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An Analytic Hierarchy Process Model Approach to Selecting a Maintenance Strategy for a New Nuclear Power Plant

Andy Irvin Joseph

(Student number: 1802239)

School of Engineering and the Built Environment

University of the Witwatersrand

Johannesburg, South Africa.

Supervisors

Dr Timothy Hutton

Mr. Bradley Oaker

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DECLARATION

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ABSTRACT

Maintenance strategies are important for the reliability and safety of nuclear power plants. Cost competitiveness in the energy markets and closure of nuclear power plants highlighted the need to optimise maintenance strategies to reduce cost while preserving safety and reliability. This research proposes using the Analytic Hierarchy Process (AHP) decision model to determine the optimal maintenance strategy mix where nuclear safety, cost and reliability are considered as the primary criteria. Nuclear experts are used to conduct pairwise comparisons to select the preferred maintenance strategy for different Continents and WANO centres. The research concludes that nuclear experts prefer safety as the highest criteria and also prefer a maintenance strategy that have a split between the preventive maintenance (PM), predictive maintenance (PdM) and reliability centered maintenance (RCM) strategies, with PM as the highest ranked maintenance strategy followed by PdM and RCM. The study also concludes that the AHP model is an effective model to be used in the nuclear industry and is comparable with results from other industries.

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LIST OF ACRONYMS

ACM	Availability Centered Maintenance
AHP	Analytic Hierarchy Process
AIJ	Aggregation of Individual Judgments
AM	Availability Maintenance
BAC	Boric Acid Corrosion
CBM	Condition Based Maintenance
CI	Consistency Index
CM	Corrective Maintenance
CNSC	Canadian Nuclear Safety Commission
CR	Consistency Ratio
DM	Decision Maker
DNP	Delivering the Nuclear Promise
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
EQ	Equipment Qualification
FAC	Flow Accelerated Corrosion
FID	Functional Importance Determination
FMECA	Failure Mode Effects and Critical Analysis
IAEA	International Atomic Energy Agency
INPO	International Nuclear Plant Operators
ISI	In-service Inspection
IST	In-Service Testing
LTSO	Long-Term Safe Operation
MR	Maintenance Rule
NEI	Nuclear Energy Institute
NPP	Nuclear Power Plant
OECD	Organisation for Economic Co-operation and Development
OM	Opportunistic Maintenance
PM	Preventive Maintenance
PdM	Predictive Maintenance

PT&I	Performance Testing and Inspection
PRA	Probabilistic Risk Assessment
RCM	Reliability Centered Maintenance
RI	Random Index
RTFM	Run to Failure Maintenance
SPV	Single Point Vulnerability
SSC	Structures, Systems and Components
VBM	Value-Based Maintenance
US NRC	United States Nuclear Regulatory Commission
WANO	World Association of Nuclear Operators

CHAPTER 1
INTRODUCTION AND STATEMENT OF PROBLEM

1. INTRODUCTION

1.1. Purpose of the Study

This study aims to determine what an optimal maintenance strategy would be for a new Nuclear Power Plant (NPP). Various maintenance strategies are applied across the nuclear power industry and with the added regulatory requirements inherent to the nuclear industry it is vital for nuclear safety, reliability and cost optimisation that the correct maintenance strategies are selected for a new NPP. Maintenance strategies evolve with the use of operating experience, the incorporation of component failures and with the ageing of the power plant (Shafiee, 2015). The nuclear regulator, utility shareholders and nuclear industry partners are interested in sustaining nuclear safety and reliability that ultimately affects the operational cost. A large contributor to these criteria is the chosen maintenance strategy. The study will examine the key aspects of the different maintenance strategies and compare international practices for establishing an effective maintenance program and the impact it has on resource requirements, reliability, operational costs and nuclear safety. This study will use the analytic hierarchy process (AHP) model to determine the best maintenance strategy(ies) for a new NPP.

1.2 Research Background

Nuclear power generation is currently a highly contentious topic especially with global warming and the use of renewable energy sources as alternate or competing energy options (Choi, 2008). The Energy Information Administration (EIA) projects that natural gas consumption will continue to rise and will continue to place pressure of fossil fuels and nuclear industry competitiveness (EIA, 2016:2). The reduction in the global oil price and the oversupply of oil has created an environment where the economics of a Nuclear Power Plant are challenged.

Maintenance, or more broadly speaking, asset management is essential for plant equipment reliability across many industries (INPO, 2013:58). Systems or components are designed to operate within certain design parameters and are manufactured within certain specifications to achieve specific levels of performance (INPO, 2013:13). More so within the nuclear industry, where equipment failure can result in serious consequences. Critical, nuclear safety related components are designed, manufactured and operated within strict specifications while ensuring that a comprehensive maintenance program for the equipment is executed to ensure high levels of reliability and safety (INPO, 2013:64). Operating plant equipment outside its design specifications or without proper maintenance may lead to premature failure and potential nuclear incidents (INPO, 2013:17). Reliable plant equipment is therefore critical in the nuclear industry. Similar to routine vehicle services, manufacturers supplying nuclear components, design these components to the end user specifications and specify inspection or maintenance requirements that are intended to achieve equipment reliability throughout its useful life.

This research seeks to gain an understanding of what maintenance strategy will work best for plant equipment in a new nuclear power plant. Some factors considered essential when selecting a maintenance strategy includes cost, reliability and safety (Fredriksson & Larsson, 2012:4). It is thus very important not to carry out the selection of the maintenance strategy mix based just on qualitative and subjective choices but to select a correct maintenance strategy mix that optimises reliability and cost while maintaining the nuclear plant safety margins (Braglia *et al.,* 2013, Wang, 2006:7444).

Almost 33% of all maintenance costs are wasted because of unnecessary or improperly performed maintenance largely due to the lack of factual data resulting in ineffective maintenance strategies (IAEA, 2007:4). The nuclear industry is also one of the most heavily audited and regulated industries which require efficient, safe and reliable maintenance strategies from nuclear power plants (IAEA, 2007:126). Peer and public pressure are also key inputs to the way nuclear power plants conduct themselves. All these important regulatory requirements place nuclear power generation companies at a slight disadvantage to other forms of energy production from an operation and cost perspective. It is crucial to select a maintenance strategy that will satisfy the requirements of all the stakeholders while maintaining nuclear safety, competitiveness and keep costs to an acceptable level. The nuclear utilities use an array of maintenance strategies and are not consistent across all types of nuclear reactors, countries, utilities, management style, work management or rules (IAEA, 2002a; Shafiee, 2015:382). The nuclear industry has embarked on “delivering the nuclear promise” (DNP) that focuses on the optimising the maintenance strategy through the value-based maintenance approach that focuses on improving safety and reliability while decreasing cost (NEI, 2018).

1.3 Research Motivation

The maintenance strategy of a nuclear power plant influences the size of the maintenance group, the skills required for maintenance, online maintenance and outage maintenance, supplemental resource requirements, overall process efficiency, operational cost, plant reliability, nuclear and industrial safety, quantity and type of material spare resources, training plans and many other aspects of a nuclear plant (IAEA, 2018). There is no one-size-fits-all strategy when it comes to selecting a maintenance strategy. There are various maintenance strategies such as condition-based maintenance (CBM), preventive maintenance (PM), opportunistic maintenance (OM), run to failure maintenance (RTFM), predictive maintenance (PdM), corrective maintenance (CM), availability centred maintenance (ACM), reliability centred maintenance (RCM) (Shafiee, 2015). Although AHP has been used in previous studies to select maintenance strategies, studies to select the optimum maintenance strategy for a new nuclear power plant could not be found. The AHP model was successfully used in studies for the oil refinery industry, the chemical plant industry and power industry (Kirubakaran & Ilangkumaran, 2016:305).

1.4 Problem Statement

Nuclear Power utilities do not have a prescribed method for selecting a maintenance strategy. Nuclear Power utilities employs a technical analysis process that evaluates information from the reference plant, industry experts, component importance, fleet databases or manufacturer recommendations to formulate a maintenance strategy (INPO, 2013:29). This is complicated especially where power plants are being constructed in a foreign country or with new generation III, III+ or IV nuclear technologies. Differences in contracting, maintenance management, availability of spares, availability of trained or skilled resources, regulatory requirements and other factors play a role in selecting the maintenance strategy (Velmurugan & Dhingra (2015:1627). These factors can make the maintenance strategy of the reference plant ineffective in a foreign country. Having said that, ***"What is an optimum maintenance strategy for new nuclear power plant and can the AHP model be used to identify or aid in selecting the optimum maintenance strategy(ies)?"***

This study will focus on the AHP model and the factors that may be used for selecting an optimum maintenance strategy and determine through linear analytic algebra the desired maintenance strategy(ies).

1.5 Assumptions and Limitations

For the purposes of this research study the following assumptions were made:

- All types of reactors have the same factors that influence their strategic maintenance decisions.
- This report will focus on the preventive, predictive, corrective and reliability centred maintenance strategies.
- All regulators have similar maintenance requirements for new nuclear power plants.
- Maintenance activity types have no influence on the maintenance strategy selection.
- The rate of component failure is constant.
- All components on a nuclear plant has equal criticality or importance.
- All experts know and understand the differences between maintenance strategies.
- All expert opinions are considered and weighted equally.

1.6 Summary

Nuclear power plants are experiencing increasing pressure from renewable energy sources and environmentalists. The nuclear power industry initiated the delivery of the nuclear promise aimed at reducing operating costs while maintaining reliability and safety. The next chapter will explore the different maintenance strategies and its importance within nuclear power plants. The following section will also review the analytical hierarchy process theory and whether it can be used for selecting maintenance strategies.

CHAPTER 2
LITERATURE REVIEW
SECTION A: MAINTENANCE STRATEGIES

2.1 Introduction

This chapter will review the various maintenance strategies in an attempt to answer the problem identified in the previous chapter. The nuclear power industry must endeavour to reduce cost while maintaining safety, and focus on the maintenance strategies due to its high cost impact (Rogner, 2010:142). Maintenance cost accounts for almost 30% of the total cost of nuclear electricity generation (Rogner, 2010:142).

Wang (2006:7444) argues that managers are striving to reduce production costs because of the reconstruction and deregulation of the modern power system. The nuclear industry in particular seems to face mounting challenges from low cost renewable energy sources highlighting the need to reduce the main cost contributor in the nuclear industry, namely maintenance cost. Historically, maintenance practices were based on breakdown maintenance which is also known as corrective maintenance (or run-to-failure maintenance strategy). Corrective maintenance is mostly executed when a component fails before an intervention is planned and can either be a result of an ineffective preventive maintenance strategy or component being pre-selected to run-to-failure (Wang, 2006:7444). Implementing this strategy on its own will have negative consequences, for example loss of production, environmental integrity, public image, protection and safety in addition to incurring repair costs within the nuclear power plant (Eti, 2006:1170).

According to Larsson (2012) maintenance has become a necessary evil in that associated costs and stoppages in the life of the plant are unavoidable, but the industry has in recent years embarked on a more proactive and pragmatic approach by focusing on predictive and preventive maintenance strategies. The nuclear industry is focussed on safety, reliability and availability in which reliability predominantly determines productivity and the onus rests on maintenance to ensure that the equipment operates reliably (Larsson, 2006:26). Typically, the engineering department is responsible for determining the maintenance strategies to eliminate recurring failures. These strategies consist of a combination of preventive, corrective and predictive maintenance strategies. This concept relates to reliability centred maintenance (RCM) which is widely used in various industries such as aviation, space and nuclear power generation and will be later discussed in detail (Larsson, 2006; Samhouri, 2009).

Unexpected component failures can be costly and have a negative impact on nuclear safety. A combination of preventive maintenance strategies to improve reliability, safety and availability at nuclear power plants are essential to keep performance at an acceptable level (Wang, 2006:7444). Wang (2006:7444) further states that too much maintenance can lead to a deterioration of equipment reliability and availability and too little maintenance can result in premature equipment failures and therefore it is important to establish effective maintenance intervals and reducing reactive maintenance. It is thus important to examine whether the nuclear industry and especially a new nuclear power plant, will benefit from a combination of different maintenance strategies that can improve equipment reliability and availability. It is also important that a balance between cost, nuclear safety and reliability is carefully considered.

Maintenance related terms are not well defined and terms such as maintenance strategy, maintenance policy, maintenance tactics or approaches and maintenance concepts are used interchangeably (Velmurugan & Dhingra, 2015:1625). The term maintenance strategy and maintenance program will be used interchangeably in this literature review. Some maintenance strategies are developed based on the priorities assigned by the maintenance managers and the behaviour of the equipment. This is seen where components are considered based on downtime, capacity, bottle neck, spare parts cost or availability (Labib, 1998:87).

The nuclear industry also considers similar criteria but is more methodical in developing and deciding on a maintenance strategy (IAEA, 2007:4; IAEA, 2018:13; INPO, 2013). These strategies are based on functional importance of the components and comprised of sub-categories such as the criticality of the component, the service condition and the duty cycle of the component (EPRI, 2012:5-5). These three sub-categories are used as part of the Functional Importance Determination (FID) process (Hayes, 2011:5). The criticality of the specific component will indicate how important the component is either to nuclear safety or production while the service condition of the component looks at the conditions under which the component must operate such as high temperature, humidity, vibrations, etc. (INPO, 2013). The duty cycle looks at the frequency at which the component is in service or not in service. The nuclear industry makes use of various operational experience and engineering judgments to facilitate changes to the maintenance strategy or periodicity. Vendor or manufacturer recommendations are also considered to develop or influence the selection of a maintenance strategy (Eti, 2006: 1164). All these factors ultimately are used to develop a maintenance basis that specifies what maintenance will be conducted and at what frequency it will be done. Some of the maintenance basis arguments are based on engineering judgment and or behavioural inputs (INPO, 2013:29). Another way to determine what strategy works best could be through component condition monitoring and strategy adjustment (operating experience).

2.2 Maintenance Strategy

World War II inadvertently brought about the maintenance philosophy as it is known today. Cost, longevity and availability were topics that were of interest in the early 1940's and gave rise to the establishment of maintenance departments (Fredriksson & Larsson, 2012:2). Maintenance is defined by the British Standard Institute as "*a combination of technical and associated administrative actions intended to retain an item or system in, or restore it to, a state in which it can perform its required function*" (BSI, 2016:10). Maintenance is thus a term that refers to the ability of keeping equipment in its original condition (similar to when it was procured) to ensure that it delivers according to design specifications (Fredriksson & Larsson, 2012:2). Huang *et al.* (2012:1015) supports this position by stating that the objective of maintenance in nuclear power plants (NPPs) is to ensure that structures, systems and components (SSCs) could always operate on a long-term safe, reliable and economic manner, and to provide the society with safe, clean, good quality power at a competitive price. This objective can be realised through the development, implementation and optimization of the maintenance strategies which will be elaborated in the following sections.

2.2.1 Defining maintenance strategy

A maintenance strategy provides direction and an approach to determining a set of maintenance activities and actions that when executed, will achieve a desired level of equipment reliability and availability (Velmurugan & Dhingra, 2015:1626). Velmurugan and Dhingra (2015) further state that a maintenance strategy consists of different techniques and policies that determine what actions are required to maintain utility plant components. Figure 2.1 provides an illustration of all the inputs to the maintenance strategy which provides a road map for how all the elements come together to create an effective maintenance strategy.

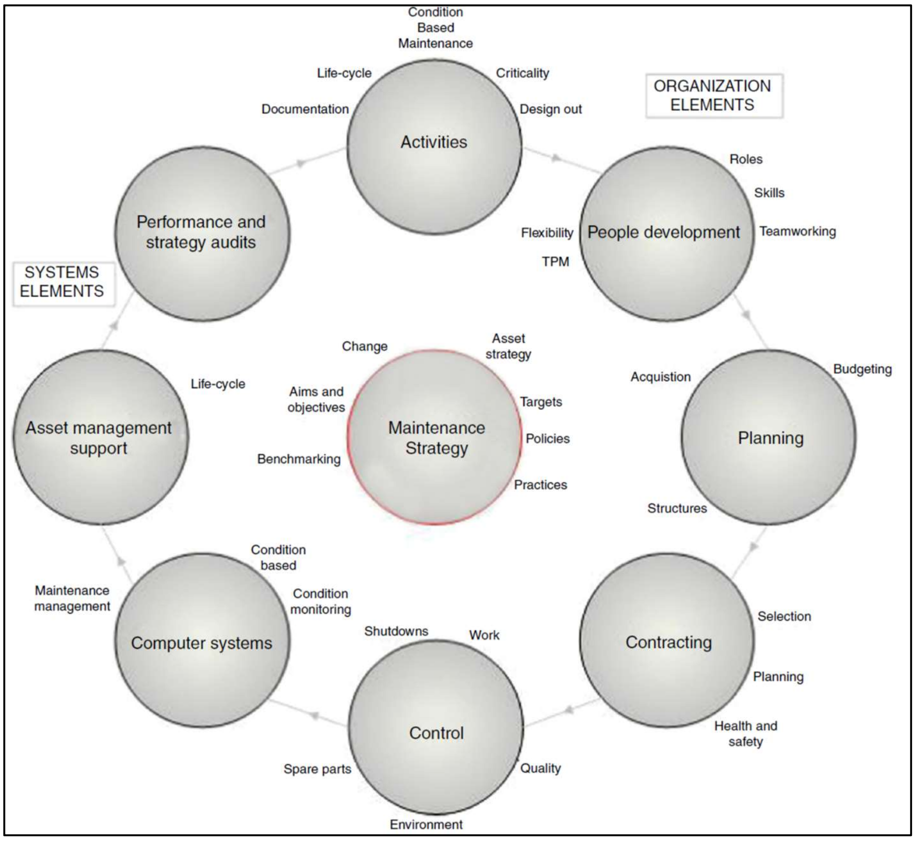

Figure 2.1: Maintenance Strategy Components

Source: Velmurugan & Dhingra (2015:1627)

Any maintenance strategy has some flexibility, a holistic approach to formulating the strategy and a structured development that *"… involves identification, researching and execution of many repairs, replace and inspect decisions and is concerned with formulating the best life plan…*" for each plant component (Velmurugan & Dhingra, 2015:1626). Selecting the best sustainable maintenance strategy depends on its FID which is supported by its maintenance base that provides the basis for the type and frequency of the equipment maintenance (EPRI, 2012:5-5; INPO, 2013:29).

Differences in contracting philosophies, maintenance management, availability of spares, availability of trained or skilled resources, regulatory requirements and other factors play a role in selecting the maintenance strategy (Velmurugan & Dhingra, 2015:1627). In Figure 2.1 both organisational elements (people, planning, contracting, control) and system elements (assets, computers, performance) are seen as important elements that influence the maintenance strategy selection. These elements facilitate the effective functioning of the maintenance strategies and their failure or absence can have a profound effect on a company's maintenance goals. The selection of the correct maintenance strategy(ies) has the added benefit that it aides in providing input to the maintenance budget and a framework for which an organisation can achieve its plant availability, safety and reliability objectives (Velmurugan & Dhingra, 2015:1627).

Nuclear power plants (NPP) are highly safety oriented but like other industries, there is a need for cost and reliability aspects to be also considered in the decision-making process to determine an optimum maintenance strategy that is inclusive of preventive maintenance (PM), predictive maintenance (PdM) and corrective maintenance (CM) (Huang *et al.*, 2012:1015). Figure 2.2 below, is an illustration of the various types of maintenance activities making up the maintenance strategy.

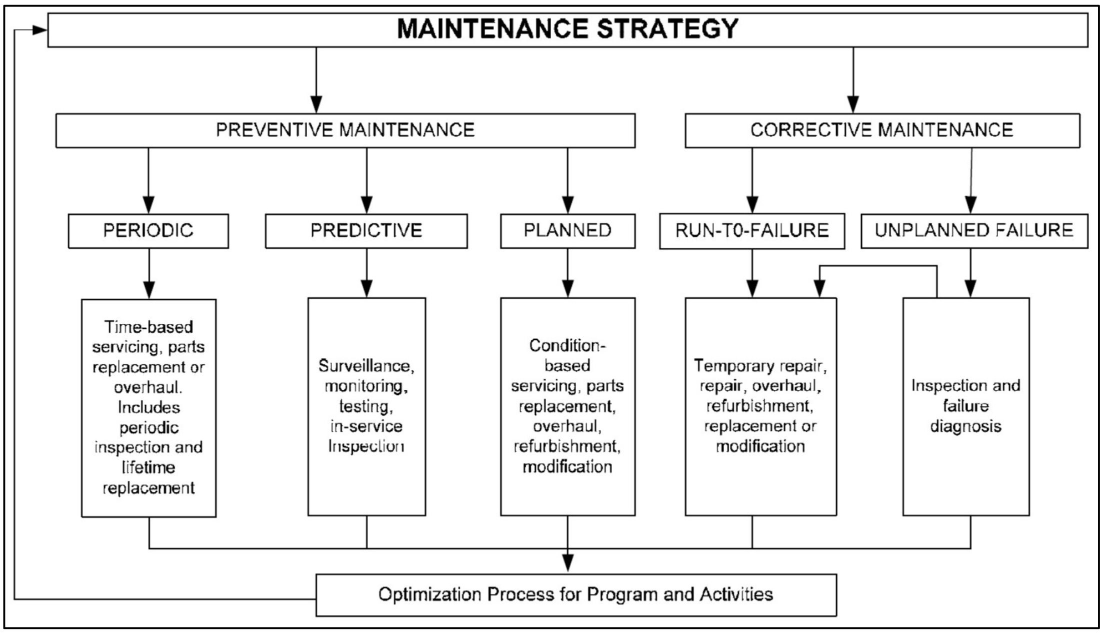

Figure 2.2: Maintenance Strategy Elements

Source: CNSC (2007:3)

Figure 2.2 shows that the preventive maintenance is inclusive of periodic maintenance (time-based servicing), predictive maintenance (surveillance monitoring and testing) and planned maintenance (condition-based servicing) where the condition of the equipment has or is deteriorating and if nothing is done it will fail at an inconvenient time resulting in unplanned failures (CNSC, 2007:3). The run-to-failure strategy implies repair of equipment only upon failure. Corrective maintenance is required if there is unplanned failure of equipment and or optimisation of the maintenance strategy may be required. Optimisation of the maintenance strategy is considered where corrective maintenance forms part of an SSC modification plan. Maintenance strategies vary from business to business and the choice of maintenance strategy is strongly influenced by the type of industry, the equipment type, profits or production and other factors forming part of its business strategy (Žilka, 2014:2).

