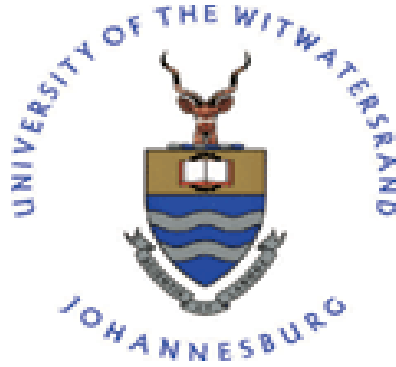




Selecting an Effective Maintenance Strategy using Analytical Hierarchical Process (AHP) algorithm on Rail Vehicles Components

by

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A research **dissertation** submitted to the Faculty of Engineering and the Built Environment, University of the Witwatersrand, in fulfilment of the requirements for the degree of Master of Science in Industrial Engineering.

April 2020

Declaration and Non- Plagiarism

I declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any university.



Abstract

To meet the needs and expectations of customer and key stakeholders, information on the condition and performance of an asset needs to be gathered consistently. This was demonstrated in a study whereby inspection data that reported on the operation and non-operation status of the components was used. This study was conducted in the rail maintenance environment with the aim to select the most appropriate maintenance strategy when faced with complex decision problems for the selected motor coach component using the Analytical Hierarchy Process (AHP) decision making algorithm. This study is important to reduce the number of systematic failures pertaining to motor coaches due to maintenance issues. The research approach adopted in this dissertation includes the application of an Analytical Hierarchy Process (AHP) mathematical decision-making model (Quantitative) and expert opinions through structured interviews (Qualitative). The approach adopted seeks to address the performance challenges in the implementation of the respective company's maintenance program by outlining the best maintenance strategies to be used for selected motor coach components. The findings from this study provide evidence that preventative maintenance is the best strategy overall. When considering the availability of spare parts factor, preventative maintenance strategy is also found to be the best strategy to be implemented. When considering the impact of failure on rail vehicle factor, corrective maintenance strategy is best the best strategy to be deployed. Whilst the reliability of maintenance data factor has shown equal importance for all strategies under investigations. And finally, the frequency of failure of the component factor, corrective maintenance strategy is best the best strategy to be implemented. The dissertation recommends that AHP methodology be used in determining the best maintenance strategy to deploy for rail vehicle components and in determining the component criticality or ranking. The limitations of the study are limited to preventative maintenance, corrective maintenance and No maintenance strategy implementation.

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Abbreviations

AHP	–	Analytical Hierarchy Process
TPM	–	Total Productive Maintenance
CI	–	Consistency index
CM	–	Corrective Maintenance
CR	–	Consistency Ratio
CW	–	Criteria Weight
MCDM	–	Multiple Criteria Decision Making
MG	–	Motor Generator
MA	–	Motor Alternator
Panto	–	Pantograph
PM	–	Preventive Maintenance
PV	–	Priorities Vector
RI	–	Random index
RI	–	Reliability Centered Maintenance
TM	–	Traction Motor

Chapter 1- Introduction

The improvement and maintenance of rail infrastructure and rolling stock is critical in providing a safe and reliable railway service for the passengers. As such, the maintenance of motor coaches plays an integral part in the railway system, and if not maintained, the system remains vulnerable. To meet the needs and expectations of customers and key stakeholders, information on the condition and performance of an asset needs to be gathered consistently. This was demonstrated in a study whereby inspection data that reported on the operation and non-operation status of the components was used. It is critical to deploy an appropriate maintenance strategy for the motor coach components as it impacts directly on the safety and comfort of the passengers. It is for this reason that the selection of appropriate model when deciding on maintenance strategy plays a key role. A motor coach is classified under rolling stock as it includes all the vehicles that move on the rail track. This dissertation aims at developing a general framework for the selection of an optimum maintenance strategy for the motor coach components with the assumption that the company has collected motor coach components maintenance records and failure patterns. The maintenance analysis to select the optimum maintenance model is carried out using the AHP mathematical model technique. The optimum maintenance strategies are defined as the improved and most effective process or approach in deploying a maintenance strategy. The different strategies grouped under the preventative maintenance and Corrective maintenance were considered in the development of the tool. The selection of the most appropriate maintenance strategy is often faced with complex decision problems involving the need to determine the best strategy to deploy for a motor coach component. As a result, decision making plays a key role in the selection of an appropriate maintenance strategy.

1.1 Background

The immediate focus of any rail company in contributing to a quality life for South Africans is to ensure timeous delivery of quality rail services that are aimed at enabling communities to access socio-economic opportunities. The unavailability of motor coaches due to components failure aligned with maintenance costs the rail company a lot. It is therefore evident that decision making in selecting an appropriate strategy when addressing these issues is critical. The response time for repairing rail

infrastructure failures remains a challenge in the South African rail industry (du Toit, et al., 2019) thus, there is a need to develop effective maintenance decision-making system to achieve the goals and requirements of railway stakeholders.

