			0.1	0.9					1.0		1.0				12.59	9.19	L
d	1		0.5	0.3	0.2	0.1	0.9			0.9	0.1					1.0			0.7	0.2	0.1	38.81	38.81	H
e	0.23		0.1	0.9			0.4	0.4	0.2		0.2		0.8			1.0				0.8	0.2	71.33	16.41	M
f	0.46	1.0				0.1	0.9			1.0						1.0		1.0				12.28	5.65	L
g	0.43		0.1	0.9		0.9	0.1				0.1	0.9			1.0				0.9	0.1		31.36	13.48	M
h	0.13		0.1	0.9			0.1	0.9				0.1	0.9		1.0					0.1	0.9	90.03	11.71	M
i	0.36	1				0.1	0.9			0.1	0.9				1.0			1				9.72	3.5	L
j	0.46			0.1	0.9		0.1	0.9			1				1.0					1		100	46	H

Appendix H : Model Display of Top 40 Critical PMTs

Table H1 Extract from MBDSS of top 40 PMTs in maintenance plan

1	Asset	Maintenance Task				P		Current Severity					
2	R - element	Maintenance Task	PE ff	PE AHI	PE DC	P	Safety	SM	UCU	TL	Cost	Sr	Cr
3	Acacia Koeberg No2 132kV Line	PoleTop Inspection-Conductors & Hardwa	0.6	0.2	0	0.8	10	0.176751311	0.109011558	100	0.057	100	80
4	Muldersvlei 400kV BB Coupler CT Bank BB No2 Side	CT Care	0.6	0.133333333	0	0.7333	12.00000	93.00000	3.60383	0.66667	2.73000	100	73.333
5	Muldersvlei No7 400kV - 132kV - 22kV Trfr Bay CT Bank 400kV	CT Care	0.6	0.133333333	0	0.7333	12.00000	93.00000	3.60383	0.66667	2.73000	100	73.333
6	Acacia Koeberg No1 400kV Fdr Bay Bkr	Breaker PMT and Mechanism Maintenanc	0.3324583	0.133333333	0.13333333	0.5991	2.666666667	93	4.298666731	9.666666667	2.46	100	59.912
7	Acacia Philippi No2 400kV Fdr Bay Bkr	Breaker PMT and Mechanism Maintenanc	0.3324583	0.133333333	0.13333333	0.5991	2.666666667	93	4.298666731	0	2.46	100	59.912
8	Koeberg 400kV BB Coupler A Bkr	Breaker PMT	0.3324583	0.133333333	0	0.4658	2.66667	0.17675	4.52458	100.00000	7.86000	100	46.579
9	Koeberg 400kV BB Coupler B Bkr	Breaker PMT	0.3324583	0.133333333	0	0.4658	2.66667	0.17675	4.52458	100.00000	7.86000	100	46.579
10	Koeberg No2 400kV Gen Bay Bkr	Breaker PMT	0.3324583	0.133333333	0	0.4658	2.66667	0.17675	4.52458	100.00000	7.86000	100	46.579
11	Muldersvlei 400kV BB Coupler Bkr	Breaker PMT and Mechanism Maintenanc	0.3324583	0.133333333	0	0.4658	2.66667	93.00000	4.29867	0.66667	2.46000	100	46.579
12	Muldersvlei No7 400kV - 132kV - 22kV Trfr Bay Bkr 400kV	Breaker PMT and Mechanism Maintenanc	0.3324583	0.133333333	0	0.4658	2.66667	93.00000	4.29867	0.66667	2.46000	100	46.579
13	Acacia Philippi No2 400kV Line	Pole Top Inspection	0.6	0.133333333	0	0.7333	30	21.96406057	0.109011558	0	0.057	52.13	38.229
14	Acacia Philippi No1 400kV Line	Pole Top Inspection	0.6	0.133333333	0	0.7333	30	21.96406057	0.109011558	0	0.057	52.13	38.229
15	Muldersvlei No1 132kV - 11kV Trfr Bay CT Bank 132kV	CT Care	0.6	0.133333333	0	0.7333	12.00000	27.24551	3.60383	0.66667	2.73000	46.246	33.914
16	Muldersvlei No7 400kV - 132kV - 22kV Trfr Bay CT Bank 132kV	CT Care	0.6	0.133333333	0	0.7333	12.00000	27.24551	3.60383	0.66667	2.73000	46.246	33.914
17	Muldersvlei Greenville No1 132kV Fdr Bay CT Bank	CT Care	0.6	0.133333333	0	0.7333	12.00000	27.24551	3.60383	0.00000	2.73000	45.579	33.425
18	Muldersvlei No2 BB 132kV Bus Section No1 Bkr	Breaker PMT	0.3324583	0	0	0.3325	2.66667	93.00000	4.29867	0.66667	2.46000	100	33.246
19	Muldersvlei No7 400kV - 132kV - 22kV Trfr Bay Bkr 132kV	Breaker PMT and Mechanism Maintenanc	0.3324583	0	0	0.3325	2.66667	93.00000	4.29867	0.66667	2.46000	100	33.246
20	Acacia Koeberg No1 400kV Line	PoleTop Inspection-Conductors & Hardwa	0.6	0.2	0	0.8	10	20.14140105	0.109011558	9	0.057	39.307	31.446