Braglia *et al.* (2013) has a different view on the purpose of maintenance in that they view maintenance as a means to have the user's equipment perform whatever its users want rather than to prevent failures for the sake of preventing failures. Braglia *et al.* (2013) continues by stating that the RCM process should be focussed on establishing a minimum level of maintenance. Considering a value-based maintenance (VBM) proposition driven by cost optimisation while maintaining reliability. This would be an acceptable approach, however in the nuclear industry, there are other factors to consider such as mandatary or statutory requirements stipulated in the nuclear operating license and a requirement to demonstrate nuclear safety or component availability and function. There is not always a direct correlation between regulatory maintenance and inspection requirements with optimised maintenance strategies. Thus, the RCM focus from a nuclear industry perspective must consider programmatic operating license requirements. These component maintenance and inspection frequency selections consider:

- The relative SSC importance to the risk to national security, health, safety and environment;
- The technical basis for demonstrating that safety goals and performance criteria are met;
- The requirements of all applicable industry codes and standards;
- The radiation protection principle As Low As Reasonably Achievable (ALARA);
- Design and operating conditions;
- Vendor recommendations;
- Operating experience; and
- Ageing management requirements (CNSC, 2007:4).

It is important to establish the right maintenance strategy mix at a NPP from the start as it is extremely costly to optimise or change a strategy at a later stage as maintenance departments are required to consider several factors as illustrated in Figure 2.1. Every component that is considered maintenance significant (i.e. a component that needs to be maintained) will require a comprehensive maintenance basis that provides the reason for the maintenance of the particular component (EPRI, 2012:5-5). Early optimization of a maintenance strategy is thus vital to minimize cost, improve maintenance effectiveness and efficiency as well as reducing nuclear safety risks (Paulsen, 2002:2). Selecting the correct maintenance strategy in the highly competitive energy market can provide adequate safety, reliability and cost margins.

2.2.2 Maintenance strategy alternatives

Selecting a maintenance strategy can be an arduous task as there exists a mix of different approaches which traditionally were made up of preventive (scheduled maintenance before failure) and corrective (breakdown maintenance after failure) maintenance (Eugen, 2011; Velmurugan & Dhingra, 2015; Wang, 2006;). Maintenance strategies have evolved over the years due to studies and operating experience which introduced new approaches and a broad range of maintenance strategies each having a different focus area. Shafiee (2015:382) provides the following comprehensive maintenance strategy list:

- Corrective maintenance;
- Periodic maintenance;
- Preventive maintenance;
- Reliability-centred maintenance;
- Condition-based maintenance;
- Predictive maintenance;
- Opportunistic maintenance;
- Total productive maintenance;

Set out below is a discussion of the above key characteristics of the maintenance strategies in an attempt to contrast the distinct differences or similarities between these strategies.

2.2.2.1 Corrective maintenance

Corrective maintenance is a simple and straightforward type of reactive maintenance and can also be considered as “no maintenance” management approach as equipment is allowed to run-to-failure (Mobley, 2004:2). Equipment is only maintained when it requires repairs, overhaul or replacement (IAEA, 2002:3). This type of break-fix maintenance is one of the oldest types of maintenance strategies but in the nuclear industry one has to consider the importance and criticality of the equipment and this strategy on its own will not be acceptable due to the safety critical nature of nuclear operations. Corrective maintenance is responsive to other ineffective, failed or missed maintenance strategies for important components (INPO, 2013:24). It would thus be necessary to carefully select the components for this strategy based on system or component redundancies, consequence of failure, lead time of spares and cost of recovery (Awad, 2016:435). The corrective maintenance approach is on average three times more expensive than the same repair in a preventive approach (Larsson, 2006:29). This is potentially due to the inconvenience of delay, downtime and emergent order of spare parts and overtime work.

2.2.2.2 Periodic maintenance

Periodic maintenance is a time-based preventive maintenance strategy that is designed to keep or verify equipment functioning within its operational parameters (INPO, 2013:24). Periodic maintenance includes servicing, parts replacement, surveillance or testing, lubrication, cleaning, inspections, calibrations, overhauls and alignments scheduled at set periodicity (IAEA, 2002; INPO, 2013).

2.2.2.3 Preventive maintenance

Preventive maintenance is a proactive maintenance strategy that aims to prevent failure of components by assuming that operating time is the key factor in determining equipment condition and therefore a likelihood exists to demobilising the fault before failure occurs (IAEA, 2007:13; Eti, 2006:1164). Preventive maintenance is not a guaranteed prevention strategy as it can lead to over maintenance or introduce unintentional failures and thus worsening the condition of the equipment which in turn result in premature failure (IAEA, 2007:23). NASA (2008:2-1) clarifies this by referring to the theory that the underlying maintenance assumption was based on the fundamental cause-and-effect relationship between scheduled maintenance and reliability in that component failures are directly related to equipment age. They held the belief that the higher the maintenance on the equipment the better protected it was against the likelihood of failure. It is known today through various case studies and research that this theory is not correct as supported by the Nuclear Energy Institute (2018) and Wang (2006:7444).

Preventive maintenance is a calculated maintenance strategy based on a fixed schedule that includes activities such as lubrication, minor adjustments, machine rebuilds, repairs to control degradation and failures to an acceptable level (Mobley, 2004:3; IAEA, 2002:3). INPO (2013:24) states that preventive maintenance (PM) on critical components receive high priority in routine scheduling and is rarely deferred. PM activities detect, preclude or mitigate degradation to improve safety, reliability and extend the useful life of the components (INPO, 2013:24).

2.2.2.4 Reliability-centred maintenance

Reliability Centred Maintenance (RCM) focusses on establishing a comprehensive inclusive maintenance strategy that takes advantage of the respective strengths of preventive, predictive and corrective maintenance strategies to maximize equipment reliability, minimizing cost, improving plant safety and increasing productivity (Paulsen, 2002:2). RCM strategy is strictly speaking a decision-making process that utilizes a decision logic tree to determine the most effective approach to determine an optimal maintenance strategy mix (Huang *et al.*, 2012:1015, IAEA, 2002:69; NASA, 2008:3-1). RCM is viewed as an engineering framework aimed at reducing risk by encapsulating the essence of a complete maintenance strategy using failure mode effects and criticality analysis (FMECA), consequences, rationale development and historical performance to determine the best maintenance tasks and frequencies (EPRI, 2012:1-5; Eti, 2006:1169; Larsson, 2006:49).

The RCM methodology uses experience to justify its decisions and to focus the maintenance resources on concentrating on critical components and assign less priority to other non-critical components (IAEA, 2003:16). According to the IAEA (2003:16) the RCM aims to answer the following questions to optimise the maintenance function:

1. What are the functions and the associated performance requirements of the selected component, considering its present operating environment?
2. In which ways does it fail to fulfil its functions?
3. What causes each functional failure?
4. What happens when each failure occurs?
5. In what way does each failure matter?
6. What can be done to prevent each failure?

7. What should be done if a suitable preventive task cannot be found?

Fredriksson and Larsson (2012:47) argues that the overall goal of the RCM strategy is to "…reduce the Life-Cycle Cost (LCC) of equipment to a minimum and at the same time allow the equipment to function as intended with required availability and reliability". The International Atomic Energy Agency supports this view of developing an RCM strategy which has minimal economic or cost impact but requires consideration to be given for all components critical to plant safety or production (IAEA, 2003:16).

According to the IAEA (2003:16) the benefits of the RCM process are:

1. Concentrate maintenance resources where they will do the most good.
2. Eliminate unnecessary and ineffective maintenance.
3. Devise the simplest and most cost-effective means of maintaining equipment, or testing for degradation, focusing on predictive or condition monitoring activities, where applicable.
4. Develop a documented basis for the maintenance program.
5. Make use of plant maintenance experience when determining PM tasks and frequencies.
6. Provide a greater synergy between operation & maintenance teams.

Figure 2.3 illustrates the components of the RCM program and highlights how it incorporates the reactive (corrective) maintenance, preventive maintenance, performance testing and inspections (PT&I) as well as the proactive (predictive) maintenance strategies. Furthermore, Figure 2.3 provides some clarity on what components are covered under each maintenance strategy.

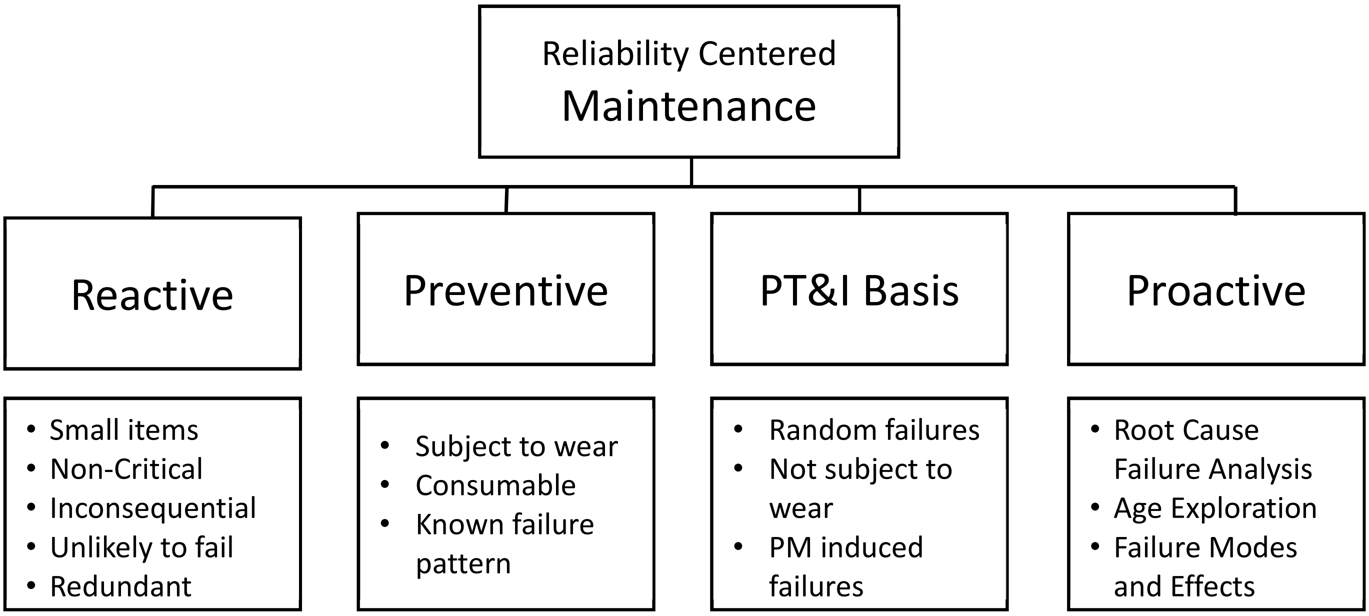

Figure 2.3: Components of an RCM Program

Source: NASA (2008:3-1)

NASA (2008:3-4) list the RCM principles as follows:

- Function-oriented – seeks to preserve system and not just operability;
- System-focused – more concerned with system function than component function;
- Reliability-centered – not overly concerned with failure rate but seeks to find the conditional probability of failure at specific ages;
- Acknowledge design limitations: maintain the inherent reliability of equipment design and maintenance feedback can improve the original design;
- Safety, security and Economics - Safety and security must be ensured at any cost; life-cycle cost-effectiveness is a tertiary criterion.
- Failure as any unsatisfactory condition – failure may be a loss of function or quality;
- Logic tree to screen maintenance tasks – provides a consistent approach to equipment maintenance
- Tasks must be applicable – tasks must address the failure mode and consider failure mode characteristics

- Tasks must be effective – task must reduce failure probability and be cost effective.

RCM acknowledges that components do not fail at predefined failure frequencies and are more complex and unpredictable than expected (Fredriksson & Larsson, 2012:47). RCM uses equipment function analysis in combination with risk analysis in prioritizing the required maintenance activities and frequencies to optimise cost, reliability and safety (Eti, 2006:1169).

2.2.2.5 Condition-based maintenance

The condition-based proactive strategy is based on an inspection schedule with the outcome of the inspection determining the correct preventive maintenance strategy (Awad, 2016:435). The condition-based maintenance (CBM) strategy aims to prevent over maintenance and premature replacement of components by monitoring the condition of the equipment and scheduling the appropriate corrective maintenance when the condition begins to deteriorate (IAEA, 2007:13). Under the CBM strategy, the equipment condition determines the desired maintenance activity at the correct time to optimize reliability and availability (IAEA, 2007:12). The type of condition-based monitoring activities includes vibration monitoring, thermography, oil analysis or performance-parameter analysis that can detect impending failure of equipment as well as to avoid costly maintenance (Eti, 2006:1164; IAEA, 2007:12).

2.2.2.6 Predictive maintenance

Predictive maintenance (PdM) is a maintenance strategy that, as the name suggest, focus on predicting equipment failure and implementing corrective measures to avoid failure (Huang *et al.*, 2012:1016). Mobley (2004:4) states that predictive maintenance improves productivity, product quality and overall effectiveness of production plants. PdM includes servicing such as lubrication, filter changes, cleaning, testing and it is used as alternatives when PM activities cannot be performed within its scheduled timeframe (INPO, 2013:24). Mobley (2004:4) argues that predictive maintenance is a philosophy or attitude that optimizes total plant operation by using the operating condition of the plant and that it is not simply a set of inspection methods such as vibration monitoring, thermography, oil analysis or non-destructive testing. In support of this, Huang (2012:1017) views PdM as a maintenance strategy whose core lies in condition monitoring and failure diagnosis. This is further supported by INPO (2013:24) which states that PdM "…includes vibration analysis, acoustic monitoring, infrared surveys (thermography), oil analyses (tribology) and diagnostic testing." The International Atomic Energy Agency (IAEA) supports INPO's stance by stating that predictive techniques may include CBM and RCM techniques (IAEA, 2002:3).

2.2.2.7 Opportunistic maintenance (planned corrective maintenance)

Opportunistic maintenance is a term that is not widely used in the nuclear maintenance environment, however Samhouri (2009:247) defines it "… as a systematic method of collecting, investigating, pre-planning, and publishing a set of proposed maintenance tasks and acting on them when there is an unscheduled failure or repair "opportunity". This type of maintenance format is more commonly referred to as a run-to-fail maintenance that occurs randomly and where opportunities arise to repair a component without incurring cost or safety consequences.

Rao, Bhadury, Kaspi and Shabtay (Samhouri, 2009) states that the opportunity to replace a component may arise either due to shut down or failure of other components. An example could be that when problems are being experienced with a particular valve on a steam system and the pump that feeds that system is scheduled for maintenance or fails an opportunity arises to repair or replace that particular problematic valve. Should the valve repair exceed the time required to maintain the pump the opportunity is either partially or completely voided. This opportunity maintenance provides the maintenance department an opportunity to eliminate or partially eliminate future costs or need to replace the defective components (Ab-Samat & Kamaruddin, 2014:105). The principle of the opportunistic maintenance is to take advantage of a situation where maintenance conduct PM or CM maintenance on one component while conducting PM or CM on another component. The benefits of this type of maintenance is a reduction of overall maintenance downtime, a reduction of the frequency of service interruption, an extension of the mean time between failures and a reduction in cost by taking advantage of resources (Ab-Samat & Kamaruddin, 2014; Samhouri, 2009).

Nuclear refuelling and short duration outages make extensive use of opportunistic maintenance.

2.2.2.8 Total productive maintenance

Larsson (2006:39) argues that total productive maintenance maximizes the overall equipment reliability and it give rise to both direct and indirect benefits such as reduced customer complaints, improved reliability and improved worker morale and confidence. Velmurugan and Dhingra (2015:1645) views total productive maintenance as a philosophy where the maintenance of a component is integrated into the manufacturing process. This maintenance is aimed at minimizing rework and repairs are focused on correcting issues before they get worse (Velmurugan & Dhingra, 2015:1645).

2.2.2.9 Summary

Selecting an ideal maintenance strategy requires an understanding of the plant design, plant function, operating regime, organisational structure, statutory requirements, inspection techniques and many other parameters. The nuclear industry uses a combination of maintenance strategies that forms part of an overall maintenance program aimed at optimising cost, improving plant reliability, availability and nuclear safety. The definitions and scope of the maintenance strategies overlap and creates some confusion where authors refer to a specific maintenance strategy which is used interchangeably (i.e. predictive maintenance and condition-based maintenance).

Selecting the appropriate maintenance strategy or combination of strategies is important as it impacts organisational structure, operating cost, spares, availability, reliability, performance and initial profit for shareholders (Velmurugan & Dhingra, 2015). Each of these maintenance strategies have advantages and disadvantages that can benefit or pose additional risks to a nuclear power plant.

2.2.3 Advantages and disadvantages of maintenance strategies

All maintenance strategies aim to improve component reliability and reduce overall cost. Each of the maintenance strategies have distinct advantages and disadvantages.

Corrective Maintenance has the advantage that maintenance is only performed when components fail which places less demand on maintenance planning and management as well as requiring less maintenance staff (NASA, 2008). The disadvantages are however that failures caused unforeseen downtime which can escalate cost and have secondary failures (Žilka, 2014; Mobley, 2004). Preventive Maintenance on the other hand focuses on limiting unplanned failures and thus require more maintenance to be performed which aims to reduce risk but increases financial expenditure (Žilka, 2014:210). Excessive intrusive preventive maintenance can also increase the probability of maintenance induced failures, particularly due to inadequate maintenance procedures or practices or when there is a lack of skills and experience amongst maintenance personnel. Predictive Maintenance reduces the need for intrusive maintenance which minimize functional failures while allowing for pre-emptive corrective maintenance and in turn making the maintenance planning process more scientific (IAEA, 2007; NASA, 2008:5-7).

Etchison (2016:n.d) believes that human safety has a direct link to the importance of equipment reliability and that the probability of injuries significantly increased with non-routine maintenance activities resulting from equipment failures. Figure 2.4 illustrates below how injury significance tracks the non-routine failures.

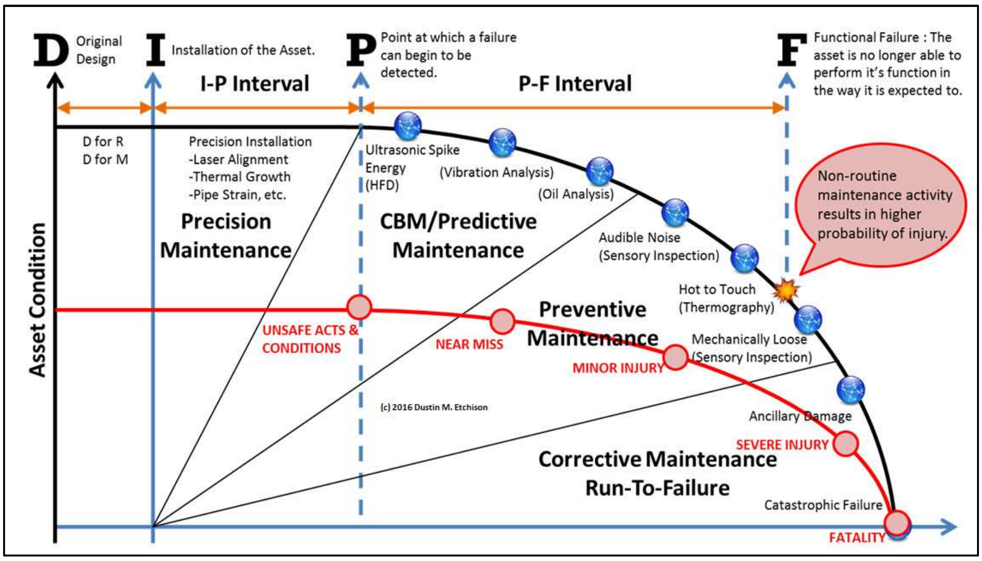

Figure 2.4: Asset (Potential - Functional) Failure Curve

Source: Etchison (2016:n.d)

The overall objective of a maintenance strategy is to ensure the physical assets are maintained in such a way to avoid the consequence of failure and injuries. It is this consequence of failure that influences the maintenance strategy selection. The x-axis of the asset failure curve in Figure 2.4 represents the time which indicates that the longer a component is installed the higher the probability for functional failure in the absence of effective maintenance strategies. Figure 2.4 also highlights how cost would increase due to catastrophic failures and the need to perform corrective maintenance. Authors such as Basri (2017), IAEA (2007), NASA (2008) and Žilka (2014) have reached consensus on the fact that Corrective maintenance strategy results in increased downtime and high cost. This is due to the unpredictability of the failure especially with major critical components. Should a catastrophic failure occur on a component such as a turbine due to the absence of maintenance, it could cause significant damage and potential personnel injuries.

Table 2.1 below provides an indication of how each maintenance strategy affects the component reliability, cost and nuclear safety factors. Table 2.1 also indicates that reliability centered maintenance seems to be the only maintenance strategy that provides high reliability and safety while having low cost impact.

Table 2.1: Advantages and Disadvantages of Maintenance Strategies

	Advantages and Disadvantages		
	Component Reliability	**Overall Cost**	**Nuclear Safety**
Maintenance Strategy	**High, Medium, Low**	**High, Medium, Low**	**High, Medium, Low**
Corrective Maintenance;	Low	High	Low
Periodic maintenance;	Medium	Low	Medium
Preventive maintenance;	High	Medium	High
Reliability-centred maintenance;	High	Low	High
Condition-based maintenance;	Medium	Low	Medium
Predictive maintenance;	Medium	Low	Medium
Opportunistic maintenance;	Medium	Low	Medium
Total productive maintenance;	Medium	Medium	Medium

Source: Derived from Huang *et al.* (2012); IAEA (2007); IAEA (2003); NASA (2008); Žilka (2014)

2.2.4 Maintenance Strategy Features

Nuclear power plants are under pressure to reduce operating and capital expenditure in an uneven energy market while maintaining reliability and improving safety standards (NEI, 2017:1).

Table 2.2 draws clear distinctions between the features of the maintenance strategies (preventive, predictive and corrective) and that a correct balance between these strategies are selected to reap the maximum benefit by increasing reliability, reducing cost and improving safety without increasing the risk.

Table 2.2: Maintenance Strategy Features

	Maintenance Strategies		
Features	**Corrective (CM)**	**Preventive (PM)**	**Predictive (PdM)**
Maintenance Approach	Reactive	Proactive	Proactive
Maintenance Category	Fix After Failure	Periodic Maintenance	Condition Monitoring
Downtime	Highest	Less	Close to Minimum
Expensive (Manpower)	Maximum	Little Less	Moderate
Initial Deployment Cost	None	Slightly higher	Expensive
Computational Cost	Least	Little Higher	Higher

Source: Basri (2017:117)

The nuclear industry is continuously evolving on its maintenance approach especially considering recent challenges in the energy markets. See Appendix A1.1.1 and A1.1.2 for additional advantages and disadvantages of the maintenance strategies.