1.2 Problem Statement

Important rail networks are overloaded, rail freight tariffs are high, transit times are long and uncertain, rail terminal quality is poor, there is diminished flexibility in carrying different types of products and railway carriages are uneconomical for the industries that cannot provide full train loads (Haldar, et al., 2017). If one system fails, the whole service can be severely affected (Conradie, et al., 2015). The rolling stock in rail industries are capital intensive as they service passengers daily and need to be maintained continuously for safety of the physical assets and of passengers. Decision making on the type of strategy to be deployed for the components of the motor coach is crucial in avoiding any failures.

1.3 Purpose of the Research

This dissertation aims to address decision making ability in the selection of an optimum maintenance strategy for motor coach components.

1.4 Research Question

The research question that guided the study:

- 1.4.1 How AHP algorithm can be used in selecting the best maintenance strategies for motor coach components?

1.5 Research Objectives

The research objectives of the study are

- ✚ To select the most appropriate maintenance strategies for the motor coaches' components and the most critical component using AHP methodology
- ✚ To develop the general framework based on AHP for the selection of optimum maintenance strategy for motor coach components
- ✚ To validate the AHP algorithm results using the Delphi methodology

1.6 Research Delimitations

- ✚ The research is limited to the maintenance of rail vehicles critical components
- ✚ There is inconsistency in capturing input data for all works carried out in the database

1.7 Assumptions

- ✚ The maintenance data clearly outline the type of maintenance carried out
- ✚ The maintenance data includes timelines to carry out the task
- ✚ There is an effective maintenance system in place
- ✚ There is a fault/failure analysis procedure in place

1.8 Dissertation Layout

The layout of this research consists of five chapters, broken down as follows:

Chapter 1 introduces the background of the study, the problem statement, research question and the objectives that need to be achieved by the study. Then highlights how the study was conducted, and the delimitations of the study and finally how this report is compiled or presented.

Chapter 2 outlines the literature gathered to provide a context for the research objectives to address the problem statement. This brought about an understanding of the important theoretical viewpoints of the problem and assisted in creating a new model for problem being researched. The context covered ranges but not limited to Maintenance of Rolling stock, failure data, the different rail maintenance strategies: preventative and corrective maintenance, decision making criteria and finally the AHP mathematical algorithm.

Chapter 3 presents the research methodology that outlines the research approach taken to define what data was collected & how, the data collection techniques employed, data analysis and how to implement the AHP methodology.

Chapter 4 presents the analyses of the maintenance data collected and the application of the AHP methodology to decide on the optimal strategy. The consistency check of the data was carried out to ensure that there is consistency for a decision.

Chapter 5 discusses the results and analysis obtained in chapter 4

Chapter 6 concludes the research study, highlights the significance of the study and its limitations. It also gives recommendations to improve the organizations approach in addressing rail components maintenance decisions and future work.

1.9 Summary

This chapter introduced the background of the study, the problem encountered, the purpose of the research, the research question, the objectives that needed to be achieved, the research delimitations and how this report is compiled and presented. The next chapter considers the review of applicable literature.

Chapter 2 - Literature review

2.1 Introduction

This chapter highlights the literature that assisted in defining the research and reviewing the status. The literature review covers the following rail maintenance concepts: Maintenance, Rolling stock, maintenance of rolling stock, corrective maintenance, preventative maintenance, failure data, AHP, Decision criteria analysis and the critical review of literature.

2.2 Maintenance

Maintenance is defined as the repair actions that are taken for failed components (Takeshi, 2012). There are two categories of maintenance, namely, Preventative maintenance and Corrective maintenance (Zaim, et al., 2012). Maintenance is made up of mathematical models aimed at finding balances between costs and time of maintenance, or the most appropriate moment to execute maintenance (Dekker, 1998). It is essential that organizations implement a system of preventive maintenance and corrective maintenance to minimize the inconvenience caused by lack of maintenance (Costa & Balduino, 2018). Maintenance planning is fundamental to improving maintenance efficiency (du Toit, et al., 2019). In railway infrastructure asset management, the corrective and preventative maintenance actions are appropriate maintenance strategies that are deployed to focus on measurable outputs.

2.2.1 Corrective maintenance

Corrective maintenance (CM) is that which takes place after the system has failed (Zaim, et al., 2012). The corrective maintenance process involves the detection and alert of failure, diagnosis then repair to return to service (Peres & Noyes, 2003). Corrective maintenance recovers a system from asset failure, meaning that an asset is operated until an asset within a system fails (Zhuwaki, 2017). When performing corrective maintenance on rail infrastructure, the system, or some of its parts, are usually non-operational (du Toit, et al., 2019)