21	Acacia Koeberg No1 400kV Line	Conventional Live Line Maintenance	0.6	0.2	0	0.8	10	20.14140105	0.109011558	9	0.057	39.307	31.446
22	Acacia Muldersvlei No1 400kV Line	Conventional Live Line Maintenance	0.6	0.133333333	0	0.7333	10	20.14140105	0.109011558	9	0.057	39.307	28.825
23	Muldersvlei No6 Trfr Bay 400kV - 132kV - 22kV Trfr TC 400kV	Tap Changer Maintenance	0.3324583	0.133333333	0	0.4658	4.00000	20.14140	8.56479	0.66667	27.00300	60.376	28.123
24	Muldersvlei No7 Trfr Bay 400kV - 132kV - 22kV Trfr TC 400kV	Tap Changer Maintenance	0.3324583	0.133333333	0	0.4658	4.00000	20.14140	8.56479	0.66667	27.00300	60.376	28.123
25	Acacia Koeberg No2 132kV Line	Inspection for Porcelain Insulators	0.1352357	0.133333333	0	0.2686	10	0.63241619	0.109011558	100	0.057	100	26.857
26	Muldersvlei No6 Trfr Bay 400kV - 132kV - 22kV Trfr Bushing Bank 132k	Bushing Tan Delta Test	0.1352357	0.133333333	0	0.2686	92.00000	20.14140	10.00000	0.66667	24.60000	100	26.857
27	Muldersvlei No6 Trfr Bay 400kV - 132kV - 22kV Trfr Bushing Bank 22k	Bushing Tan Delta Test	0.1352357	0.133333333	0	0.2686	92.00000	20.14140	10.00000	0.66667	24.60000	100	26.857
28	Muldersvlei No6 Trfr Bay 400kV - 132kV - 22kV Trfr Bushing Bank 400	Bushing Tan Delta Test	0.1352357	0.133333333	0	0.2686	92.00000	20.14140	10.00000	0.66667	24.60000	100	26.857
29	Muldersvlei No7 Trfr Bay 400kV - 132kV - 22kV Trfr Bushing Bank 132k	Bushing Tan Delta Test	0.1352357	0.133333333	0	0.2686	92.00000	20.14140	10.00000	0.66667	24.60000	100	26.857
30	Muldersvlei No7 Trfr Bay 400kV - 132kV - 22kV Trfr Bushing Bank 22k	Bushing Tan Delta Test	0.1352357	0.133333333	0	0.2686	92.00000	20.14140	10.00000	0.66667	24.60000	100	26.857
31	Muldersvlei No7 Trfr Bay 400kV - 132kV - 22kV Trfr Bushing Bank 400	Bushing Tan Delta Test	0.1352357	0.133333333	0	0.2686	92.00000	20.14140	10.00000	0.66667	24.60000	100	26.857
32	Koeberg No1 Trfr Bay 400kV - 132kV - 22kV Trfr TC 400kV	Tap Changer Maintenance	0.3324583	0.133333333	0	0.4658	4.00000	10.15908	8.56479	6.66667	27.00300	56.394	26.268
33	Acacia No2 Trfr Bay 132kV - 66kV - 11kV Trfr TC 132kV	Tap Changer Maintenance	0.3324583	0.133333333	0	0.4658	4	10.15907618	8.564793055	0.666666667	27.003	50.394	23.473
34	Muldersvlei No8 Trfr Bay 66kV - 11kV Trfr TC 66kV	Tap Changer Maintenance	0.3324583	0.133333333	0	0.4658	4.00000	10.15908	8.56479	0.00000	27.00300	49.727	23.162
35	Muldersvlei No1 BB 132kV Bus Section No1 Bkr	Breaker PMT	0.3324583	0.133333333	0	0.4658	2.66667	27.24551	4.29867	0.66667	2.46000	37.338	17.391
36	Muldersvlei Greenville No1 132kV Fdr Bay Bkr	Breaker PMT	0.3324583	0.133333333	0	0.4658	2.66667	27.24551	4.29867	0.00000	2.46000	36.671	17.081
37	Muldersvlei No1 132kV - 11kV Trfr Bay Bkr 132kV	Breaker PMT	0.3324583	0.133333333	0	0.4658	2.66667	27.24551	4.29867	0.00000	2.46000	36.671	17.081
38	Muldersvlei No6 400kV - 132kV - 22kV Trfr Bay CT Bank 132kV	CT Care	0.6	0.133333333	0	0.7333	12.00000	2.22724	3.60383	0.66667	2.73000	21.228	15.567
39	Muldersvlei No8 66kV - 11kV Trfr Bay CT Bank 66kV	CT Care	0.6	0.133333333	0	0.7333	12.00000	2.22724	3.60383	0.66667	2.73000	21.228	15.567
40	Koeberg Sterrekus No1 400kV Line	PoleTop Inspection-Conductors & Hardwa	0.6	0.133333333	0	0.7333	10.00000	0.86025	0.10901	9.00000	0.05700	20.026	14.686