2.2.5 Maintenance strategy criteria within the nuclear industry

Nuclear power plants are concerned with maintaining equipment reliability and maintaining nuclear safety that underpins the goals to reduce overall production costs and avoid failures that require extensive downtime (IAEA, 2007:6). Reliability Centred Maintenance (RCM) utilises feedback from failure finding tasks (such as inspections, tests and monitoring) or corrective maintenance to inform future maintenance decisions with the view to improve equipment reliability.

The optimization and effective implementation of the correct maintenance strategies ensures that components critical to nuclear safety are improved (IAEA, 2003:25). Braglia *et al.* (2013) states that a benefit of an effective maintenance strategy is the extension of equipment life. This improved component or system reliability is a direct result of an optimized maintenance strategy that further leads to reduced downtime and failures (IAEA, 2003:25). Mobley (2004:2) states that cost varies for the different maintenance strategies based on whether it is reactive or proactive. The cost of maintenance can be optimized through the continuous review of existing maintenance activities and techniques. Activity based costing is viewed as a more accurate indicator of maintenance strategy cost (IAEA, 2003:25).

The factors that influence a nuclear power plant (NPP) ability to compete in the energy market includes safety, reliability and the economics of components and systems (IAEA, 2003:7). A nuclear power plant can optimize its maintenance strategy by looking at maximising the value and contribution of its assets especially since it competes against conventional forms of generation (IAEA, 2003:19). Figure 2.5 illustrate equipment condition as it relates to the different maintenance strategies over time.

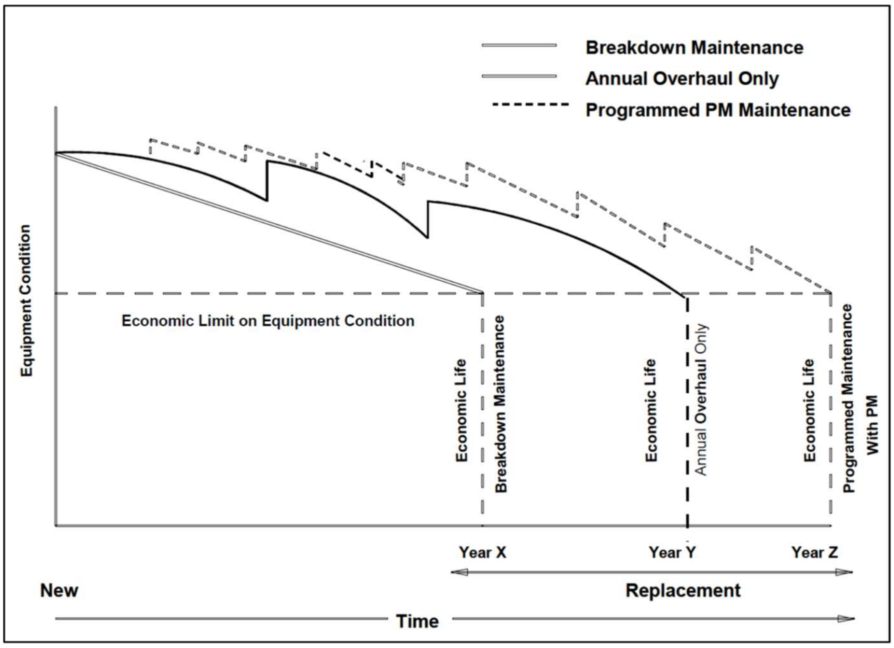

Figure 2.5: Equipment condition, Economic limit versus time.

Source: LCE (n.d)

Figure 2.5 provides a reference to what the economic life of a component will be given the use of each different maintenance (corrective, periodic and predictive with preventive maintenance) strategy. In Figure 2.5 the PM (programmed) maintenance provides the highest reliability with the corrective (breakdown) maintenance displaying the lowest reliability with the highest cost due to unforeseen failures. The annual overhaul of the component does provide extended economic life before the equipment condition deteriorates to the point of requiring an overhaul. Based on Figure 2.5, maintenance strategies for a nuclear power plant thus strive collectively to achieve three key outcomes namely, low operating cost, high reliability through reduced unplanned failures and high safety assurance of its systems or components (IAEA, 2003:19).

2.2.6 The impact of maintenance strategies on cost, reliability and safety

Maintenance on a nuclear power plant (NPP) implies work and this work implies increase in operating cost with an increase in risk. All maintenance strategies as discussed in Table 2.1 indicates that cost, safety and reliability are three factors that requires consideration when deciding on an optimum maintenance strategy mix.

Maintenance managers at NPP’s are bound by regulatory rules that require certain maintenance and inspection activities such as surveillance tests to be performed on a periodic basis which impacts cost, reliability and safety. If safety related equipment fails a statutory surveillance test by not meeting the operating license or safety analysis requirements, the system is declared inoperable and the unavailability of the system will usually require immediate maintenance intervention to restore the equipment to full operability or the NPP may have to reduce output or complete unit shutdown. The unexpected failure of safety related equipment identified during statutory surveillance testing can therefore lead to unplanned shutdown and impact on maintenance resources and cost (Braglia *et al.*, 2013:1002).

Safety is viewed as the overriding priority at a nuclear power plant therefore safety always comes first when engineering, operating or maintenance decisions are made. Reliability of equipment gives some assurance that components on a nuclear power plant is available when needed to perform its safety function. When components fail at unforeseen times, it directly affects cost, because emergency spares might be required, labour must be sourced, and safety might be compromised (Braglia *et al.*, 2013:1003; Mobley, 2004:2).

Figure 2.6 shows that reactive (corrective) and proactive (preventive) maintenance strategies determines the overall maintenance cost. It also highlights that proactive maintenance cost can be higher than reactive maintenance cost as reliability improves due to the proactive maintenance and thus resulting in less unexpected component breakdowns. This in turn improves the reliability of the plant but also reduce the total maintenance cost. Reactive maintenance strategies employ a run-to-failure philosophy, which is an expensive maintenance strategy that negatively affects the cost, reliability and safety of a nuclear power plant.

Figure 2.6 also illustrates how the total maintenance cost reduces with time below the average cost due to the benefits of proactive maintenance. Determining the correct maintenance strategy mix is a delicate balance that can take years to optimise through continuous experience feedback and engineering analysis.

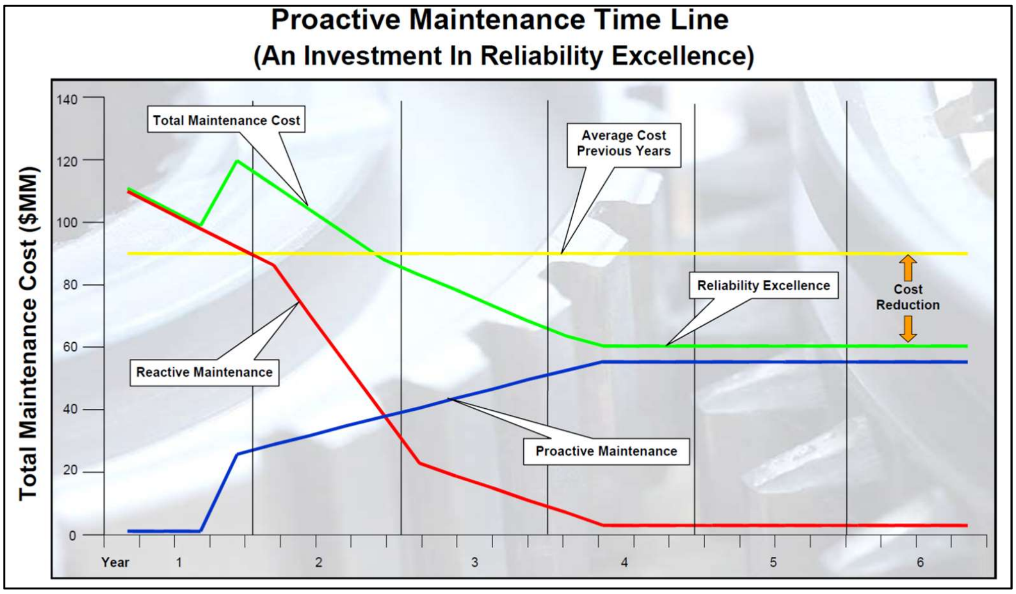

Figure 2.6: Proactive Maintenance Time Line

Source: LCE (n.d)

The Institute for Nuclear Power Operators (INPO) has compiled the INPO AP-913: Equipment Reliability Process Description document detailing the need to identify critical components and determining its maintenance requirements. INPO have provided guidelines for ensuring that the equipment reliability is improved and sustained at nuclear power plants by specifying the need to evaluate and identify systems, structures and components critical to nuclear safety, reliability and production. These would include components that affects power generation, environmental factors, station blackout, fire protection, reactor scrams, shutdown, emergency functions, pressurized thermal shock and core refuelling functions (INPO, 2013:14). This implies that even if there are hundreds of thousands of components on a nuclear power plant it is essential to identify and maintain those that affects key functions that can impact safety and reliability. This guidance has also aided nuclear power plants in reducing unnecessary costs as it limits the amount of proactive maintenance required to mostly those that can affect plant safety or production.

The Electric Power Research Institute (EPRI) has developed EPRI templates that help nuclear and other industries to develop a maintenance strategy that can be used to optimise maintenance cost while maintaining plant reliability and mitigating risk to ensure safe plant operation. According to Velmurugan *et al.* (2015:1635) and Larsson (2006:36) reliability is the probability that a component will perform satisfactorily under certain conditions for a specified period and thus a selected maintenance strategy should include preventive maintenance that allows for the effective management of spare parts at the right time to improve profitability. Any new maintenance strategy that involves the acquisition of equipment, establishment of additional training programs and investment in additional resources for proactive maintenance will increase the maintenance costs but may also improve reliability which in turn may result in a decrease in overall maintenance cost (NASA, 2008:3-8).

Figure 2.7 illustrates the division between reactive and proactive maintenance strategy costs. Over time the total direct cost of maintenance is reduced because of the proactive maintenance repairs. According to Lapa (2006) the more proactive maintenance interventions are performed the higher the overall cost will be.

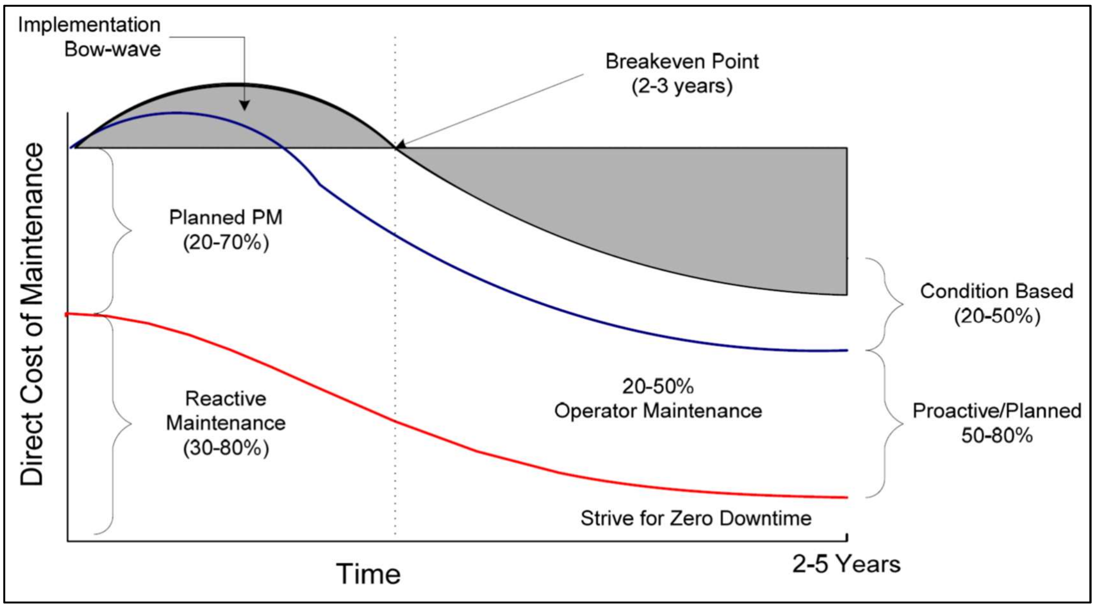

Figure 2.7: Direct Cost of Maintenance with Time

Source: NASA (2008:3-8)

Lapa (2006) continues by stating that the maintenance costs in pressurized water reactor nuclear power plants represent about 30% of the total operation costs. Any optimization in the maintenance strategy will result in reduced operating expenditure.

Figure 2.7 illustrates that the direct cost of maintenance only reaches breakeven point at two to three years after implementing the maintenance optimization strategy. It would seem then that to implement the correct maintenance strategy mix before starting a new nuclear power plant will hugely benefit the plant in reducing cost and eliminate unnecessary costly maintenance program changes.

Table 2.3 provides a summarised breakdown of the relative costs for each of the three main maintenance strategies as well as the reliability centred maintenance (RCM) strategy that incorporates all three strategies. Similar to the benefits listed in Table 2.1, Table 2.3 indicates that the RCM strategy provides the best maintenance strategy from a cost perspective.

Table 2.3: Maintenance Strategies and Relative Costs

Maintenance strategies	Technical requirements		Relative costs		
	Specialised knowledge	Specialized equipment	Maintenance activities	Repairs after failure	Downtime and extended damages
CM	Minimal	Minimum	None	Very large	Extensive
PM	Extensive	Moderate	Extensive	Moderate	Moderate
PdM Off-line	Extensive	Moderate	Moderate	Minimal	Minimal
PdM On-line	Moderate	Extensive	Moderate	Minimal	Minimal plus
RCM (CM+PM+PdM)	Extensive	Extensive	Moderate plus	Minimal	Minimal plus

Source: Huang *et al.* (2012:1016)

Maintenance strategies must also consider the redundancies of safety related components at nuclear power plants which may affect the operating and surveillance testing regime as well as wear rates of standby equipment versus in-service equipment to minimise production losses and cost (IAEA, 2002b:1; Lapa, 2006).

2.2.7 Summary

Nuclear power plants are selecting maintenance strategies aimed at ensuring component reliability as well as reducing cost and improving safety. Braglia *et al.* (2013) emphasize that maintenance must be thought of as an investment opportunity to be optimized rather than it being focussed on cost minimization. This especially holds true for nuclear power plants as costs are not the only criteria to consider when developing the maintenance strategy. Some strategies for certain components may have better benefits but it is best to consider maintenance strategies from a holistic viewpoint as it affects various factors of a nuclear power station of which most importantly, safety (Velmurugan & Dhingra, 2015:1626). Maintenance strategies have both advantages and disadvantages and because all nuclear power plants have limited resources it is common to combine predictive, preventive and corrective maintenance strategies in the overall maintenance program (Žilka, 2014:211).

The decision on how to proportion each strategy for each nuclear power plant is in most cases either based on EPRI guidelines, engineering judgement or management intuition (Žilka, 2014:211). Choosing an appropriate maintenance strategy should be based on the type of component, the criticality of the component, the failure type of the component, industry operating experience of the component, manufacturer recommendations, operating conditions, risks, availability of maintenance facilities, frequency of use and system design requirements (Hemmati *et al.*, 2018:125; INPO, 2013:29). Favouring one maintenance strategy over another is not in the best interest of nuclear power plants as they require a combination of these strategies to achieve the optimum blend of safety, cost and reliability while adhering to regulatory requirements. Selecting the correct mix of maintenance strategies require typically a multi-criteria decision-making analysis and most authors tend to use an analytic hierarchy process (Hemmati *et al.*, 2018:1253; Velmurugan & Dhingra, 2015:1631). The tool necessary to aid in making the selection decision must be widely acceptable with a proven success record. This study will explore the use of the AHP model which is a powerful tool in solving complex decision-making problems including selecting a maintenance strategy (Zaim *et al.*, 2012:19). The next literature review section explores the analytic hierarchy process theory.

SECTION B: ANALYTICAL HIERARCHY PROCESS

2.3 Introduction

The previous section summarised that the best option might be to obtain a combination of the various maintenance strategies as it does not seem that one strategy will suffice as an optimal strategy option for a nuclear power plant. This section will explore the analytic hierarchy process which is a qualitative decision-making tool that rely on expert judgement to perform pairwise comparisons to derive a priority scale (Saaty, 2008:83).

2.4 Analytical Hierarchy Process (AHP) Model

The analytic hierarchy process (AHP) is a general theory of measurement that is often used in multicriteria decision making (Saaty, 1987:161; Triantaphyllou & Mann, 1995:35). Saaty (1987:161) created the AHP model in 1971-1975 and describes it as "… a nonlinear framework for carrying out both deductive and inductive thinking … by taking several factors into consideration simultaneously and allowing for dependence and for feedback and making numerical trade-offs to arrive at a synthesis or conclusion." The AHP model allows for better relative judgements in a multi-criterion pairwise comparison matrix (Franek & Kresta, 2014:165). According to Benítez *et al.* (2011a:4455), Zhu and Xu (2014:794) the AHP model is a well-established and widely used decision-making technique that use hierarchical representation to allow for decision making of complex multi criteria problems.

There is a concern of uncertainty within the AHP model as judgements are used and can be inconsistent (Saaty, 2008:83). The AHP model is viewed by some scholars as a time-tested method that has been used in multibillion-dollar decisions in various organisations and industrial engineering applications (Triantaphyllou & Mann, 1995:35). The AHP uses matrix algebra by deriving ratio scales from paired comparisons of factors and selected options. The AHP model can be used for the importance determination of all the relevant criteria, alternatives and the ranking of each alternative indicating a different maintenance strategy (Triantaphyllou *et al.*, 1997:17). In these decision models the relative importance of the alternatives when examined in terms of a single decision criterion at a time must be expressed in terms of their relative importance (Triantaphyllou *et al.*, 1997:25).

2.4.1 The AHP model theory

Decision making in a nuclear power plant is important and requires an understanding of the criteria, the objective, the sub-criteria and alternatives that provides input to make informed decisions. Decisions are made daily and without thinking about it while ranking of alternatives are made based on many factors (Saaty, 2008:84). Introducing expert opinion into the AHP multi-criteria decision-making model plays an important role and adds significant value to the decision-making process (Tsyganok, 2012:4785). Tsyganok (2012:4786) argues that expert opinion should be considered credible if the person is an expert in the given domain because the more credible the expert is, the closer they lie to the benchmark value.

According to Muller and Clarke (2001:846) pairwise comparison and expert judgement is used to quantify the relative importance of two or more alternatives. These judgements are recorded in a matrix and its selected value on a numerical scale is used to calculate the relative importance of the alternatives. The importance of one alternative relative to the other in relation to a specific criterion is given by the ratio of importance (Muller & Clarke, 2001:847).

Saaty (2008:85) describes how to use the AHP model as follows:

- Define the problem and the kind of knowledge sought;
- Structure the decision hierarchy from high level drivers on top with the goal of the decision;
- Add the objectives specific criteria from a broad perspective (criteria on which subsequent elements depend) to measure value of alternatives;
- Construct pairwise matrices. This is done using scale of relative importance ranking (see Table 1 below) to compare two alternatives or criteria's;
- Use the priorities obtained from the comparisons to weigh the priorities in the level immediately below;
- Add the weighted values and obtain its overall or global priority;

- Repeat this process until all final priorities of the alternatives in the bottom most level is obtained.

Figure 2.8 illustrates a typical hierarchical structure with the goal being considered at level 1. Level 2 being the multi-criteria or factors (A, B, C and D) and level 3 being the alternative choices (X, Y and Z).

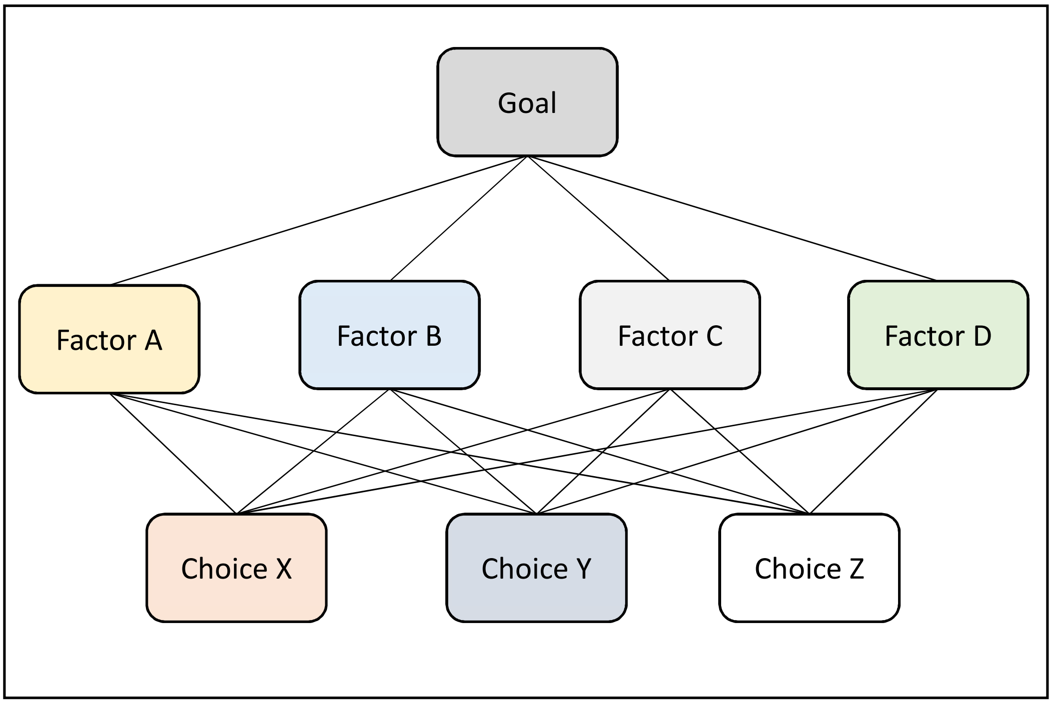

Figure 2.8: Example of AHP structure

Source: Saaty (1980:13)

Saaty (1980:13) explains the typical AHP structure as follows:

- The elements of each group are assumed to be independent;
- There is a relationship between the factors and the choices and between the factors and the goal;
- The factors are compared to each other and the choices are compared with respect to the factors to each other;
- The level 2 comparison is a 4 x 4 comparison matrix;
- The level 3 comparison is a 3 x 3 comparison matrix.

The decision tree is structured hierarchically in levels like an organisation structure with the overall goal at the top and a finite number of alternatives and criteria at the bottom (Zaim *et al.*, 2012). These alternatives and criteria are compared using Table 2.4 below to construct a linear algebraic matrix model. Benítez *et al.* (2011b:1785) suggests that the ratio integer scale of 1 to 9 as suggested by Thomas L. Saaty and shown in Table 2.4 be used to represent judgements ranging from “equal importance” to “extreme importance” in the pairwise comparison exercise. There are many other scales and ratios that can be used, and various schools of thought and arguments are being made in support and disagreement to the nine-point integer ratio scale. Thomas L. Saaty postulated in 1994 “…that ratio scales are the only possible measurement if we want to be able to aggregate measurements…” (Franek & Kresta, 2014:166). It can be concluded that even with differing views of which scale should be used, there is no definitive proof that one scale is better than the other, however applying the various comparisons to different judgement scales do play a significant role in AHP decision making (Franek & Kresta, 2014:166).

The use of the AHP model requires the decision-maker to express his opinion about the value of a single pairwise comparison and thus choose an answer among 15 to 25 discrete choices where each choice is a linguistic phrase. These phrases can include examples such as: “…A is more important than B", or "A is of the same importance as B", or "A is a little more important than B″, and so on (Triantaphyllou & Mann, 1995:37). According to Triantaphyllou and Mann (1995:38) the critical step is to quantify these choices into integer numbers in multi-criteria decision-making methods which use qualitative data.

Muller and Fairlie-Clarke (2001:853) uses the same method stated above and reiterates the importance of using expert in-house staff judgement to identify and prioritise the criteria. One alternative is compared to another alternative in terms of its relative importance to a specific criterion. The expert is required to judge what the importance of one alternative is to another based on some selected criteria by assigning a degree of importance as listed in Table 2.4. Pairwise comparisons can now be performed in mathematical format where X and Y are the criteria to be considered in terms of its importance for each alternative.

Table 2.4: Scale of Relative Importance

Intensity of Importance	**Definition (Importance)**	**Explanation**
1	Equal	Two activities contribute equally to the objective
3	Weak	Experience and judgement slightly favour one activity over another.
5	Essential or Strong	Experience and judgement strongly favour one activity over another.
7	Demonstrated	An activity is strongly favoured and its dominance demonstrated in practice
9	Absolute	The evidence favouring one activity over another is of the highest possible order.
2,4,6,8	Intermediate between two adjacent judgements	When compromise is needed
Reciprocals of Above Zero	If X has one of the above nonzero numbers assigned to it when compared with activity Y, then Y has the reciprocal value when compared to X.	

Source: Triantaphyllou & Mann (1995:37)

It is important to understand the extent to which researchers or decision makers can rely on the outcome of the pairwise comparison decision making method. The AHP methodology allows for slightly non-consistent pairwise comparisons which brings into question the consistency of the comparison combinations. Consistency in the AHP model refers to firstly homogeneity and relevance (Saaty, 1990:18). This refers for example to an instance where a plane and bus are compared where transport speed is the relevant criteria but not where flying is the criteria. Secondly consistency also refers to the intensities by which each object based on a particular criterion relates to another object in some logical way (Saaty, 1990:18). For example, consider that a lemon is two times greater than an apple and the apple is 10 times greater than a grape, then it stands to reason that the lemon is twenty times greater than the grape. Saaty (1990:18) explains that if the lemon is judged to be only six times greater than the grape, then the judgements are inconsistent. In order to use the judgements for decision making purposes, it is important that there is a relatively high level of consistency so that there is some acceptable repeatability in the judgements.

Where two criteria C_i and C_j are compared a value of a_{ij} is proposed so that it represents the judgements of the relative importance for C_i over C_j (Benítez *et al.*, 2011a:4449). Benítez *et al.* (2011a:4449) states that if C_i and C_j are considered to be equally important, then $a_{ij} = 1$ and if C_i is preferred to C_j then $a_{ij} > 1$. Where $a_{ij} = 1$ for all $i = 1, 2, \ldots, n$ a homogeneous matrix of pairwise comparisons are compiled.

The judgement matrix:

$$a_{ij} = a_{ik}a_{kj} \qquad \ldots (2.1)$$

should always be true if all the comparisons are perfectly consistent (Saaty, 1980:49). The judgement matrix is adequately consistent if the consistency ratio (CR) is smaller than 10% and further examination of the problem is required where the CR is greater than 10% (Saaty, 1990:83). Most AHP models will result in some inconsistency and the quantification of the inconsistency level provides a measure of the extent of the experimental error (Saaty, 1990:83). It does matter how strongly consistency is violated and thus pairwise comparisons are used in the AHP model to improve consistency (Saaty, 1980:11).

Triantaphyllou *et al.* (1995:39) further explains that the priority vectors (pv) namely:

- The consistency index (CI) = the degree of logical consistency amongst pairwise comparisons,
- The consistency ratio (CR) = the amount of allowed inconsistency,
- Number of comparisons (n) and
- The maximum eigenvalue scalar (λ_{max}) can be calculated to allow for multi-criteria decision making.

The consistency index will be calculated according to the formula below (Triantaphyllou *et al.*, 1995:39; Saaty, 1980:19):

$$CI = (\lambda_{max} - n) / (n - 1) \qquad ...(2.2)$$

The matrix is considered perfectly consistent (CI = 0) when λ_{max} equals n. The higher the number of pairwise comparisons the higher the possibility of inconsistency (Entani & Sugihara, 2012:379). Saaty (1980:19) recommended to use another measure where the ratio of CI is taken to the average random index (RI) in the same order matrix can be calculated as:

$$CR = CI / RI \qquad \ldots(2.3)$$

Table 2.5: Random Consistency Index

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

Source: Saaty (1980:19); Shyjith (2008:381)

The values of the pairwise comparisons in the AHP model are determined by the values and their reciprocal values as displayed in Table 2.5. The available values for the AHP method are the numbers of {9, 8, 7, 6, 5, 4, 3, 2, 1, 1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9}. As an illustrative example consider the following situation in relation to Figure 2.7. Suppose that a decision should be made on which car to buy and there are three alternatives to choose from, options A, B, and C. Also, suppose that one of the decision criteria or factors are engine power. Suppose that car A has a higher-powered engine than car B, and car C has the lowest engine power. Suppose that the following is the judgement matrix when the three alternative configurations are examined in terms of this criterion.

Table 2.6: Example: Importance of Strategy Criteria

X / Y	Car A	Car B	Car C
Car A	1	1/8	5
Car B	8	1	1/9
Car C	1/5	9	1

Source: Saaty (2008:86)

The corresponding maximum eigenvector are approximated by using the geometric mean of each row (Triantaphyllou *et al.*, 1995). Using a complex linear algebra calculation tool to determine the results for the example in Table 2.6, it is concluded that car B is the best option. The allowed inconsistency Index (CI) is above 10% which means the comparisons are less consistent and the pairwise comparisons needs to be revisited (Triantaphyllou *et al.*, 1995:39). The consistency ratio will provide insight into the consistency of the judgements.

$$pv = (0.1614; 0.7855; 0.0531)$$

$$\lambda_{max} = 3.2523, CI = 0.1262, \text{ and } CR = 0.2426.$$

The numerical data calculations will be expanded in this study to compute the alternative (maintenance strategy) pairwise comparisons and to provide alternative rankings of importance resulting in a decision on the preferred or recommended maintenance strategy(ies). The inconsistency is an important aspect of the AHP model and if the allowed inconsistency is made too small (e.g. 1%), new knowledge which change preference order cannot be admitted (Saaty, 1987:172). The analytic hierarchy process reflects how we normally think and uses a process of systematic rationality and thus perfect consistency (CI = 0) is nearly impossible to achieve and contradicts human experience (Saaty, 1990:24).

2.4.2 Advantageous of the AHP model

The AHP model is very effective as it allows for the evaluation of qualitative and quantitative criteria, the consideration of multiple scenarios and alternatives on the same numerical, verbal or graphical scale (Franek & Kresta, 2014:165; Larrodé *et al.* 2012:4890). Franek and Kresta (2014:165) states that the AHP has the advantage of providing users with clarity on specific criteria and sub-criteria. AHP also has the advantage of measuring the inconsistency of the actors when applying the judgements (Larrodé *et al.* 2012:4894). The AHP model allows for some ambiguity in non-trivial and highly complex problems by using pairwise comparisons of which there can be tangible or intangible factors (Franek & Kresta, 2014:165; Larrodé *et al.,* 2012:4894; Ishizaka *et al.*, 2012:4768). The model is highly reliable as it detects top and least priorities and can thus be considered as an adequate support decision tool in many decision problems (Ishizaka & Philippe, 2013:1811).

2.4.3 Limitations of the AHP model

According to Gass (2005:309) "the main criticisms of the AHP are its measurement scale, rank reversal, and transitivity of preferences."

2.4.3.1 Measurement scale

Entani and Sugihara (2012:379) argues that a major drawback of the AHP model centres around the increase in uncertainty relative to the increase in the number of combinations of comparisons. Two kinds of uncertainty are inherent to the AHP model namely inconsistency and incompleteness of comparisons (Entani & Sugihara, 2012:379). Benítez *et al.* (2011a:4456) states that the inconsistency of the judgements in the AHP models is present when dealing with both tangible and intangible factors. According to Ishizaka *et al.* (2012:4768) the AHP model is better when the problems have a low number of alternatives as the pairwise comparisons place an increased demand of evaluations on the decision maker. Saaty suggests a upper limit of 7 ± 2 alternatives where a matrix of n elements is $(n^2-2) / 2$ (Ishizaka *et al.,* 2012:4768).

According to Frank and Kresta (2014:165) there is a lack of sensitivity when comparing elements, which are preferentially close to each other. This is further complicated by using the 9-point scale that restricts the consistency ratio (CR) due to the standard deviation of the consistency index for random matrices being relatively small (Franek & Kresta, 2014:165). Ishizaka *et al.* (2012:4779) argues that the AHP model is unable to resolve real-world problems as it is limited by its inability to address problems that require sorting.

2.4.3.2 Rank reversal

The AHP model is susceptible to the rank reversal phenomenon in hierarchies with four or more levels or where a new criterion is added for which the largest local priority corresponds precisely to the alternative which also has the largest global priority (Pérez *et al.*, 2006:99). When alternatives are added or removed from the comparison pool, the ranking of alternatives determined by the eigenvector may change (Yue *et al.*, 2006:190). According to Gass (2005:309) the "rank reversal occurs when, after the decision maker (DM) ranks the given set of alternatives, the DM adds a new, irrelevant alternative to the set. Upon ranking the modified set, the DM finds that the previously highest ranked alternative is downgraded. Yue *et al.* (2006:190) states that rank reversal does not happen if all comparison matrices are consistent.

2.4.3.3 Transitivity of preferences

"Transitivity between preferences means that if alternative A is preferred to alternative B, and alternative B is preferred to alternative C, then alternative A is preferred to alternative C" (Gass, 2005:309). A comparison matrix that is partially filled can be completed through deducing comparisons by using transitivity rule, however these comparisons are not always consistent so that (equation 2.1) holds true (Franek & Kresta, 2014:166; Ishizaka, 2012:4769). In section 2.3.1 it was discussed that perfect consistency in human behaviour examples is virtually impossible and thus it can be concluded that transitivity rule does not hold for all comparisons (Franek & Kresta, 2014:166). This implies that a consistency ratio of < 0.1 will be difficult to achieve in human behaviour examples.

2.4.4 Summary

The AHP is a successful model and has been both highly praised and strongly criticised as a multi-decision-making model (Ishizaka *et al.*, 2012:4767; Ishizaka &, Philippe, 2013:1810). The nuclear industry is operating in a competitive energy market that requires optimised maintenance strategies to minimise downtime while improving profits in a safe and reliable manner. Decisions are required that consider all the alternatives, criteria and sub-criteria. The AHP model is an ideal tool to allow experts to weigh in on the selection of an effective maintenance strategy to address this problem (Hemmati *et al.*, 2018:1253). Various experiments have been conducted to validate the multi-criteria decision-making methods and it can be concluded that no single method is considered the best in all aspects (Ishizaka &, Philippe, 2013:1802). Benítez *et al.* (2011a:4456) suggest that methods to improve consistency are necessary in order to improve the reliability of the AHP model. Since the AHP model has been widely used, it can produce results that are easily understood and implemented. Gass (2005:311) argues that some authors believe that the AHP model is flawed by listing various shortcomings in its approach to determine priorities, but other authors (e.g. Bevilacqua & Braglia, 2000; Kirubakaran & Ilangkumaran, 2016; Wang *et al.* 2007) have argued in support of the AHP model. The analytic hierarchy process is thus a viable and acceptable model to use for the maintenance strategy decision making exercise for a nuclear power plant (refer to Appendix A1.2 for studies where the AHP model have been used). The next section explores the specific requirements of the nuclear industry especially from an energy competitive and regulatory perspective.

SECTION C: NUCLEAR POWER PLANTS

2.5 Introduction

Any nuclear power plant is constrained by the ageing of its non-replaceable critical system, structures and components (SSC's) (OECD, 2006:18). This requires that NPP's be practical in selecting an effective maintenance strategy to preserve and protect these SCC's from failing (CNSC, 2012:1). It is thus essential that nuclear power plants must evolve to consider options to reduce operational costs while improving plant reliability and safety (OECD, 2006:9). This chapter will explore the unique requirements of the nuclear power industry and build on the previous sections for the development of the maintenance data and the cost component of nuclear power plants. This cost component can impact safety and reliability decisions and is an important aspect of selecting the maintenance strategy that forms part of the AHP criteria.

2.6 Nuclear Power Plant Requirements

2.6.1 Nuclear power plant maintenance requirements in regulatory context

All nuclear power plants need to comply with nuclear operating license requirements which include requirements for equipment surveillance testing, inspection and comprehensive maintenance programs. To achieve an optimised maintenance strategy, it is important that proper information is available and structured in a systematic way to ensure effective decision making (NASA, 2008). Often within the nuclear environment the root causes of plant component failures are identified but the factors that led to these failures are not properly addressed. At times the 'more is better' approach leads to increase cost, increase dose, more manpower and unavailability of systems (IAEA, 2003:10).

The OECD (2006:10) stated that NPP's are looking at life extension beyond their initial design period. Most nuclear plants with a lifespan of 40 years were constructed during the 1970s and will reach its designed lifespan between 2010 and 2020 (OECD, 2006:18; Meserve & Moniz, 2002:64). Many of these existing plants are either increasing their operational timeframe or modifying their plants to allow for such extensions. They currently compete with other energy technologies that are cleaner and more efficient with higher profit margins and lower operational costs. Nuclear power plants still hold the advantage over these newer energy technologies in that it is a reliable baseload energy source that can produce enormous amounts of energy to significantly greater populations (Meserve & Moniz, 2002:68).

Maintenance strategies for nuclear power plants are required to involve or consider the supporting factors such as the program basis, the maintenance organisation, maintenance practices, spare parts, processes, policies and procedures, training and information systems (CNSC, 2012:4). All new nuclear power plants are designed and constructed taking these factors into account with the aim to achieve the highest standards of safety and efficiency which are subject to stringent regulation and licensing requirements supported by a degree of conservatism (OECD, 2006:8). The maintenance strategy development therefore must be based on the operating and design requirements that are underpinned by the regulatory rules for operating and maintaining a nuclear power plant (CNSC, 2012:4). According to the OECD (2006:9), nuclear plants will undergo several technological advances as experience is gained from operation or from similar plants that will allow for life extension and improved safety and reliability levels. The maintenance strategies are subsequently adjusted to reduce costs and improve plant performance based on the operating experience.

The regulatory rules specify that maintenance surveillance, inspection, testing, calibration, repair, replacement of spare parts and monitoring activities be part of the maintenance scope that will ensure the safe operation of an NPP (CNSC, 2012:1). The OECD (2006:18) states that the non-replaceable SCC's are normally those that the regulator considers to be crucial for the safe operation and life extension of a nuclear power plant. A nuclear power plant is a very large and long-term investment that require safe, reliable operation as well as meeting regulatory requirements, while achieving high capacity factors to maximise financial return (OECD, 2006:25).

Every nuclear power plant has a set of requirements for safety related plant equipment that must be inspected or tested to ensure compliance to its nuclear license. These requirements include the in-service inspection (ISI) and in-service testing (IST) programs, equipment qualification (EQ) program, flow accelerated corrosion (FAC) program, boric acid corrosion (BAC) program, maintenance rule (MR) program, single point vulnerability (SPV) and other license binding nuclear programs (CNSC, 2012). Regulatory requirements underpin the operational requirements of any NPP and may lead to increase maintenance costs without direct increase in safety (IAEA, 2003:8). Nuclear regulators of each member state country have their own set of requirements that are aimed at protecting the public, but these requirements have proven over the years to be sometimes redundant or conflicting (IAEA, 2003:8). Regulatory requirements have placed significant pressure on the nuclear industry that cut into the bottom line of the nuclear utilities to the point where governments considered moving away from future nuclear power plant construction (Bose, 2000:2012). Regulators have started to recognise that optimized maintenance strategies results in an improved availability of safety critical components and that some modified or deleted requirements can have negligible or no impact on either safety or the environment (IAEA, 2003:8). Nuclear regulators have accumulated operating experience in design and or operating margins and made advances in quantifying the risks associated with reactor accidents through a technique called probabilistic risk assessment (PRA) that shown some of these margins were unnecessarily large (Meserve & Moniz, 2002:69).

Optimised maintenance programs should first seek to meet the regulatory requirements, then identify the excessive requirements and then seek to reduce the operational burden (IAEA, 2003:8). The United States Nuclear Regulator (US NRC) introduced the maintenance rule that aims to control the maintenance effectiveness and performance (IAEA, 2003:8). The IAEA recommends that NPP's consider the use of risk informed maintenance strategies to provide a balance between corrective, preventive and predictive maintenance (IAEA, 2002:34). This is especially necessary for SSC's that are not normally in service and therefore to prevent their over testing but also to safeguard their availability when called upon for emergency situations (IAEA, 2002b:34).

2.6.2 Establishing master data for the maintenance strategy

To establish any maintenance strategy a clear understanding of the information relevant to that strategy should be obtained. A systematic approach is taken to identify which maintenance activities are to be performed on each component, structure or system and at what frequencies (CNSC, 2012:5). The nuclear power plant is required to demonstrate to the nuclear regulator that the following inputs have been considered:

- design information (what are the parameters of the components);
- functional data (plant location and description of equipment);
- vendor maintenance manuals (suggested repair instructions or tasks);
- industry operating experience;
- regulatory requirements and their frequencies (ISI and IST);
- environmental conditions and operating conditions;
- the importance of the structure, system or component as it relates to the safety analysis, severe accident management guidelines and supporting documentation;
- material data (purchasing information for spares);
- engineering data (nuclear program data and safety specifications); and
- radiation protection principles (CNSC, 2012:5; INPO, 2013:33).

All these data sets are referred to as master data. Licensees (nuclear power plants) must also demonstrate that its maintenance strategy has its basis in the approved plant design and safety analysis, and that all SSCs will function as per design by including the following five criteria in its maintenance program:

- "a process is in place to ensure that relevant design information is identified and used in developing the maintenance program;
- the design authority is clearly defined to maintenance personnel and has responsibility for the design philosophy, plant safety and design basis, and safety margins;
- documents regarding plant design details and operational configuration status are accurate and accessible to maintenance personnel;

- communication interfaces are defined among groups responsible for design, engineering, operations and maintenance; and
- operational requirements and restrictions imposed by the plant design are documented in specifications and incorporated into maintenance procedures or work instructions” (CNSC, 2012:5).

The nuclear regulators are not prescriptive as to what information management systems should be used to manage these data sets provided that the information is managed in such a way to confirm that the regulatory requirements through the maintenance strategy are being met (IAEA, 2002b). INPO (2013:33) recommends that new and existing NPP’s consider predictive or condition monitoring as an alternative to intrusive maintenance. This recommendation is in line with latest trends to minimise cost and to minimise errors.” Nonintrusive monitoring reduces the probability of maintenance-induced equipment failures” (INPO, 2013:33). PM templates are used to establish the maintenance program or strategy and it cannot exclusively consist of predictive monitoring as this strategy may not detect all failure modes (INPO, 2013:33).

INPO (2013:33) further recommends that manufacturer recommendations are also considered when selecting an optimal maintenance strategy and that risk-rank PM revisions be established to determine the first and highest-priority performance dates. Nuclear power plants are thus not able to defer preventive maintenance activities without carefully considering the frequency, the risk classification, the as-found conditions, history of equipment and the regulatory requirements (INPO, 2013:23). Maintenance, Work Management, Engineering and Operations Managers view preventive maintenance (PM) on critical components for an NPP as high priority and would rather defer other work than deferring critical PM’s (INPO, 2013:23). PM activities normally receive a 25% tolerance period on the established periodicity and a management review is required should the tolerance period be exceeded while significantly degraded critical components receive a formal engineering and maintenance review (INPO, 2013:24). The maintenance department at a nuclear power plant strives for excellence by fostering a culture of intolerance in unplanned equipment failures (INPO, 2013:23).

The International Atomic Energy Agency (IAEA) recommends that all nuclear power plants adopt a systematic approach to maintenance by ensuring that critical SSC's are based on reliability centred maintenance (RCM) strategies with a focus on long term maintenance objectives (IAEA, 2002:3). The IAEA also prescribes an adequate condition-based monitoring program that supports the optimization of the maintenance program (IAEA, 2002:3). The scope of the CBM program should include:

- "…SSCs which ensure safe operations or whose failure could challenge a safety function; and
- SSCs which are relied on to remain functional … to ensure the continued performance of safety functions, or whose failure could prevent safety related SSCs from performing their safety related functions" (IAEA, 2002:3).

Establishing accurate data and developing the correct maintenance tasks and frequencies for each component is essential to deliver the required low cost, safety and reliability focussed maintenance strategies.

2.6.3 Nuclear power cost investment

A nuclear power station has a significantly large investment cost with some degree of uncertainty (such as construction cost or licensing delays) that further impacts the investors risk (Roques *et al*., 2006:19; Yarrow & Newbery, 1988:85). Operating and maintenance cost of a nuclear power plant add to the overall cost of generating electricity and thus affect the bottom line of each plant. The magnitude of the maintenance cost depends on the flexibility of the labour force, the cost of spares, maintenance strategy and processes (Yarrow & Newbery, 1988:91). Achieving higher capacity factors of above 90% has become possible through better management, maintenance, training, and attention to detail (Meserve & Moniz, 2002:61). Meserve and Moniz (2002:61) argue that the improved performance in the nuclear industry contributed to a decline in operating costs that placed nuclear power amongst the cheapest sources of electricity. A well-run nuclear power plant is a low-cost generator with considerable profit margins which forms a very good investment (Rogner, 2010:140). Rhodes and Beller (2000:38) uses the example of the United States of America where the production cost has dropped so far that it is fully competitive with electricity generated from fossil fuels. Striving for excellence in nuclear is essential to improve safety while driving productions costs lower.