Appendix I : Ethics Approval

UNIVERSITEIT
STELLENBOSCH
UNIVERSITY

NOTICE OF APPROVAL

REC: Social, Behavioural and Education Research (SBER) - Initial Application Form

16 April 2020

Project number: 11109

Project Title: Development of a Transmission Power Grid Maintenance Budget Decision Support System

Dear Mr Lester Geldenhuis

Your response to stipulations submitted on 9 January 2020 was reviewed and approved by the REC: Social, Behavioural and Education Research (REC: SBE).

Please note below expiration date of this approved submission:

Ethics approval period:

Protocol approval date (Humanities)	Protocol expiration date (Humanities)
4 November 2019	3 November 2022

GENERAL COMMENTS:

1) There is currently a **postponement of all research activities at Stellenbosch University,** apart from research that can be conducted remotely/online and requires no human contact, and research in those areas specifically acknowledged as essential services by the South African government under the presidential regulations related to COVID-19 (e.g. clinical studies).

2) Remote (desktop-based/online) research activities, online analyses of existing data, and the writing up of research results are strongly encouraged in all SU research environments.

Please take note of the General Investigator Responsibilities attached to this letter. You may commence with your research after complying fully with these guidelines.

If the researcher deviates in any way from the proposal approved by the REC: SBE, the researcher must notify the REC of these changes.

Please use your SU project number (11109) on any documents or correspondence with the REC concerning your project.

Please note that the REC has the prerogative and authority to ask further questions, seek additional information, require further modifications, or monitor the conduct of your research and the consent process.

FOR CONTINUATION OF PROJECTS AFTER REC APPROVAL PERIOD

You are required to submit a progress report to the REC: SBE before the approval period has expired if a continuation of ethics approval is required. The Committee will then consider the continuation of the project for a further year (if necessary).

Once you have completed your research, you are required to submit a final report to the REC: SBE for review.

Included Documents:

Document Type	File Name	Date	Version
Research Protocol/Proposal	RESEARCH PROPOSAL v1	15/05/2019	v1
Proof of permission	20190719141502[12949]	19/07/2019	ver1
Informed Consent Form	Written-Consent LG 11409754	04/09/2019	ver1
Data collection tool	Semi Structure Interview Guide LG 11409754	04/09/2019	Ver 1
Proof of permission	Lester Geldenhuis Institutional Permission Letter - ING-2019-11109	08/01/2020	0
Default	REC RESPONSE LETTER - ING-2019-11109	08/01/2020	0

If you have any questions or need further help, please contact the REC office at cgraham@sun.ac.za.

Sincerely,

Clarissa Graham

REC Coordinator: Research Ethics Committee: Social, Behavioral and Education Research

National Health Research Ethics Committee (NHREC) registration number: REC-050411-032.
The Research Ethics Committee: Social, Behavioural and Education Research complies with the SA National Health Act No.61 2003 as it pertains to health research. In addition, this committee abides by the ethical norms and principles for research established by the Declaration of Helsinki (2013) and the Department of Health Guidelines for Ethical Research: Principles Structures and Processes (2nd Ed.) 2015. *Annually a number of projects may be selected randomly for an external audit.*