In contrast to Rhodes and Beller an argument can be made that the availability of adequate amounts of cheap shale gas has limited the need for additional nuclear power stations to be built. The abundance of shale gas has indirectly contributed to the shutdown of six nuclear reactors since 2012 due to significant competition in the energy market; the low investment and operating cost model of shale gas and the relatively high maintenance and investment cost of nuclear power in the United States (Pearce, 2015; Rogner 2010:142). The size of constructing nuclear power plants, the long construction periods and slow payback periods of beyond twenty years limit the investment market in nuclear power plants to large corporations or governments (Rogner, 2010:142).

Nuclear events such as the Fukushima disaster that occurred in 2011 have caused governments and nuclear regulators to pause and reconsider their role in the protection of the public. This has led to the consideration of additional designs and or maintenance activities (Moniz, 2011:86). Maintenance cost, fuel cost, operating cost, investment cost, decommission cost, waste disposal, fixed and variable costs are considered standard generating costs of nuclear power and dominated by capital costs (Rogner, 2010:143).

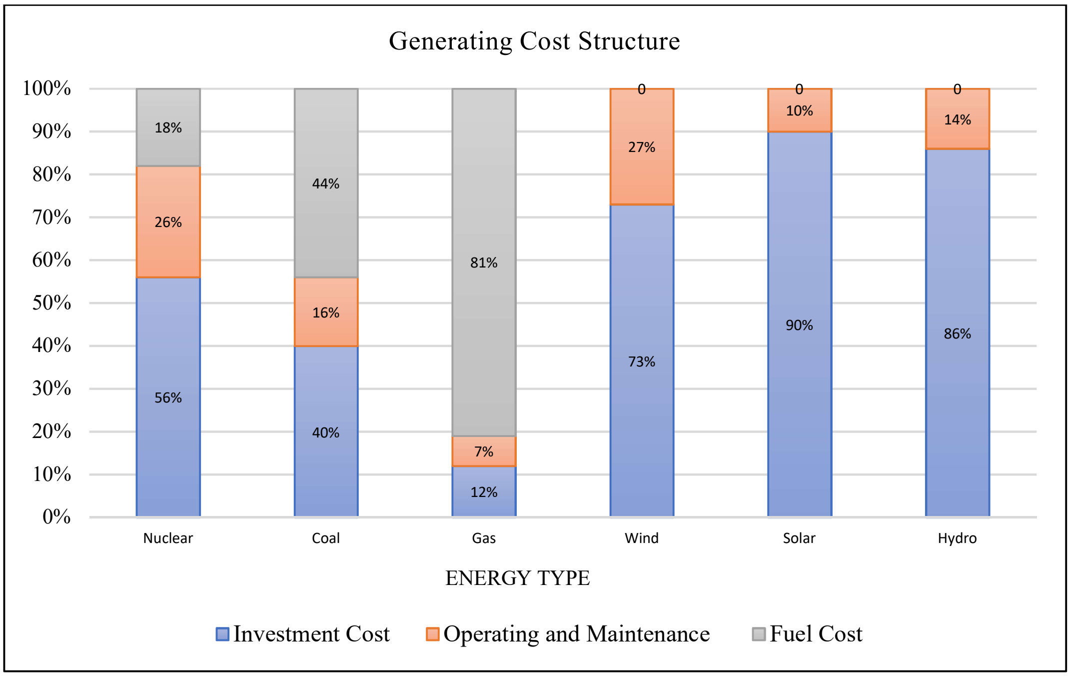

Figure 2.9: Generating Cost Structure for different Energy Sources

Source: Derived from Rogner (2010:142)

Figure 2.9 provides an illustration of the generating cost comparison between various energy sources. Nuclear energy has a relatively large percentage of its cost assigned to the operating and maintenance component although it is considered as a low operating cost energy source. Opponents and proponents of nuclear power make strong arguments for and against the cost structures as these plants have marginal generating costs but have huge initial capital costs which sets it apart from alternative energy sources (Rungsuriyawiboon, 2008:2).

2.6.4 Summary

The literature review highlights that nuclear regulators across the world have prescriptive requirements relating to maintenance, testing and inspection requirements that may not be optimised for improving the safety and reliability of SSC's. Nuclear power stations must carefully select the correct balance in maintenance strategies and consider various inputs when determining the optimal strategy mix. A new NPP presents the opportunity to select the ideal maintenance strategy at the outset, however the absence of adequate operating experience of similar plants could cause maintenance and engineering departments to be over conservative and result in having many unnecessary maintenance tasks with non-ideal frequencies within the new maintenance program. The ideal maintenance program should consider the regulatory requirements and design a maintenance program that is well balanced between PM, PdM and CM strategies. The effectiveness of the maintenance strategy mix is ultimately dependent on the NPP leadership that manages the implementation of the maintenance program.

The AHP model has advantages and disadvantages and have been used extensively in various studies. The AHP methodology's limitations are known and are considered when determining the priority vectors. Careful consideration will need to be given to rank reversal and the consistency ratio. The literature refers to RCM and CBM that potentially forms part of the PdM strategy and thus it is important to determine whether the AHP model will predict the PdM to have the priority vector since we will evaluate the PM, PdM, CM and RCM strategies. Rogner (2010:139) states that coal, solar, nuclear, wind or any other form of energy is inherently good or bad, and each is only valuable in as far as it can deliver to this end.

Businesses are looking differently at the maintenance function as it is no longer seen just as an expense but as an investment opportunity to protect future revenue or to reduce future unexpected losses (Fredriksson & Larsson, 2012:2). PdM driven RCM maintenance strategies have vastly improved equipment maintenance at NPP's that in turn improved plant reliability and safety (Huang *et al.*2012:1021). Minimizing the downtime of major equipment especially where redundancies are not available has received greater focus hence the need for proactive maintenance strategies to plan and limit unexpected downtime. These maintenance strategies have resulted in less failures, minimized downtime, higher profits and higher component reliability that increased plant safety (Fredriksson & Larsson, 2012:2).

CHAPTER 3
RESEARCH DESIGN AND METHODOLOGY

3.1 Introduction

The research method is based on the discussions of the literature review and will use qualitative data obtained from maintenance and engineering experts within the nuclear power plant industry to conduct pairwise comparisons to select an effective maintenance strategy. Qualitative data will be used in numerical format within the AHP Model. Linear algebra forms the basis for the decision-making process and complex mathematical problem-solving software is used to calculate and validate results. A search to determine if questions exist will be conducted and it may need to be modified to conform to the intent of this study.

The main aspects of this study involve the use of the Analytic Hierarchy Process model. The study will focus on four alternatives (PM, PdM, CM and RCM) and three criteria (safety, cost and reliability). The criteria and alternatives will be discussed in detail as well as the structure of the questions to achieve the desired comparisons. A questionnaire will be launched on SurveyMonkey and will be designed to obtain the expert judgements for the pairwise comparison criteria. SurveyMonkey is a customizable internet-based survey platform that includes data analysis and representation tools which can be used for almost any type of survey.

The response to questions will be analysed to determine if there is consistency in the maintenance strategy approach across the main continents (America, Europe, Africa, Asia) and WANO centres. (Atlanta, Paris, Moscow, Tokyo). Challenges are expected in obtaining a suitable amount of expert email addresses especially in the eastern regions (India & Pakistan, Russia, China and Korea) and having them respond within the required time to complete the study. For the purpose of this research the limitations of the AHP as discussed in section 2.3.3 will be investigated. The sample size, the relevance of the expert sampling group, the questions and the method(s) for soliciting participation will be discussed in detail. A detailed roadmap of the research methodology approach is provided in Appendix B1.5.

3.2 AHP Model Structure

The analytic hierarchy structure is based on Figure 2.8. Figure 3.1 illustrates the hierarchy model used in this research.

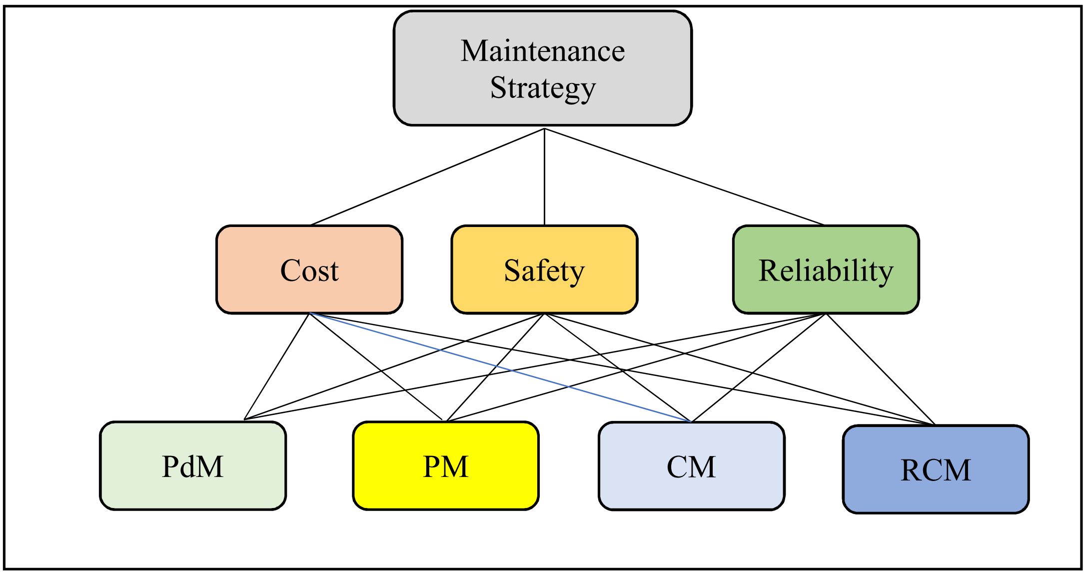

Figure 3.1: Maintenance Strategy Selection Model

Source: Derived from Saaty (1980:13)

3.3 Question Structure

The research methodology centres around questions that are answered via the web-based SurveyMonkey platform. The structure of each question to determine the priority vectors in the AHP model are kept simple to minimise ambiguity and to allow ease of interpretation and understanding. The participants (experts) are required to compare the criteria importance (C_i, C_j, C_k) of:

- Cost to safety,
- Safety to reliability, and
- Reliability to cost.

The participants will also compare each alternative (a_{ij}, a_{jk}, a_{ik}, etc.) with respect to the three criteria, i.e.:

- Compare the importance of PM in relation to CM with respect to cost, or
- Compare the importance of CM in relation to PdM with respect to safety.

The experts are required to select a value from two opposite scales that range from 1 to 9 per the Saaty 9-point scale (Table 2.4) to the left and to the right. See below two examples of the question structures.

"How important is safety when it is compared with cost?" (Kirubakaran & Ilangkumaran, 2016:305).

Safety | | | | | | | | | | | | | | | | Cost

9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

With respect to reliability
How important is PM when it is compared with CM with respect to reliability?

PM | | | | | | | | | | | | | | | | CM

9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

If for example the expert considers safety to be more important than cost, then a number more to the left should be selected. If PM is less important than CM with respect to reliability then the expert should mark the number on the right of the importance level (Kirubakaran & Ilangkumaran, 2016:305). See Appendix 2.1 for the list of survey questions that the experts are expected to complete.

3.4 Research Limitations

This research study has some limitations but still provides valuable information in the selection of a maintenance strategy. These limitations are related mostly to the detail being used in the analytic hierarchy process model. The AHP model in this study uses four of the listed maintenance strategies and three criteria are considered in this model. Additional factors are considered when deciding on a maintenance strategy for a nuclear power plant and could even include socio-economic factors such as the number of reactors being build, the population of the country, the education levels and experience levels of the workers, as well as the availability of the industry required to support the NPP. This study will use a limited number of alternatives and criteria to minimise inconsistency since group discussions do not form part of the study. Entani and Sugihara (2012:379) supports the limiting of alternatives and criteria as they argue that the measurement scale is limited as the AHP model increases its inconsistency value when the criteria and alternatives are increased.

This study however only considers the common maintenance strategies and the most significant factors that impact the decision making of the NPP maintenance function as discussed throughout the literature review. The research is also limited because a select number of surveys are used as input to the AHP model which are grouped into regions. The researcher is not using focus groups to allow for consensus on the answers but instead is using basic statistics to account for a central tendency to each question. These limitations do not invalidate the results and thus do not significantly impact the outcome of the decision but are providing opportunities to expand this study into future research topics, especially within the nuclear field.

3.5 Research Methodology

3.5.1 Research survey team

The researcher opted to select maintenance, work management and engineering experts as these individuals either have significant experience in performing, planning or determining the maintenance strategies. Maintenance staff are very familiar with the preparation and execution of maintenance activities which gives them a unique perspective of the complexities, the risk, the cost, safety and viability of certain maintenance strategies. They have an in-depth knowledge, skill and experience of which maintenance activities work and do not work. They are very familiar with the terminology and understanding of the preventive, corrective and predictive maintenance strategies.

Work management staff are familiar with the scheduling and planning of maintenance activities and thus have expert knowledge on grouping activities to minimise cost, reducing risk and thus improving safety. Work management staff uses risk management tools to plan and schedule activities in a manner which minimises plant unavailability and nuclear safety risk while respecting statutory requirements such as plant operating technical specifications. Work management staff work closely with the operations and maintenance staff to ensure that opportunities to conduct maintenance are optimised.

Engineering uses various models and programs to ensure that the plant is maintained within its operational and design limits. Engineers have the overall accountability to sustain and improve the reliability of the plant with the help of Maintenance and Operating departments. The use of work management, maintenance and engineering experts provide a balanced view in this study.

3.5.2 Questionnaire

The survey questionnaire used in this study contains 23 questions and they are as explained in section 3.2 and Appendix B1.1 similar in nature to using the Saaty L. Thomas 1 to 9-point scale. The first 21 questions will be used as input to the AHP matrix model to calculate the eigenvectors which in turn are the required priorities for this research study. The questionnaire allows the researcher to use the responses and compile several intermediate matrices based on the WANO centre and Continent of the expert. An overall matrix will be compiled from all the responses (irrespective of the WANO centre or Continent) to establish the collective judgement of the experts.

3.5.3 Using the AHP tool

The researcher has opted to use a free web-based AHP tool that is available at www.123ahp.com. This AHP tool allows the researcher to enter the criteria and alternatives as required by this study. The questions used in the survey monkey are also aligned to the way the AHP tool requires the data to be entered in the website application. The AHP application tool is also used to calculate the consistency indexes to indicate which matrix provides the most consistent answers and therefor the most reliable information to base a decision on for a specific region.

According to Ragsdale (2004:809), the AHP model follows a systematic process that includes the following steps:

1. Each criterion will be compared with the other criterion to rank the criteria.

2. The ratings for each decision alternative will be developed using a pairwise comparison with respect to each criterion followed by normalising the resulting matrix and averaging the values in each row to return the preferred rating. These ratings are then used to check the consistency ratio.

3. Develop the weights for the criteria by developing a pairwise comparison matrix for each criterion, normalizing the resulting matrix, averaging the values in each row to get the corresponding ratings followed by calculating and checking the consistency ratio

4. Calculate the weighted average rating for each decision alternative. Choose the one with the highest score as the preferred choice.

The steps below will be used in conjunction with the 123ahp.com web application to analyse the results. The entry of the data will be sequenced as follows in the 123ahp.com web application:

my alternatives:

<alternative 1> = PM
<alternative 2> = PdM
<alternative 3> = CM
<alternative 4> = RCM

my criteria:

<criteria 1> = Safety
<criteria 2> = Cost
<criteria 3> = Reliability

The sequence alternatives and the criteria have to be entered in this sequence to align the survey questions with the web application.

3.6 Data Gathering Survey

The researcher used the email system to distribute the survey link and the letter of consent. The researcher also opted to approach different experts to broaden and diversify the feedback input to the AHP model. The researcher distributed the survey to 40 respondents and attempted to achieve a 60% response rate. A minimum of 4 responses per Continent or WANO centre are selected to allow for meaningful calculations.

The respondents were randomly selected from different regions and field of expertise. A maximum of three weeks was allowed for the questionnaires to be completed. The survey data was entered from the web-survey platform into the web-based AHP model to calculate the matrices for further analysis. Any significant outliers will be identified and explained during the Data Analysis section in chapter 4.

3.7 Assumptions in Research Design

The researcher is assuming that the time allocated for the survey was adequate and that the experts were under no undue pressure to complete the survey. The researcher also assumes that the experts understood the questions and that they have answered it to the best of their own personal view and therefore were not influenced by anyone. The questionnaire is designed to take a maximum of 15 minutes to complete. The researcher assumed that the experts know and understand what each of the terms mean, by defining the terms PM, CM, PdM, RCM, cost, safety and reliability.

3.8 Statistical Data and Usage

The data collected by the researcher is subjective data that is converted through the 9-point measurement into linear data. This data is then used to calculate the basic statistic data such as the arithmetic mean, geometric mean, median and mode. Depending on the distribution of the data, the appropriate central tendency (as explained in Appendix B1.4) measure will be entered in the AHP model to determine the priorities of the matrices. The complexity in the survey answers are embedded in the fact that every question has two criteria being compared resulting in support for both criteria across the various responses.

In order to use Appendix B1.4 to determine the mean of each question, the values of one criterion will be the reciprocal of the other value as listed in Table 3.2. The method for calculating the mean is based on the fact that individuals are assumed to be acting as a unit from a Continent, WANO centre or overall unit. The geometric mean of individual judgments (AIJ) satisfies the reciprocity requirement which implies that "… a synergistic aggregation of individual preferences…" are made "…in such a way that the group becomes a new 'individual' and behaves like one" (Foreman & Peniwati, 1997:169). The criteria mean values will be subtracted from each other to determine the preferred criteria integer value for the matrix calculation.

Table 3.1: Example of determining the Preference scores

Factor	Factor Weighting Score																	Factor
	More Important than								Equal	Less Important than								
A1	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**A2**
A2	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**A3**
A3	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	**A1**

Source: Derived from Bunruamkaew (2012:8)

The consistency index and consistency ratio are calculated to determine the transitivity of the data and whether the judgements between the various experts are consistent. The example above in Table3.1 and below in Table 3.2 illustrates how the expert judgements are entered to form the pairwise matrices. The alternative factor (such as A1 = 5) in the row is preferred and the alternative factor A2 equal 0.2 will then be the reciprocal of this rating.

Table 3.2: Example of Pairwise inputs from Expert Responses

Alternative	A1	A2	A3
A1	1.00	5.00	6.00
A2	0.20	1.00	3.00
A3	0.17	0.33	1.00

3.9 Summary

The selection of the experts was designed to ensure that participants have substantial nuclear expert background in either maintenance, work management or engineering as well as being previous or current members from different WANO centres and Continents. Various methods were used such as emails, direct contact, telephone, LinkedIn, and WhatsApp to solicit the support for the completion of the survey. The data was entered directly by the experts into SurveyMonkey, AHP Maintenance repository which assisted in collecting the required information for each question and provided a basic view of the data distribution per question. The data for each question will be reviewed to determine which central tendency measure to use based on Appendix B1.4.

This chapter discussed the research question structure, AHP model structure, the statistical data, survey, data gathering and research limitations. The basic statistics in Appendix B1.4 is important for the determination of the input data for each question. The questionnaire used on SurveyMonkey is detailed in Appendix B1.2. The researcher used Appendix B1.3 to explain the intent of the survey to the prospective experts. The paid option of SurveyMonkey was used to allow for more than 10 questions to be answered by the experts. The researcher used the calculation of the consistency ratio to determine the transitivity of the judgements and the usefulness of the eigenvectors.

The researcher used question 22 and 23 to determine the difference of judgments per WANO centre and per region. This information was compared with each other and with the overall matrix calculation. Conclusions based on the calculations are drawn that are supported by the literature review. The next chapter details the results from the survey and the data analysis with conclusions as it relates to the existing literature.

CHAPTER 4
RESULTS AND DATA ANALYSES

4.1 Introduction

The development of a maintenance strategy is not an exact science and there are various factors that influences the outcome of any selected strategy. This chapter uses the research methodology explained in chapter 3 to gather the expert judgements to use as input to the AHP model and to determine the priorities of the four selected maintenance strategies (PM, PdM, CM and RCM). The eigenvectors determined by each matrix are evaluated against the literature described in chapter 2 and conclusions are made either in support of the literature or new information is added to the body of knowledge. The information is provided in this chapter or referenced in the Appendices. The researcher starts with the breakdown of the responses obtained from the survey discussed in chapter 3 and use the central tendency measures, the application of the AHP model, the validation of the data and the interpretation of the data to conclude the data analysis.

4.2 Responses and Data Validation

Thousands of skilled and experienced maintenance, engineering and work management workers are available worldwide within the nuclear industry. This research does not require a large number of participants as it does not attempt to achieve consensus but rather to determine a central viewpoint around each comparison that impacts the priorities. Outliers and deviations from the central viewpoint are minimised through the aggregate calculations. Thomas L. Saaty's argues that although group sessions pose special problems it does allow for brainstorming and sharing of ideas and leads to a more complete representation than would otherwise not be possible with single decision makers (Saaty, 1990:225). In the absence of having group sessions the AHP model does lend itself well to elicit judgements through the use of a questionnaire for single decision makers (Saaty, 1990, 225). No research data or literature could be found that supports the need for high participant numbers. Saaty states that "only repetition of the process and continued interaction with the real world can bring the AHP closer to a true representation of the problem…" (Saaty, 1990:251).

This research aimed to obtain 24 respondents (average 6 per continent). A group size of 6 respondents were considered adequate to allow for meaningful central tendency calculations and large enough to prevent bias judgments. A total of 40 survey respondents were invited to participate. Table 4.1 provides a summary of the responses.

Table 4.1: Summary of Responses

Continent	Required	Responded	Percentage
Africa (South Africa)	6	9	150%
Europe (UK, France, Germany, Romania, etc.)	6	4	67%
America (USA, Brazil, Mexico, Canada)	6	5	83%
Asia (India, Pakistan, Russia, China, Korea, Japan)	6	6	100%
Total	24	24	100%

A total of 24 responses were obtained, however a limited number of participants responded from the European and American continents. A minimum of 67% of the required participant number for the survey was deemed acceptable. This research study focussed on two areas namely WANO centres (Paris, Atlanta, Moscow and Tokyo) and the four continents (Africa, America, Asia and Europe).

4.3 Central Tendency Measures

The data being used for this study is referred to as ordinary data and basic statistics such as the arithmetic mean, median and geometric mean calculations can be used to determine the central point for the data sets (refer to Appendix B1.4). Using Appendix B1.4 and reviewing the data collected by the survey the central tendency can be calculated for each question.

Table 4.2 provides the central tendency data and the preferred criteria for the survey responses. This research used multiple expert judgments to be grouped into a single unit for each question and thus the geometric mean is calculated by using the aggregation of individual judgments (AIJ) to satisfy the reciprocity requirement (Formen & Peniwati (1997:166). The data is displayed as integers to allow for entry into the AHP model using the 123ahp.com internet program application. The researcher has opted to use the median as a guide to determine the preferred criteria from the responses and used the geometric mean to determine the input value for each question to aggregate the individual judgments.

Table 4.2: Overall Survey Question Responses

Question	Arithmetic Mean	Median	Geometric Mean	Criteria
Question 1	8	9	8	Safety
Question 2	6	7	4	Safety
Question 3	4	5	2	Reliability
Question 4	3	4	1	PM
Question 5	6	7	5	PM
Question 6	3	3	1	PM
Question 7	4	6	2	PdM
Question 8	3	3	1	PdM
Question 9	4	5	2	RCM
Question 10	4	3	2	PdM
Question 11	6	7	5	PM
Question 12	3	4	1	RCM
Question 13	5	5	3	PdM
Question 14	3	3	2	PdM
Question 15	4	5	3	RCM
Question 16	3	1	1	PdM
Question 17	7	8	7	PM
Question 18	4	3	2	PM
Question 19	5	7	3	PdM
Question 20	4	5	2	PdM
Question 21	2	5	3	RCM

The median allows the researcher to identify what the respondent's preference criteria is while the geometric mean provides a reasonable calculation for skewed data that range from 0.11 (1/9) to 9 and thus provides a meaningful central tendency value. The geometric values along with the criteria preferences in Table 4.2 will be used to calculate the overall maintenance strategy preference of the respondents. The 1 to 9-point scale is ideally suited for using the geometric mean as this scale does not have a zero value. Similar calculations are used for determining the WANO centre and

Continent preferences. Refer to Appendix B1.4, Appendix C1.4.1 and Appendix C1.4.2 for further understanding of the input data.

4.4 The AHP Model Data Analysis

Each matrix calculation is unique and each calculation per WANO centre and per Continent will be discussed in this section. The consistency index, consistency ratio, criteria ranking, and preferred alternative are determined for each matrix.

4.4.1 Results of the overall maintenance strategy survey

Using the geometric mean data and the criteria from Table 4.2 as input data for the AHP model the following results are obtained. The consistency index (CI) and the consistency ratio (CR) for the criteria is 0.01% and 0.02% respectively which indicates that the criteria data is very consistent, and the expert input can be trusted. The negative sign implies that the maximum eigenvalue scalar (λ_{max} = 2.9998) was slightly smaller then the number of criteria used as it applies to equation 2.2 in section 2.3.1.

Table 4.3: Criteria Preference Results

criteria preferences	Safety	Cost	Reliability
Safety	1.00	8.00	4.00
Cost	0.13	1.00	0.50
Reliability	0.25	2.00	1.00
CI: -0,0001 CR: -0,0002 λ: 2,9998			

This is potentially as a result of the rounding of some of the central tendency values. The alternatives with respect to safety, cost and reliability show similar inconsistency ratios of less than 8% as listed in Appendix A1.1 to Appendix A1.3.

These low inconsistency values provide reasonable assurance that the judgements used in the AHP model can be trusted as reasonably reliable. The maintenance strategy selected by the experts is the preventive maintenance strategy (35.3%) followed by the predictive maintenance (29.33%) and reliability centred maintenance (25.27%). It can be concluded that although the preventive maintenance is judged to have the secondbest cost weight, it remains the preferred choice for the maintenance strategy. The nuclear maintenance experts do not seem to prefer the corrective maintenance strategy as it only received an importance preference of 10.11%. The results displayed in Table 4.5 indicates that preventive maintenance received the highest preference when it comes to safety and reliability. The nuclear experts assigned a high weight value (72.73%) to the safety criteria in comparison to the other criteria. The reliability (18.18%) and cost (9.09%) criteria received low weight values which could potentially be attributed to a common view held by nuclear experts that safety is the overriding priority in all nuclear aspects. See table 4.4 below for the criteria ranking.

Table 4.4: Overall Survey Criteria Ranking

Ranking of Criteria	Result
Safety	0,7273
Cost	0,0909
Reliability	0,1818

It is coincidental that the corrective maintenance strategy and the importance of the cost criteria receiving the same percentage consideration. The results displayed in Table 4.5 indicates that preventive maintenance received the highest preference when it comes to safety and reliability. The overall consistency ratio (CR) for all the responses were 0.0247. This indicates that the experts were highly consistent in their preference of this survey problem and thus it can be inferred that the scores obtained from the matrix is reasonably accurate and the AHP model yielded meaningful results (Ragsdale, 2004:812).

The predictive maintenance strategy and the RCM strategy scored high and have a combined preference value of 54.6%. This is significant seeing that RCM is a maintenance philosophy that determines the most effective approach to achieve an optimal maintenance strategy mix (Huang *et al*., 2012:1015, IAEA, 2002:69; NASA, 2008:3-1).

Table 4.5: Final Alternative Ranking Results

Alternatives rankings	Safety	Cost	Reliability	Result
PM	0,2547	0,0250	0,0733	0,3530
PdM	0,1965	0,0369	0,0599	0,2933
CM	0,0796	0,0078	0,0137	0,1011
RCM	0,1965	0,0213	0,0350	0,2527

Table 4.5 also indicates that maintenance experts do not view preventive maintenance strategy as the only maintenance strategy, but that a combination of preventive, corrective and predictive maintenance of which RCM contributes to selection of the overall strategy mix is required. Corrective maintenance ranks last and only score 10.11% as it is not a preference due to cost, safety and reliability where it scored the lowest amongst the maintenance strategies.

Table 2.1 provides the advantages and disadvantages of preventive, predictive, corrective and reliability centred maintenance and some understanding of the benefits and drawbacks of the maintenance strategies to make informed decisions. It is evident from the research performed by NASA, Žilka, IAEA and Huang *et al.* that PM and RCM rank high on nuclear safety while CM is relatively low with predictive being medium. This research found similar results except that predictive maintenance is also relatively high and on par with the RCM maintenance strategy where safety is concerned. This slight difference could be explained with this research being performed on a different industry to ones investigated by the authors mentioned above and possibly due to the trend seen in the nuclear industry where the maintenance strategies are moving towards predictive maintenance. Value Based Maintenance (VBM) is shifting the focus from intrusive maintenance (preventive) to predictive maintenance focusing on a smaller amount of equipment that are critical to nuclear safety and reducing total maintenance cost while maintaining required reliability (NEI, 2018; NEI, 2017:5).

RCM and PdM strategies are ranked as the low-cost strategies in Table 4.6 for minimising cost, while CM is ranked as a high cost maintenance strategy. Preventive maintenance is rated as a medium cost strategy as cost is involved but this goes to planned cost and not unforeseen breakdown cost. Nuclear Energy Institute supported this view by stating that "simply reducing preventive maintenance will likely not reduce costs if it results in increased corrective maintenance, reduced safety or reliability, or increased regulatory scrutiny" (NEI, 2017:2). Table 4.6 is an adaptation of Table 2.1 with the results from Table 4.5 incorporated to contrast the research results against the literature review.

Table 4.6: Survey Results of Maintenance Strategies vs Literature Results

	Advantages and Disadvantages		
	Component Reliability	**Overall Cost**	**Nuclear Safety**
Maintenance Strategy	**High, Medium, Low**	**High, Medium, Low**	**High, Medium, Low**
CM – Literature -Table 2.1	Low	High	Low
CM – Research – Table 4.5	Low	High	Low
PM– Literature -Table 2.1	High	Medium	High
PM – Research – Table 4.5	High	Medium	High
RCM - Literature -Table 2.1	**High**	**Low**	**High**
RCM – Research – Table 4.5	**Medium**	**Medium**	**Medium**
PdM – Literature -Table 2.1	**Medium**	Low	Medium
PdM – Research – Table 4.5	**High**	Low	Medium

This survey concluded that PdM has the highest weighting for cost and thus is the preferred option as a maintenance strategy from a cost perspective. RCM and PM were found to be relatively on par as a medium cost strategy in this research and CM was the most cost significant maintenance strategy. There is thus some similarity between the other studies except for RCM being a medium cost strategy in this research and not being a low-cost strategy. This is potentially due to PM having a significant weighting on RCM as can be seen in Appendix C1.2.

Figure 4.1 supports the idea that the PM strategy can be both beneficial and negative from a cost and reliability perspective.

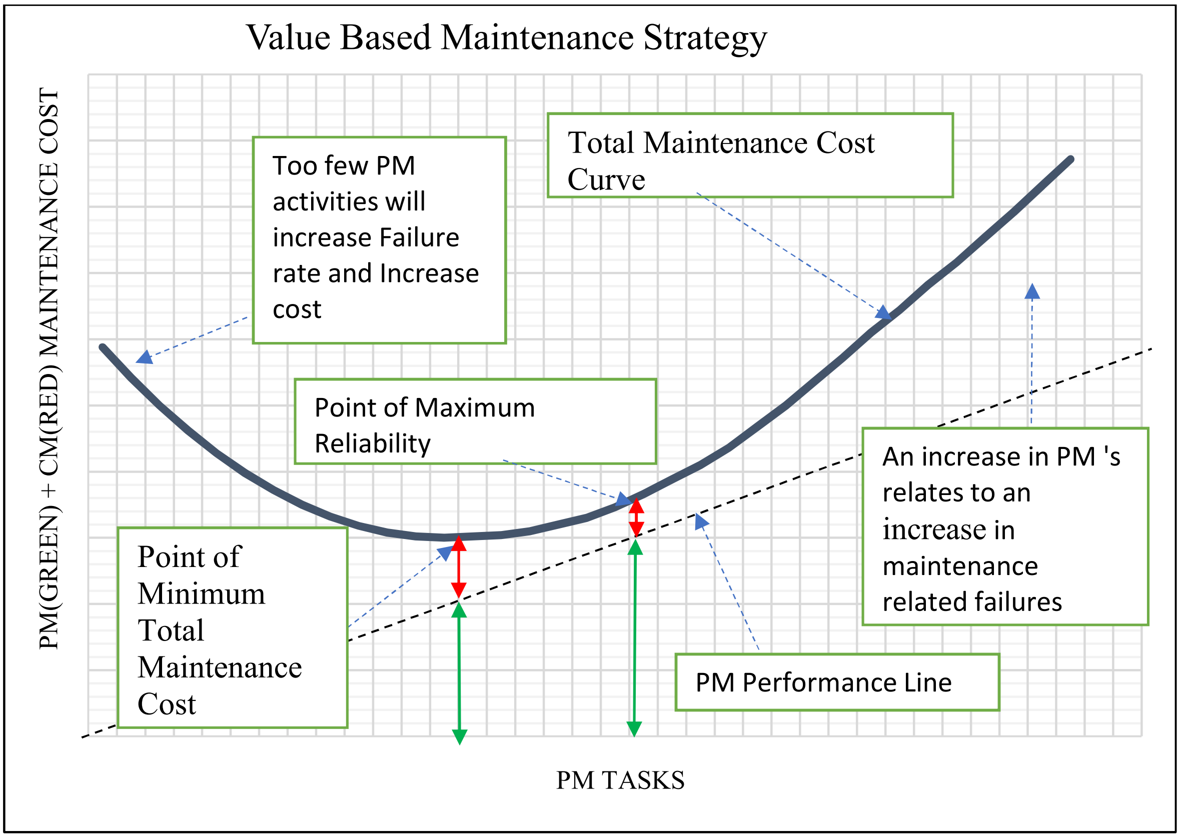

Figure 4.1: Value-Based Maintenance Strategy

Source: Derived from NEI (2017:7)

The value-based maintenance philosophy centres around the idea that an optimal mix of PM and CM needs to be obtained to ensure that maximum reliability and minimum cost is derived. Table 4.5 in this survey supports this philosophy in that the results reflect that to obtain an effective maintenance strategy, almost 90% preference is assigned to PM, PdM and RCM and only about 10% preference is assigned to CM. In order to minimise the cost and not to over or under maintain equipment in a nuclear power plant the division between PM, PdM and RCM is almost 30% each. The point of maximum reliability can be achieved where the CM is the lowest while the PM is not too high and not too low. Figure 4.1 explains why the nuclear experts supported the maintenance strategy mix and why CM received a low weighting because reliability and optimised cost is not synonymous with the CM strategy. This coincides with the literature as depicted in Figure 2.6 and 2.7.

This research study also found that the highest reliability criteria were assigned to the PM and PdM strategies which have respective weighting values of 0.0733 and 0.0599. The CM strategy has the lowest reliability weighting with RCM almost three times better at 0.035. The difference between this research study and the studies provided in Table 2.1 is the fact that PdM and RCM weighing for reliability is the opposite for what was found in those studies. This is potentially based on the current narrative in the nuclear industry that preventive maintenance (a sub-component of RCM) is not always effective to ensure reliability as components that are maintained still fail and that predictive maintenance performed on specific important components ensure greater reliability. Figure 4.1 illustrates this phenomenon where preventive maintenance can still lead to loss of reliability and increase cost.

4.4.2 Results for Continents

Respondents from each continent viewed the criteria for the alternatives differently and assigning weights to each of these criteria impacted the overall outcome of the preference. Africa, America and Asia respondents have provided overall CR's of 0.0714, 0.0789 and 0.0230 which indicates that the data can be trusted. Appendix C1.6 also provides criteria preference CR's of 0.0337, 0.0334 and 0.0334 for Africa, America, Asia respectively which is an indication of strong transitivity in the criteria ratings. Europe has a criteria preference CR value of 0.2090. This adds to the overall inconsistency value of 14.85% for Europe which indicates that the criteria ratings provided by this category of experts are unreliable and thus cannot be used for meaningful decision making.

Safety (see Appendix C1.6) is the criteria with the highest weighting although Africa had the lowest score (63.01%) amongst the Continents. This does not imply that Africa does not value safety as much as the other continents, but it is merely an indication that consideration was given to the other criteria in the context of this survey exercise. African judges assigned the highest weighting in the criteria of reliability (26.14%) in relation to the other continents. This is almost double the weighting of any of the other continents. This also does not imply that the other continents do not value reliability. These values are merely relative to the survey question and the criteria being used and no further inference should be drawn on the intermediate calculations. Cost across the Continents received the lowest criteria weighting with Europe (14.63%) having the highest value and America & Asia receiving the lowest value (8.13%). The values of Europe do not have good transitivity and thus these values can be ignored for this continent. No further statements or consideration regarding the European results will be made.

Table 4.7: Continent – Alternative Preference Results

Continent	African Results	American Results	Asian Results	European Results
PM	0,3987	0,1876	0,4428	0,4213
PdM	0,2687	0,4595	0,2302	0,2833
CM	0,1002	0,0509	0,1010	0,2018
RCM	0,2323	0,3020	0,2260	0,0936
Safety CI	0,1285	0,0941	0,0068	0,0202
Safety CR	0,1444	0,1057	0,0077	0,0227
Cost CI	0,0201	0,1074	0,0405	0,3803
Cost CR	0,0225	0,1207	0,0455	0,4274
Reliability CI	-0,0001	0,0846	0,0474	0,2597
Reliability CR	-0.0001	0,0950	0,0533	0,2918

Table 4.7 provides the alternative preferences and the consistency ratios for each criteria's intermediate calculation. Africa has a safety criteria inconsistency percentage of 14.44% which is high and indicates that some uncertainties in the judgments exist. Respondents from Africa and Asia prefer the preventive maintenance strategy above the other three strategies as it achieved 39.87% and 44.28% respectively. American respondents on the other hand placed stronger preference on the predictive maintenance strategy with a percentage of 45.98%. All three continents have assigned very little preference to the corrective maintenance strategy with values ranging between 5% and 10%. Africa and Asia prefer relatively similar values for predictive and reliability centered maintenance strategies which shows some alignment between these continents. America only has 18.76% preference for the preventive maintenance

strategy. This is low in comparison to the other countries and could imply a different view to the maintenance strategy.

Since the initiation of "Delivering the Nuclear Promise" (DNP) in 2015, the USA has started to drive its nuclear power industry to strengthen safety and reliability while implementing efficiencies to minimise cost for nuclear power plants (NEI, 2018). This initiative has sparked an objective to redefine which components are critically important for plant safety and reliability and limit the maintenance on non-critical components and thereby reducing the number of maintenance related failures (NEI, 2018). This partly explains why the American respondents value the PdM strategy more as this initiative have not yet filtered through to the rest of the nuclear industry.

4.4.3 Results for WANO centres

The consistency ratio for the Atlanta and Tokyo WANO centres were calculated using a similar method as described in section 4.4.2. Insufficient response numbers or data were obtained to perform meaningful calculations for the Paris and Moscow WANO centres and thus no calculations were performed for these WANO centres. The Atlanta WANO Centre and the Tokyo WANO centre has overall consistency ratios of 0.0466 and 0.0485 respectively. The criteria preferences inconsistency percentages of 0.89% and 10.04% for Atlanta and Tokyo were respectively calculated. The inconsistency level for the WANO Tokyo criteria of greater than 10% brings uncertainty to the criteria judgments.

Safety as tabulated in Appendix C1.6 also received the highest weighing scores of 69.42% and 77.66% for Atlanta and Tokyo WANO centres respectively. The Tokyo WANO centre score is unfortunately questionable as the inconsistency percentage is 10.04% which cast doubt over the transitivity of the judgements. Atlanta has a cost criteria weight of under 10% and a reliability criterion weighing of above 20%. Refer to Appendix C1.9 to see how the maintenance strategies for the WANO centres relates to the criteria rankings. Both the WANO Tokyo and WANO Atlanta criteria inconsistency calculations have uncertainties in the judgements which means that further investigations are required.

Table 4.8 provides the alternative preferences and the consistency ratio for each criteria's intermediate calculation of the WANO centres.

Table 4.8: WANO - Alternative Preference Results

Continent	WANO Atlanta	WANO Tokyo
PM	0,4611	0,5190
PdM	0,2129	0,2128
CM	0,1050	0,0695
RCM	0,2210	0,1985
Safety CI	0,0806	0,0089
Safety CR	0,0906	0,0100
Cost CI	0,0203	0,0717
Cost CR	0,0228	0,0805
Reliability CI	0,0154	0,0270
Reliability CR	0,0173	0,0303

Both Atlanta and Tokyo WANO centres prefer the preventive maintenance strategy. Atlanta respondents has a preference of 46.11% and Tokyo has a preference of 51.90%. Atlanta and Tokyo have almost identical preferences (21.3%) for predictive maintenance and a RCM preference of around 20%. Atlanta and Tokyo have low preference for corrective maintenance with 10.5% and 6.95% respectively. The consistency ratios for all the criteria are below 0.1 and the overall inconsistency is below 5% for Atlanta and Tokyo WANO centres.

4.5 Summary

The results indicate that the judgments of the experts to calculate the overall maintenance strategy preferences can be trusted as the inconsistency value is below 10% (CR = 0.00247). The same can be said for the Asia, WANO Atlanta and WANO Tokyo centres. The result also highlights the importance of safety as an input criterion when determining a maintenance strategy as well as the need for establishing a mix in the maintenance strategy. It can be concluded that although corrective maintenance is not a preferred strategy within the nuclear industry it is a necessary part of the maintenance strategy mix as it prevents unnecessary maintenance from being performed on non-critical components that do not have safety or reliability implications.

The inconsistency ratio of 0.89% for WANO Atlanta and 10.04% for WANO Tokyo centres are showing the homogeneity and relevance of the judgement differences between the Atlanta and Tokyo centres. A closer look at the Atlanta and Tokyo input responses revealed that most of the questions have relatively similar results except for question 2. Question 2 from Appendix B section 1.1, "How Important is the safety when it is compared with reliability?" have shown differences between the two WANO centres. An iterative process to examine the extent to which question 2 had an influence on the outcome of the inconsistency ratio identified the significance of the question 2 responses. Changing the WANO Tokyo centre response for question 2 to three or five brings about an inconsistency ratio of 2.77% or 1.33% respectively. The analysis of this result affirms the theory that WANO Atlanta Centre utilities are focusing on "delivering the nuclear promise" by increasing reliability and safety. WANO Tokyo centre respondents seem to be lagging behind WANO Atlanta in adopting this approach and places higher emphasis safety over reliability.

All Continents and WANO centres are consistent on safety carrying the highest weighting and PM being the preferred maintenance strategy except for the American continent that prefers the predictive maintenance strategy. The American intermediate calculations highlighted some inconsistencies that are not acceptable although the overall inconsistency ratio for the American Survey is 7.89%. Closer scrutiny of the results show that the American alternative preferences differs significantly from the other Continents and the criteria inconsistency ratios for safety and cost were 10.57% and 12.07% respectively. This discrepancy between inconsistency values of the American overall result and its intermediate steps (criteria) shows that the American judgements were not consistent for each criterion relative to the Alternative options. This means that the American decision makers made mistakes when they evaluated the four maintenance strategies with respect to safety and cost but not when they performed a pairwise comparison between the criteria.

The research data supports the base arguments of the current literature and add new perspectives as it is performed within the nuclear industry. Several of the judgements especially the intermediate steps resulted in unacceptable high inconsistencies. Saaty referred to this as “a concern of uncertainty” that exists within the AHP model (Saaty, 2008:83).

CHAPTER 5
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and Conclusion

Maintenance strategies aim to improve nuclear safety and reliability while optimising or reducing cost. Most maintenance strategies are evaluated on three criteria namely safety, cost and reliability and some studies may add availability. The international Atomic Energy Agency established that there is an optimal maintenance strategy applied to nuclear plant equipment to minimise cost but sustain desired reliability standards (IAEA, 2007:23; Wang ,2006:7444). This research has found that selecting a maintenance strategy is not a straight forward decision and that the criteria weighting significantly influence the preferred strategy. Furthermore, there is no single strategy that fits all situations or industries. The best option for new nuclear power plants seems to be a combination of maintenance strategies to leverage the advantages of each strategy and minimise their disadvantages. The research supports existing knowledge of other studies with regard to the advantages and disadvantages of maintenance strategies but differs where it concerns reliability-centered maintenance (refer to Table 4.6).

Nuclear experts do not believe that preventive maintenance is a guaranteed failure prevention strategy, thus the need for the other three strategies to complement it. It was however surprising that the RCM strategy was not the overall preferred maintenance strategy for the nuclear experts given that it is a philosophy that prioritises the required maintenance activities and frequencies to optimise cost, reliability and safety (Eti, 2002:2). This is possibly based on the fact that not every participant understands the fundamental philosophy of the RCM strategy or the fact that RCM is co-dependent on the other three strategies. Paulsen (2002:2) stated that RCM focusses on establishing a comprehensive inclusive maintenance strategy that takes advantage of the respective strengths of preventive, predictive and corrective maintenance strategies to maximize equipment reliability, minimizing cost, improving plant safety and increasing productivity. The argument for nuclear power plants might be slightly different and that the RCM strategy might require further research using the AHP model.

The experts from the different continents do differ on their preference but the overall preferred maintenance strategy remains the preventive maintenance strategy for the nuclear power industry. Previous studies (in the power plant and oil refinery industries) have come to similar conclusions where the PM strategy is the preferred maintenance strategy as seen in Appendix A1.2. This research study has also shown that the weighting of the three criteria are dominated by the safety criteria in all three calculations of the overall result, the WANO centres and the continent analysis. This is due to the fundamental belief and philosophy in the nuclear industry that safety is the overriding priority. The literature review supports the selected criteria for nuclear power plants and the results obtained in this research highlighted the impact that these criteria have on the selected preference. The inconsistencies seen in the European and American judgments require further investigation. An option could be to analyse the judgment of each individual and eliminate those with high inconsistencies.

The AHP model has supporters and critics but it has proven to be a highly reliable and very effective model for decision making problems. The AHP method used in this research study proved useful and allowed the researcher to investigate and analyse the intermediate steps of the process to better understand and conclude on the overall result. In this study various sub-categories of the survey were explored to determine the consistency across the various continents, the WANO centres and the expert responses. This research established that most of the calculations are reliable expert judgments in that the data has adequate consistency to draw conclusions. These conclusions were supported by the literature and in some instances provided a different perspective to existing literature knowledge. Group judgments were not used in this study, but each individual judgment was taken to calculate the geometric mean to determine the central tendency for each comparison preference. Saaty (1987:174) believes that group judgments can be resolved through consistency checks when people score radically different. The researcher eliminated different scores by first calculating the median to determine the preference and then calculating the geometric mean by taking all the results into account using the example provided by Bunruamkaew (2012:8). The results of the AHP analysis does not prescribe which maintenance strategy should be selected but merely indicates which alternative is preferred based on the criteria (safety, cost and reliability) that was selected. The benefits and limitations of using the AHP model was discussed in detail and the researcher managed the limitations of the AHP model by using the Saaty 9-point measurement scale that allowed the use of the geometric mean, calculated the consistency ratios to determine transitivity and avoided the rank reversal phenomenon by limiting the AHP model to three criteria in one level.

This study explored the different maintenance strategies and their advantages and disadvantages. The nuclear industry is moving towards initiatives that minimise intrusive interventions and or limiting it to critical components that are essential for safety and reliability. Most nuclear experts in the survey do not favour corrective maintenance as an effective strategy. The European respondents were the only respondents that placed preference on cost and the CM strategy, but their comparisons were not useable due to the high judgment inconsistencies. Predictive maintenance and reliability-centered maintenance are viewed by the experts as important alternatives and key to the maintenance strategy mix.

The nuclear industry is challenged by low cost electricity generating options such as the use of shale gas. Several nuclear power plants have closed in the USA due to high costs. More than a quarter of the nuclear industry cost is made up of operating and maintenance costs. Nuclear power plants are very capital-intensive projects that require low operating and maintenance cost structures to allow for early payback to investors or shareholders. The development of effective maintenance strategies using the value-based maintenance principles allows for maintenance cost reduction while improving nuclear safety and improving reliability. The nuclear industry is moving away from maintaining every component and is starting to focus on the critical components while maintaining the regulatory requirements. The opportune time to develop an optimal living maintenance strategy is during the construction phase prior to operation of a nuclear power plant considering industry best practices (INPO AP-913), regulatory requirements, company needs, manufacture specifications, expert judgments and other requirements (INPO, 2013:64). The entire maintenance strategy seeks to address the nuclear requirements as stipulated by the regulators which is to maintain nuclear safety and reliability. It is therefore not surprising that the experts assigned an almost equal split in preference to the PM, PdM and RCM strategies not to guarantee reliability but to preserve reliability and safety.

This study reaffirms that nuclear safety is the overriding priority for nuclear experts and that an effective combination of maintenance strategies will improve reliability and reduce cost. Analysing the survey results against the literature, it is clear that the maintenance strategy selection affects the organisations operating cost, plant safety and equipment reliability. Optimising the maintenance strategy also affects the long-term safe operation (LTSO) and viability of the nuclear power plant. Since the maintenance activities include monitoring, surveillance, inspection, testing, calibration, service, overhauls, repair and replacements of parts it is essential that SSC's are maintained within the bounds of the nuclear power plant (CNSC, 2012:1).

Maintenance programs are designed to ensure that watershed moments such as the Davis-Besse incident do not occur, where inspection surveillances on the reactor head were delayed and boric-acid built up to the point where the resultant corrosion problem were ignored and not corrected posing a nuclear safety risk (Nelson-Burns, 2004:269). These types of nuclear incidents serve as reminders for the nuclear industry why it is important to consider safety above all other priorities and why effective maintenance strategies are important from a safety perspective. The selection of any maintenance strategy has far reaching consequences and the initiatives to use the VBM initiative along with a systematic approach to maintenance on critical SSC's to improve cost, reliability and safety has become inevitable for nuclear power plants to survive in the future energy market.

5.2 Recommendations

This research was conducted during the construction phase of a nuclear power plant which is an ideal time to consider an optimum maintenance strategy. The research was also done by individuals completing surveys and thus no group discussions occurred. The following actions could be taken to address future research in this area:

- Groups from various WANO centres could be asked to conduct focus sessions on this topic and to complete a similar survey;
- Future research could explore expanding the criteria and adding sub-criteria for each of the criteria to provide a more comprehensive analysis into what consideration is taken when determining a maintenance strategy;
- Actual maintenance strategy mixes could be compared against industry expert opinions and the basis for these maintenance strategies could be analysed to understand the underlying factors that drive these decisions that differ from the literature;
- To achieve greater consistency, the sample size could be increased and outliers eliminated.
- To allow the AHP to close the gap to the real world is to repeat the study in multiple regions and analyse the similarities and differences in the decisions.
- Finally, although this research showed some inconsistencies for Europe and America participants, it would be worthwhile to explore why Europe respondents tend to prefer CM and American respondents prefer PdM.

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Appendix A: Literature Tables

1.1.1 Maintenance Strategy Advantages and Disadvantages

Maintenance Strategy	Advantages	Disadvantages
Corrective Maintenance	Less demand on inspections, diagnostics and maintenance that results in lower cost	Increased cost due to unplanned downtime resulting in repair and replacement of equipment.
	Less staff required to manage and plan maintenance activities	Increased cost due to unplanned downtime of equipment.
		Inefficient use of staff resources with unsystematic approach to planning
		Failures can lead to higher losses
Preventive Maintenance	Flexibility allows for the adjustment of maintenance periodicity.	Labor intensive.
	Increased component life cycle and energy savings	Includes performance of unneeded maintenance.
	Possibility of implementation of systematic maintenance management and maintenance planning	Potential for incidental damage to components in conducting unneeded maintenance.
	Reduced equipment or process unexpected failures due to timely, routine repairs that circumvent fewer large-scale repairs.	High demands on resources: tangible, intangible (software support), human (maintenance staff)
	Estimated 12% to 18% cost savings corrective maintenance	High direct maintenance costs (spare parts, maintenance staff wages, outsourced
	Reduced production downtime, resulting in fewer machine breakdowns.	Parts are replaced too late, which may cause deterioration in the quality of production,
	Better conservation of assets and increased life expectancy of assets, thereby eliminating premature replacement of machinery and equipment.	
	Reduced cost of repairs by reducing secondary failures. Improved safety and quality conditions.	

Source: Fredriksson & Larsson (2012:47); NASA (2008); Žilka (2014:210)

1.1.2 Maintenance Strategy Advantages and Disadvantages (continues)

Maintenance Strategy	Advantages	Disadvantages
Predictive Maintenance	Increased component operational life/availability.	Increased investment in diagnostic equipment.
	Allows for pre-emptive corrective actions.	Increased investment in staff training.
	Decrease in equipment or process downtime.	Savings potential not readily seen by management.
	Decrease in costs for parts and labour.	High costs of diagnostics equipment and software tools
	Better product quality.	Increased demands on staff in servicing diagnostics equipment and software tools
	Improved worker and environmental safety.	Worse possibility of maintenance planning and coordination with the production plan
	Improved worker morale and energy saving with cost reduction of 8% to 12% over preventive maintenance program.	
	Outages and maintenance procedures are carried out based on actual technical condition	
Reliability-Centered Maintenance	Greater maintenance cost-effectiveness: The activities which have the highest impact on the plant's performance are in focus. This helps to ensure that maintenance resources are spent where it will do the most good.	
	The use of on-condition maintenance techniques is emphasized to optimise the useful life of expensive equipment.	
	Greater safety and environmental integrity:	
	A comprehensive database and records of maintenance requirements of all the significant assets available when an RCM review is finished.	
	Increased motivation of individuals: The RCM process and review provides an improved understanding of the assets and also a wider "ownership" of maintenance problems.	

Source: Fredriksson & Larsson (2012:47); NASA (2008); Žilka (2014:210)

1.2 Maintenance Strategy Selection Related Articles and its Results

References	Area	Strategies	Criteria	Method	Result
Pourjavad *et al.* (2013)	Mining industry	Design out maintenance (DOM), total productive maintenance (TPM), CBM, TM, emergency maintenance (EM)	Reliability, availability, maintainability and cost	ANP and TOPSIS	CBM
Tan *et al.* (2011)	Oil refinery industry	RCM, CM, CBM and PrM	Safety, cost, added value and feasibility	Risk based inspection and AHP	
Arunraj & Maiti (2010)	Chemical plant	EM, CBM, TM and CM	Cost and risk	AHP and GP	CBM
Wang *et al.* (2007)	Power plant	CBM, TBM, CM, PrM	Feasibility, added value, cost and safety	Fuzzy AHP	PM
Bertolini & Bevilacqua (2006)	Oil refinery industry	PrM, PM, CM	Detectability, occurrence and severity	AHP and GP	PM
Al-Najjar & Alsyouf (2003)	Paper Mill (i) Bearing (ii) Pump Station	Vibration-based maintenance (VBM), failure based maintenance (FBM), PrM, reliability centered maintenance (RCM), TPM, CBM, total quality maintenance (TQM)	Considering 13 criteria	Fuzzy MCDM	TQM FBM
Bevilacqua & Braglia (2000)	Oil refinery industry	Opportunistic maintenance (OM), CM, PrM, CBM, PM	Cost, added value, applicability and damages	AHP coupled with sensitivity analysis	CM
Kirubakaran & Ilangkumaran (2016)	Paper industry	CM, PM, TM, CBM	Safety, cost, added value and feasibility	FAHP with GRA–TOPSIS	PM

Source: Kirubakaran & Ilangkumaran (2016:305)

Appendix B: Research Methodology

1.1 Research Questions

Use the Saaty 1 to 9-point scale to define the importance of alternative by criteria:

Q1 How important is the safety when it is compared with cost?

Q2 How important is the safety when it is compared with reliability?

Q3 How important is the cost when it is compared with reliability?

With respect to Safety

Q4 How important is PM when it is compared with PdM

Q5 How important is PM when it is compared with CM?

Q6 How important is PM when it is compared with RCM?

Q7 How important is PdM when it is compared with CM?

Q8 How important is PdM when it is compared with RCM?

Q9 How important is CM when it is compared with RCM?

With respect to Cost

Q10 How important is PM when it is compared with PdM

Q11 How important is PM when it is compared with CM?

Q12 How important is PM when it is compared with RCM?

Q13 How important is PdM when it is compared with CM?

Q14 How important is PdM when it is compared with RCM?

Q15 How important is CM when it is compared with RCM?

With respect to Reliability

Q16 How important is PM when it is compared with PdM?

Q17 How important is PM when it is compared with CM?

Q18 How important is PM when it is compared with RCM?

Q19 How important is PdM when it is compared with CM?

Q20 How important is PdM when it is compared with RCM?

Q21 How important is CM when it is compared with RCM?

Q22 Please select your continent where you obtained most (more than 60%) of your experience.

Q23 Please state the department your experience mostly relate to (Maintenance / Work management / Engineering).

1.2 Research Participation Request

Dear Maintenance / Engineering Expert,

Re: Participation in Research on Maintenance Strategies

I am a part-time MSc student in the School of Mechanical, Industrial and Aeronautical Engineering at the University of the Witwatersrand, under the supervision of Dr Timothy Hutton. My MSc title is: An AHP Model Approach to selecting a Maintenance Strategy for a new Nuclear Power Plant.

My belief is that the maintenance strategies are dependent on a range of factors relating to culture, work ethics, spare resources availability but it is mostly dependent on safety, reliability and cost for nuclear power plants. I would specifically like to understand the impact that cost and reliability has on the selection of a maintenance strategy of a nuclear power plant.

I would like to invite you to participate in this study. As a maintenance or engineering expert, your knowledge and experience would contribute significantly. Specific Nuclear power stations are not reported in this research and thus this research have no relation to any Nuclear Power Station.

The study will be conducted between October 2018 and 15 November 2018. Involvement in the study would entail completing the linked survey at your earliest convenience. Participation in the study is voluntary, and you may withdraw at any time. Anonymity and confidentiality of information provided will be assured and respected.

The results of the study will form part of my MSc research report and may also be reported in academic papers and at conferences.

Please contact me if you have any questions regarding the research and participation in the study.

I look forward to hearing from you.

Yours faithfully

Andy Irvin Joseph (1802239)
University of the Witwatersrand
Johannesburg, South Africa
Private Bag 3, WITS 2050, South Africa
Tel: +971 50 569 2635 Email: kj10black@hotmail.com
Supervisor: Tel: +27 (0) 11 717 9027. Email: Timothy.Hutton@wits.ac.za

1.3 Letter of Consent

I, ____, agree to participate in the MSc research entitled An AHP Model Approach to selecting a Maintenance Strategy for a new Nuclear Power Plant. to be undertaken by Andy Joseph under the supervision of Dr Timothy Hutton and certify that I have received a copy of this letter of consent.

I acknowledge that the research has been explained to me and I understand what it entails, as follows:

1. I have the right to withdraw my assistance from this project at any time without penalty, even after signing the letter of consent.
2. I have the right to refuse to answer one or more of the questions without penalty and may continue to be a part of the study.
3. I may request a result summary.
4. I am entirely free to discuss issues and will not be in any way coerced into providing information that is confidential or of a sensitive nature.
5. This project was approved by the Faculty of Engineering and the Built Environment of the University of the Witwatersrand and the School of Mechanical, Industrial and Aeronautical Research Ethics Committee (non-medical) of the University.
6. If I have any questions or concerns about my rights or treatment as a participant, I may contact the Chair of the School of Mechanical, Industrial and Aeronautical Research Ethics Committee (non-medical) of the University of Witwatersrand, Johannesburg.

Signed:

____

Date:

____

1.4 Basic Statistics: Central Tendency

Central tendency refers to a single statistical measure that provides a rough estimate of the centre of an entire data set (Deshpande *et al.*, 2016:64; Manikandan, 2014:140). Streiner (2000:834) and Deshpande *et al.* (2016:64) states that the mean, median and mode are the most commonly used measures of central tendency.

The **arithmetic mean** also commonly referred to as the average of a set of numbers refers to the calculation of the mid-point by adding all the values in the data set and dividing it by the number of the values (Manikandan, 2014:140).

The mean is given by the formula:

$$\text{Mean} = \frac{\sum X}{n} \qquad \ldots\text{B.1}$$

Where, $\sum X$ refers to summation of the individual values and n is the number of the values in the sample (sample size). E.g. 15, 2, 9, 3, 2, 10, 1. Using equation B.1 we can calculate the mean as follows:

$$\text{Mean} = \frac{\sum X}{n} = \frac{42}{7} = 6$$

The **median** is middle value of a data set once the numbers of the data set have been put in ascending or descending order (Harrison *et al.*, 2015:320). If there are an even number of values in the data set, the median value is the mean of the 2 middle values (Schindler, 2015:32). Using the same example above the median requires the numbers to be ordered. E.g. 1, 2, 2, 3, 9, 10, 15. The median in this case is 3 as it is the value in the middle of the data set. The **mode** is referred to as the most common occurring value in the data set (Harrison et al, 2015:320, Schindler, 2015:31). Using the same example above, the mode will be the value 2 as it is the number that is the most frequent in the data set.

Another way to calculate rational data means is to use the geometric mean. Geometric mean has been supported by the AHP community for aggregating the expert responses and is a term that is also referred to as the Logarithmic Least Squares Method (Alessio & Ashraf, 2009:12). The geometric mean will minimize the sum of errors and is calculated by multiplying the values in the dataset and taking the n-root of the product of these values where n is the number of values being multiplied.

Figure B1. below provide three different graphs to illustrate the differences between the mean, median and mode. In (a) the data have a normal symmetrical distribution and the mean, median and mode is the same. In (b) the data are negatively skewed with the mean being smaller than the median and mode. The data in (c) positively skewed to the left and the mean is greater than median, and mode (Schindler, 2015:32)

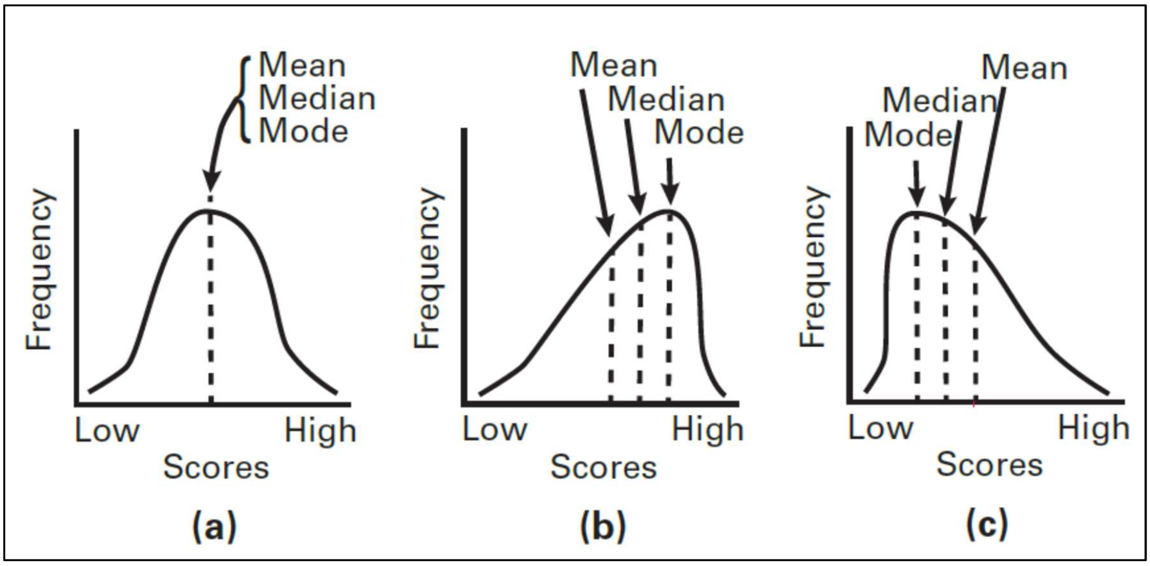


Figure B1: Data Distribution

Source: Schindler (2015:32)

It is important that each of the central tendency calculations are used within its limitations to avoid the unintentional misrepresentation of data (Schindler, 2015:33). Central tendency measures should not be used blindly, each measure has advantages and disadvantages and it all depends on "…the type of data (nominal, ordinal, or interval and ratio); the distribution of the data (symmetrical or skewed); the presence or absence of outliers; and whether the trend is linear, exponential, or some other shape" (Streiner, 2000:836). For symmetrical distribution of the numbers the mean, median and mode is equal. Schindler (2015:32) states that if the mean, median and the mode have the same value then the distribution of the data is symmetrical. If there is a skewness in the data as can be calculated in the difference between the mean and the median, then it raises questions as to the use of the mean as an indication of the central point. The larger the difference between the mean and median the greater the skewedness of the data (Schindler, 2015: 33). Table B1 lists the advantages and disadvantages of three central tendency calculations that can be used with the AHP model.

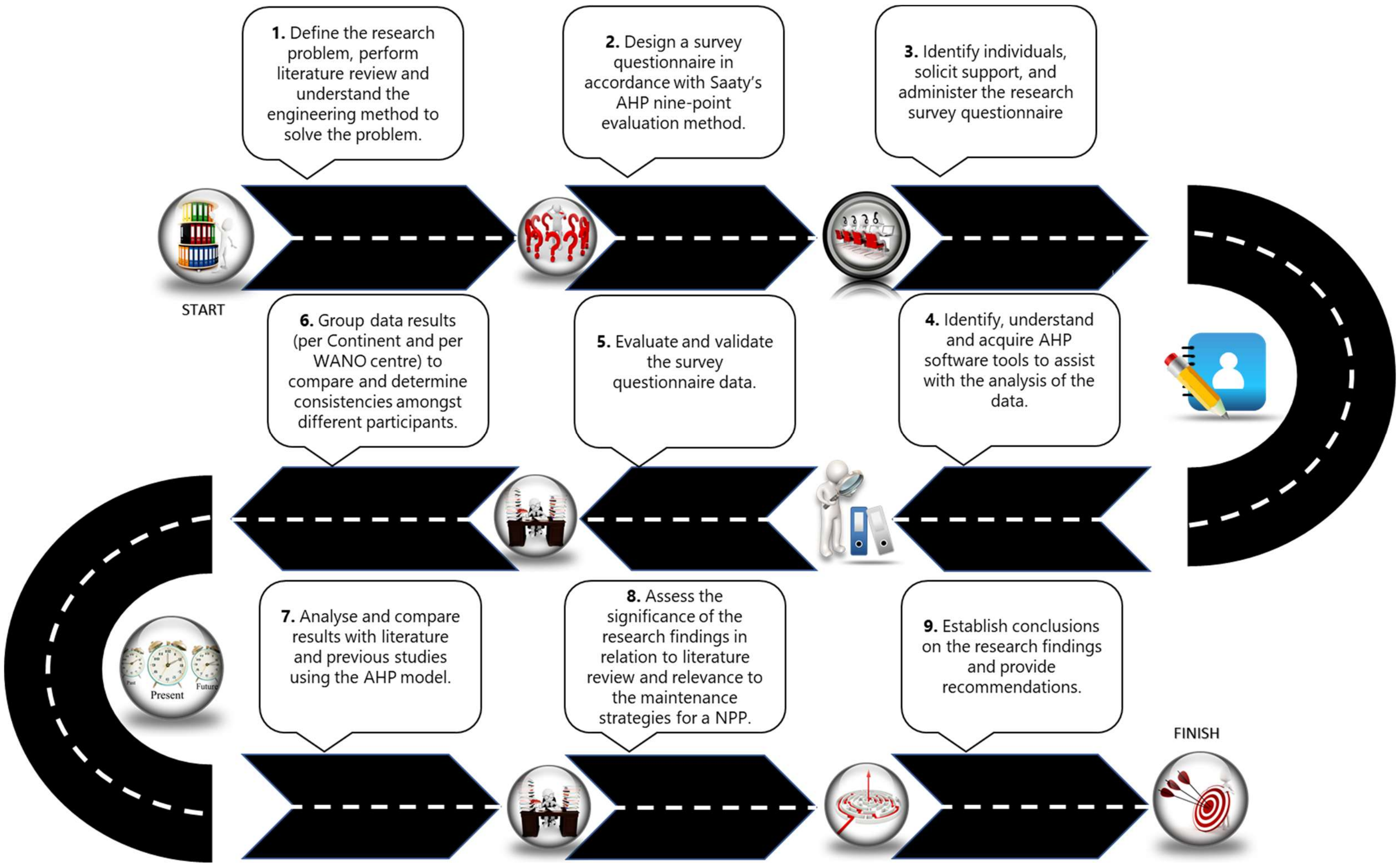
Table B1: Advantages and Disadvantages of Central Tendencies

	Arithmetic Mean	Median	Geometric Mean
Advantages	The mean uses every value in the data and hence is a good representative of the data. The mean best resists the fluctuation between different samples. The mean is used when the data have equal intervals between successive numbers (interval or ratio data). It is closely related to standard deviation, the most common measure of dispersion.	Is unaffected by a few extremely high or low observations. Used for ordinal data. Used when the nominal data distribution is skewed	All the data are used. A compromise on skewed or outlier values are offered. It is not so insensitive to it like the median and not as sensitive to it like the arithmetic mean. It handles ratios (e.g. 1/4, 2/3, 4/5) in a consistent manner. Does well with small samples of data and not so susceptible to a change in the number of datapoints. Excellent for constructing composites indices.
Disadvantages	The important disadvantage of mean is that it is sensitive to extreme values/outliers, especially when the sample size is small. Therefore, it is not an appropriate measure of central tendency for skewed distribution. Mean cannot be calculated for nominal or nonnominal ordinal data.	Do not use all the values in the data set. It requires large quantity of values to return an efficient value. Are susceptible to a change in dataset number.	Will not be informative if Zero's are present in the data set as the geometric mean will always return zero. The geometric mean is sensitive to unevenness of score or datapoints.

Source: Deshpande (2016:65); Stevens (2007:13), McChesney (2016) & Streiner (2000:834)

McChesney (2016) is a strong proponent of the use of the geometric mean and cautions the reader that the data we use is not always simple and linear and the method used to determine the central tendency have to make sense for the purpose it's being used as there are many factors to consider when using these calculations. The reader is also cautioned to avoid using the arithmetic mean just because it is popular but rather assess the data and assess the advantages and disadvantages of each of the central tendency calculations in the problem. Foreman and Peniwati (1997:166) believes that "both the geometric mean and the arithmetic mean are appropriate procedures for ratio scales". Aggregating individual judgments requires that the individual judgments are grouped into one and the group is considered to be one, the "… reciprocity requirement for the judgments must be satisfied and the geometric mean rather than an arithmetic mean must be used…" (Formen & Peniwati (1997:166).

1.5 Research Methodology Roadmap



Appendix C: Data Analysis

1.1 Overall Survey Alternative Results with respect to Safety

Safety	PM	PdM	CM	RCM
PM	1.00	2.00	7.00	2.00
PdM	0.50	1.00	4.00	1.00
CM	0.14	0.25	1.00	0.33
RCM	0.50	1.00	3.00	1.00
CI: 0,0028 CR: 0,0031 λ: 4,0084				

1.2 Overall Survey Alternative Results with respect to Cost

Cost	PM	PdM	CM	RCM
PM	1.00	0.33	7.00	0.50
PdM	3.00	1.00	5.00	1.00
CM	0.14	0.20	1.00	0.20
RCM	2.00	1.00	5.00	1.00
CI: 0,0705 CR: 0,0792 λ: 4,2114				

1.3 Overall Survey Alternative Results with respect to Reliability

Reliability	PM	PdM	CM	RCM
PM	1.00	2.00	5.00	3.00
PdM	0.50	1.00	6.00	2.00
CM	0.20	0.17	1.00	0.17
RCM	0.33	0.50	6.00	1.00
CI: 0,0637 CR: 0,0715 λ: 4,1910				

1.4.1 Survey Response A

Respondent ID	Q1. How important is the safety when it is compared with cost?		Q2. How important is the safety when it is compared with Reliability?		Q3. How important is the cost when it is compared with reliability?		Q4. With respect to Safety, How important is PM when it is compared with PdM?		Q5. With respect to Safety, How important is PM when it is compared with CM?		Q6. With respect to Safety, How important is PM when it is compared with RCM?		Q7. With respect to Safety, How important is PdM when it is compared with CM?		Q8. With respect to Safety, How important is PdM when it is compared with RCM?		Q9. With respect to Safety, How important is CM when it is compared with RCM?		Q10. With respect to Cost, How important is PM when it is compared with PdM?		Q11. With respect to Cost, How important is PM when it is compared with CM?		Q12 With respect to Cost, How important is PM when it is compared with RCM?	
	Safety	Cost	Safety	Reliability	Cost	Reliability	PM	PdM	PM	CM	PM	RCM	CM	PdM	PdM	RCM	CM	RCM	PM	PdM	PM	CM	PM	RCM
10328164603	8.00	0.13	8.00	0.13	7.00	0.14	6.00	0.17	8.00	0.13	7.00	0.14	4.00	0.25	7.00	0.14	5.00	0.20	7.00	0.14	5.00	0.20	5.00	0.20
10326102954	9.00	0.11	9.00	0.11	1.00	1.00	4.00	0.25	7.00	0.14	0.50	2.00	5.00	0.20	6.00	0.17	0.25	4.00	0.14	7.00	0.14	7.00	0.17	6.00
10325413534	7.00	0.20	5.00	0.20	0.17	6.00	6.00	0.17	7.00	0.14	5.00	0.20	0.17	6.00	6.00	0.17	0.20	5.00	3.00	0.33	7.00	0.14	5.00	0.20
10324717686	7.00	0.17	6.00	0.17	0.20	5.00	0.13	8.00	8.00	0.13	0.17	6.00	0.11	9.00	8.00	0.13	0.17	6.00	0.11	9.00	7.00	0.14	0.20	5.00
10323935866	7.00	0.14	7.00	0.14	7.00	0.14	0.14	7.00	0.14	7.00	7.00	0.14	0.14	7.00	7.00	0.14	6.00	0.17	0.14	7.00	7.00	0.14	7.00	0.14
10323660694	8.00	0.17	6.00	0.17	0.14	7.00	4.00	0.25	7.00	0.14	0.25	4.00	0.25	4.00	0.25	4.00	0.25	4.00	0.20	5.00	6.00	0.17	0.20	5.00
10322694140	9.00	0.14	7.00	0.14	5.00	0.20	7.00	0.14	5.00	0.20	3.00	0.33	5.00	0.20	1.00	1.00	9.00	0.11	3.00	0.33	7.00	0.14	3.00	0.33
10321298219	1.00	1.00	0.33	3.00	7.00	0.14	0.11	9.00	5.00	0.20	1.00	1.00	3.00	0.33	3.00	0.33	3.00	0.33	1.00	1.00	1.00	1.00	0.11	9.00
10315050981	9.00	0.11	9.00	0.11	0.14	7.00	0.14	7.00	7.00	0.14	0.20	5.00	0.14	7.00	5.00	0.20	0.14	7.00	0.14	7.00	5.00	0.20	0.20	5.00
10310796862	7.00	0.14	7.00	0.14	8.00	0.13	0.20	5.00	9.00	0.11	5.00	0.20	0.20	5.00	4.00	0.25	0.25	4.00	3.00	0.33	7.00	0.14	4.00	0.25
10309074065	7.00	0.14	7.00	0.14	0.20	5.00	1.00	1.00	4.00	0.25	0.17	6.00	0.17	6.00	0.33	3.00	0.17	6.00	3.00	0.33	6.00	0.17	0.25	4.00
10309070254	8.00	0.20	5.00	0.20	0.25	4.00	6.00	0.17	8.00	0.13	3.00	0.33	0.14	7.00	2.00	0.50	0.14	7.00	0.25	4.00	7.00	0.14	0.33	3.00
10308973350	9.00	0.14	7.00	0.14	1.00	1.00	1.00	1.00	0.25	4.00	1.00	1.00	3.00	0.33	3.00	0.33	3.00	0.33	0.33	3.00	9.00	1.00	0.20	5.00
10308933696	9.00	1.00	1.00	1.00	0.14	7.00	7.00	0.14	9.00	0.11	3.00	0.33	0.14	7.00	5.00	0.20	0.14	7.00	0.14	7.00	7.00	0.14	3.00	0.33
10307232362	9.00	0.11	0.13	8.00	0.11	9.00	0.13	8.00	9.00	0.11	0.11	9.00	0.11	9.00	8.00	0.13	0.13	8.00	0.11	9.00	9.00	0.11	0.13	8.00
10302672800	7.00	0.13	8.00	0.13	0.17	6.00	8.00	0.13			8.00	0.13	0.33	3.00	0.14	7.00	7.00	0.14			8.00	0.13	8.00	0.13
10298721500	9.00	0.11	9.00	0.11	0.13	8.00	6.00	0.17	7.00	0.14	5.00	0.20	0.14	7.00	0.17	6.00	0.14	7.00	5.00	0.20	7.00	0.14	5.00	0.20
10297150129	9.00	0.14	7.00	0.14	6.00	0.17	4.00	0.25	6.00	0.17	5.00	0.20	3.00	0.33	7.00	0.14	4.00	0.25	2.00	0.50	6.00	0.17	3.00	0.33
10296503047	7.00	0.14	7.00	0.14	0.33	3.00	0.20	5.00	5.00	0.20	0.20	5.00	0.14	7.00	1.00	1.00	0.20	5.00	3.00	0.33	5.00	0.20	0.20	5.00
10295415941	9.00	0.11	9.00	0.11	0.17	6.00	7.00	0.14	9.00	0.11	6.00	0.17	0.14	7.00	0.13	8.00	0.14	7.00	0.14	7.00	5.00	0.20	0.25	4.00
10295334970	9.00	0.25	4.00	0.25	1.00	1.00	5.00	0.20	3.00	0.33	5.00	0.20	0.25	4.00	3.00	0.33	0.20	5.00	7.00	0.14	5.00	0.20	5.00	0.20
10293625652	9.00	0.11	9.00	0.11	0.11	9.00	9.00	0.11	8.00	0.13	9.00	0.11	9.00	0.11	0.11	9.00	9.00	0.11	0.11	9.00	9.00	0.11	0.11	9.00
10293545744	9.00	0.11	1.00	1.00	0.11	9.00	1.00	1.00	9.00	0.11	0.11	9.00	0.11	9.00	1.00	1.00	0.11	9.00	1.00	1.00	3.00	0.33	0.11	9.00
10285743943	9.00	0.11	0.11	9.00	3.00	0.33	0.14	7.00	9.00	0.11	0.14	7.00	1.00	1.00	0.14	7.00	3.00	0.33	0.14	7.00	9.00	0.11	9.00	0.11

1.4.2 Survey Response B

Respondent ID	Q13. With respect to Cost, How important is PdM when it is compared with CM?		Q14. With respect to Cost, How important is PdM when it is compared with RCM?		Q15. With respect to Cost, How important is CM when it is compared with RCM?		Q16. With respect to Reliability, How important is PM when it is compared with PdM?		Q17. With respect to Reliability, How important is PM when it is compared with CM?		Q18. With respect to Reliability, How important is PM when it is compared with RCM?		Q19. With respect to Reliability, How important is PdM when it is compared with CM?		Q20. With respect to Reliability, How important is PdM when it is compared with RCM?		Q21. With respect to Reliability, How important is CM when it is compared with RCM?		WANO	Country
	CM	PdM	PdM	RCM	CM	RCM	PM	PdM	PM	CM	PM	RCM	CM	PdM	PdM	RCM	CM	RCM	Centre	Continent
10328164603	3.00	0.33	5.00	0.20	4.00	0.25	6.00	0.17	8.00	0.13	7.00	0.14	2.00	0.50	5.00	0.20	2.00	0.50	Tokyo	Asia (India, Korea)
10326102954	0.14	7.00	0.17	6.00	0.17	6.00	7.00	0.14	8.00	0.13	6.00	0.17	7.00	0.14	5.00	0.20	5.00	0.20	Atlanta	Africa (South Africa)
10325413534	0.20	5.00	5.00	0.20	0.20	5.00	0.25	4.00	5.00	0.20	0.20	5.00	0.17	6.00	6.00	0.17	0.20	5.00	Tokyo	Asia (India, Korea)
10324717686	0.11	9.00	8.00	0.13	0.17	6.00	0.13	8.00	8.00	0.13	5.00	0.20	0.13	8.00	8.00	0.13	0.14	7.00	Atlanta	America (USA)
10323935866	7.00	0.14	7.00	0.14	7.00	0.14	0.14	7.00	7.00	0.14	7.00	0.14	0.14	7.00	7.00	0.14	5.00	0.20	Atlanta	Europe
10323660694	0.25	4.00	1.00	1.00	0.25	4.00	0.25	4.00	3.00	0.33	0.17	6.00	0.33	3.00	0.20	5.00	0.25	4.00	Atlanta	America (USA)
10322694140	3.00	0.33	7.00	0.14	2.00	0.50	1.00	1.00	8.00	0.13	3.00	0.33	5.00	0.20	5.00	0.20	3.00	0.33	Paris	Europe
10321298219	0.11	9.00	1.00	1.00	1.00	1.00	9.00	0.11	9.00	0.11	9.00	0.11	0.11	9.00	1.00	1.00	0.20	5.00	Atlanta	Africa (South Africa)
10315050981	0.14	7.00	5.00	0.20	0.14	7.00	0.20	5.00	7.00	0.14	0.20	5.00	0.14	7.00	0.20	5.00	0.14	7.00	Atlanta	America (USA)
10310796862	0.25	4.00	4.00	0.25	4.00	0.25	0.25	4.00	5.00	0.20	7.00	0.14	0.20	5.00	7.00	0.14	0.25	4.00	Atlanta	America (USA)
10309074065	0.20	5.00	1.00	1.00	0.20	5.00	3.00	0.33	6.00	0.17	0.25	4.00	0.20	5.00	0.33	3.00	0.25	4.00	Tokyo	Asia (India, Korea)
10309070254	0.20	5.00	3.00	0.33	0.25	4.00	4.00	0.25	8.00	0.13	3.00	0.33	0.17	6.00	0.33	3.00	0.14	7.00	Tokyo	Asia (India, Korea)
10308973350	0.20	5.00	1.00	1.00	0.20	5.00	3.00	0.33	3.00	0.33	3.00	0.33	0.33	3.00	0.33	3.00	0.33	3.00	Atlanta	Asia (India, Korea)
10308933696	0.14	7.00	3.00	0.33	0.14	7.00	0.14	7.00	9.00	0.11	3.00	0.33	0.11	9.00	0.33	3.00	0.11	9.00	Atlanta	Europe
10307232362	0.11	9.00	0.11	9.00	0.13	8.00	0.13	8.00	9.00	0.11	0.13	8.00	0.13	8.00	0.13	8.00	0.11	9.00	Atlanta	Africa (South Africa)
10302672800	0.13	8.00			0.17	6.00	8.00	0.13	9.00	0.11	8.00	0.13	0.13	8.00	8.00	0.13	0.17	6.00	Atlanta	Africa (South Africa)
10298721500	0.14	7.00	0.13	8.00	0.14	7.00	6.00	0.17	8.00	0.13	0.14	7.00	0.14	7.00	0.14	7.00	0.13	8.00	Atlanta	Africa (South Africa)
10297150129	2.00	0.50	5.00	0.20	4.00	0.25	2.00	0.50	7.00	0.14	2.00	0.50	3.00	0.33	7.00	0.14	5.00	0.20	Atlanta	Europe
10296503047	0.20	5.00	0.20	5.00	0.20	5.00	0.14	7.00	7.00	0.14	1.00	1.00	0.14	7.00	5.00	0.20	0.14	7.00	Atlanta	America (USA)
10295415941	0.50	2.00	1.00	1.00	0.25	4.00	0.25	4.00	6.00	0.17	1.00	1.00	0.13	8.00	7.00	0.14	0.14	7.00	Tokyo	Asia (India, Korea)
10295334970	4.00	0.25	0.20	5.00	0.20	5.00	7.00	0.14	5.00	0.20	5.00	0.20	0.20	5.00	5.00	0.20	0.33	3.00	Atlanta	Africa (South Africa)
10293625652	0.14	7.00	9.00	0.11	0.14	7.00	9.00	0.11	9.00	0.11	9.00	0.11	0.14	7.00	0.11	9.00	0.11	9.00	Atlanta	Africa (South Africa)
10293545744	0.14	7.00	1.00	1.00	0.11	9.00	1.00	1.00	8.00	0.13	0.11	9.00	0.11	9.00	1.00	1.00	0.11	9.00	Atlanta	Africa (South Africa)
10285743943	1.00	1.00	7.00	0.14	1.00	1.00	0.14	7.00	9.00	0.11	8.00	0.13	1.00	1.00	7.00	0.14	1.00	1.00	Atlanta	Africa (South Africa)

1.5 Survey Responses per WANO Centre

Questions	Atlanta Geometric Mean	Atlanta Preferred Criteria	Tokyo Geometric Mean	Tokyo Preferred Criteria
Question 1	8	Safety	8	Safety
Question 2	3	Safety	7	Safety
Question 3	2	Reliability	3	Reliability
Question 4	2	PM	4	PM
Question 5	6	PM	7	PM
Question 6	2	PM	3	PM
Question 7	2	PdM	3	PdM
Question 8	2	RCM	1	PdM
Question 9	1	RCM	3	RCM
Question 10	1	PdM	1	PM
Question 11	6	PM	6	PM
Question 12	1	RCM	1	RCM
Question 13	3	PdM	2	PdM
Question 14	1	PdM	2	PdM
Question 15	3	RCM	3	RCM
Question 16	2	PM	1	PdM
Question 17	8	PM	6	PM
Question 18	2	PM	1	PM
Question 19	4	PdM	4	PdM
Question 20	2	PdM	2	PdM
Question 21	3	RCM	3	RCM

1.6 Criteria Ranking and Consistency

Ranking of Criteria	Africa	America	Asia	Europe	Atlanta	Tokyo
Safety	0,6301	0,7838	0,7838	0,7375	0,6942	0,7766
Cost	0,1085	0,0813	0,0813	0,1463	0,0955	0,0704
Reliability	0,2614	0,134	0,134	0,116	0,2103	0,153
Consistency Index	0,0175	0,0173	0,0173	0,1087	0,0046	0,0522
Consistency Ratio	0,0337	0,0334	0,0334	0,2090	0,0089	0,1004

1.7 Survey Responses per Continent

Question	Africa Geometric Mean	Africa Preferred Criteria	America Geometric Mean	America Preferred Criteria	Asia Geometric Mean	Asia Preferred Criteria	Europe Geometric Mean	Europe Preferred Criteria
Question 1	7	Safety	8	Safety	8	Safety	8	Safety
Question 2	2	Safety	7	Safety	7	Safety	4	Safety
Question 3	2	Reliability	2	Reliability	2	Reliability	2	Cost
Question 4	1	PM	3	PdM	3	PM	2	PM
Question 5	7	PM	7	PM	4	PM	2	PM
Question 6	1	PM	3	RCM	2	PM	4	PM
Question 7	2	PdM	6	PdM	2	PdM	1	PdM
Question 8	1	RCM	2	PdM	1	PdM	4	PdM
Question 9	1	RCM	5	RCM	2	RCM	2	CM
Question 10	2	PdM	2	PdM	1	PM	2	PdM
Question 11	4	PM	6	PM	6	PM	7	PM
Question 12	1	RCM	3	RCM	1	RCM	4	PM
Question 13	4	PdM	6	PdM	3	PdM	2	CM
Question 14	2	RCM	2	PdM	2	PdM	5	PdM
Question 15	4	RCM	3	RCM	3	RCM	2	CM
Question 16	2	PM	5	PdM	2	PdM	2	PdM
Question 17	8	PM	6	PM	6	PM	8	PM
Question 18	2	PM	1	PM	1	PM	1	PM
Question 19	4	PdM	6	PdM	4	PdM	3	PdM
Question 20	1	PdM	2	PdM	1	PdM	3	PdM
Question 21	4	RCM	6	RCM	3	RCM	2	CM

1.8 Continent - Alternative vs Criteria Preferences Calculations

Continent/ Preferences	Africa	America	Asia	Europe	Africa	America	Asia	Europe	Africa	America	Asia	Europe
Criteria	**Safety**				**Cost**				**Reliability**			
PM	0,249	0,145	0,377	0,318	0,027	0,017	0,028	0,063	0,123	0,026	0,039	0,040
PdM	0,161	0,354	0,154	0,193	0,046	0,034	0,028	0,045	0,062	0,071	0,049	0,046
CM	0,077	0,039	0,085	0,159	0,008	0,005	0,007	0,029	0,015	0,007	0,010	0,014
RCM	0,144	0,246	0,169	0,068	0,027	0,025	0,020	0,010	0,062	0,031	0,037	0,017

1.9 WANO – Alternative vs Criteria Preference Calculations

Continent / Preferences	WANO Atlanta	WANO Tokyo	WANO Atlanta	WANO Tokyo	WANO Atlanta	WANO Tokyo
Criteria	**Safety**		**Cost**		**Reliability**	
PM	0,3290	0,4435	0,0331	0,0244	0,0990	0,0511
PdM	0,1264	0,1360	0,0273	0,0223	0,0591	0,0545
CM	0,0841	0,0519	0,0078	0,0065	0,0132	0,0111
RCM	0,1547	0,1451	0,0273	0,0171	0,0389	0,0362