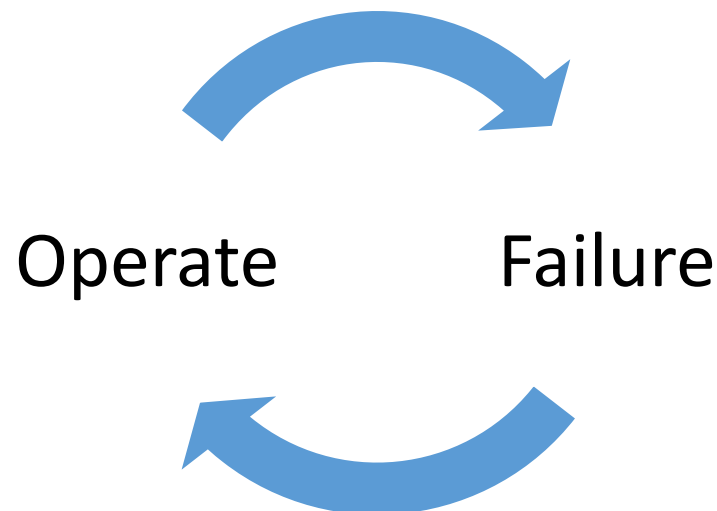


Figure 1: Operation Cycle of the Repairable Unit (Burhanuddin, et al., 2014)

Figure 1 outlines the two status conditions of a repairable component that has failed. A repairable system can produce failure data that are independent and identically distributed. Failure data plays a critical role in determining the trend using regression techniques to ascertain whether a system can deteriorate or improve over time (Conradie, et al., 2015).

2.2.2 Preventative Maintenance

Maintenance that takes place before there is a failure (Zaim, et al., 2012) or an exchange or remake of a component before wearing down (Costa & Balduino, 2018) is classified as Preventative Maintenance (PM). The process of preventative maintenance is initiated by machine defaults that require intervention before the system fails. When this takes place, a decision is made based on the demands of production to adjust or replace of defective parts or repair of failed parts before the system is operational again (Peres & Noyes, 2003). Preventative maintenance prevents a system from suffering an impending failure of an asset by scheduling maintenance tasks through monitoring (Zhuwaki, 2017).

2.3 Rolling stock

A railway system is made up of two main subsystems, the rail infrastructure and rolling stock. Rolling stock has been identified as the most important and vulnerable subsystem of the railway system. Rolling stock is classified as any vehicle such as motor coaches, wagons, and locomotives that move on a rail network (Asekun & Fourie, 2015). A motor coach is made up of components such as a traction motor, pantograph, axle, compressor and an exhauster to name a few (Fourie & Tendayi, 2016) as shown in Figure 2.

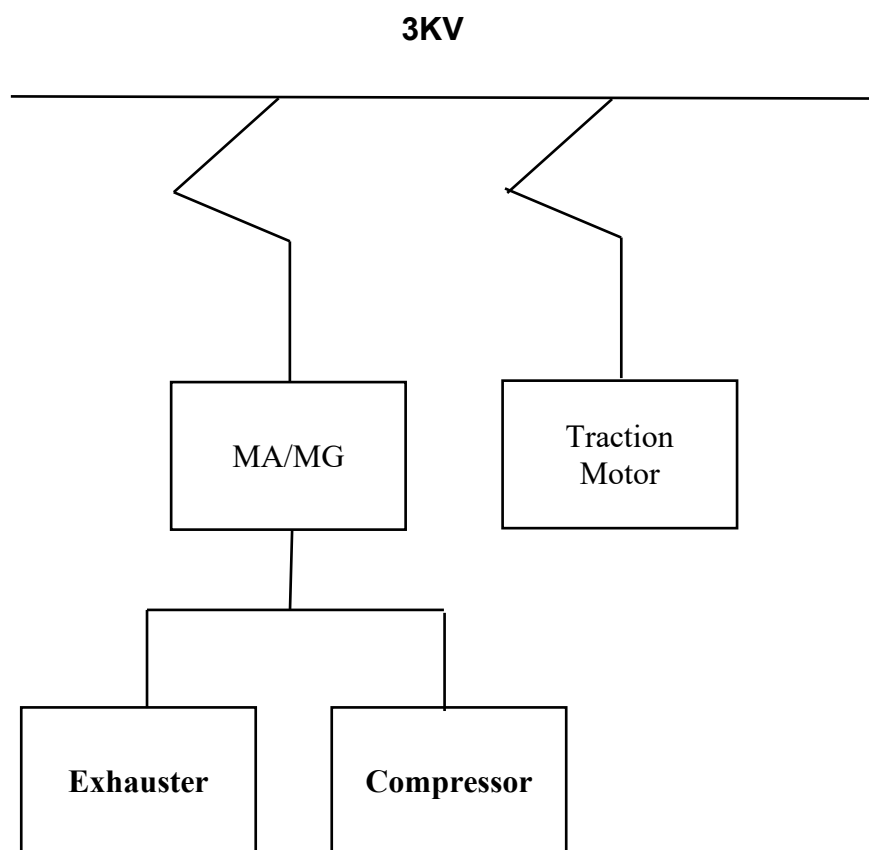


Figure 2: Reliability diagram of components (Asekun & Fourie, 2015)

A train set is made up of motor coaches connected to each other. A motor coach depicted in Figure 3 is made up of components that make up a coach (Asekun & Fourie, 2015).

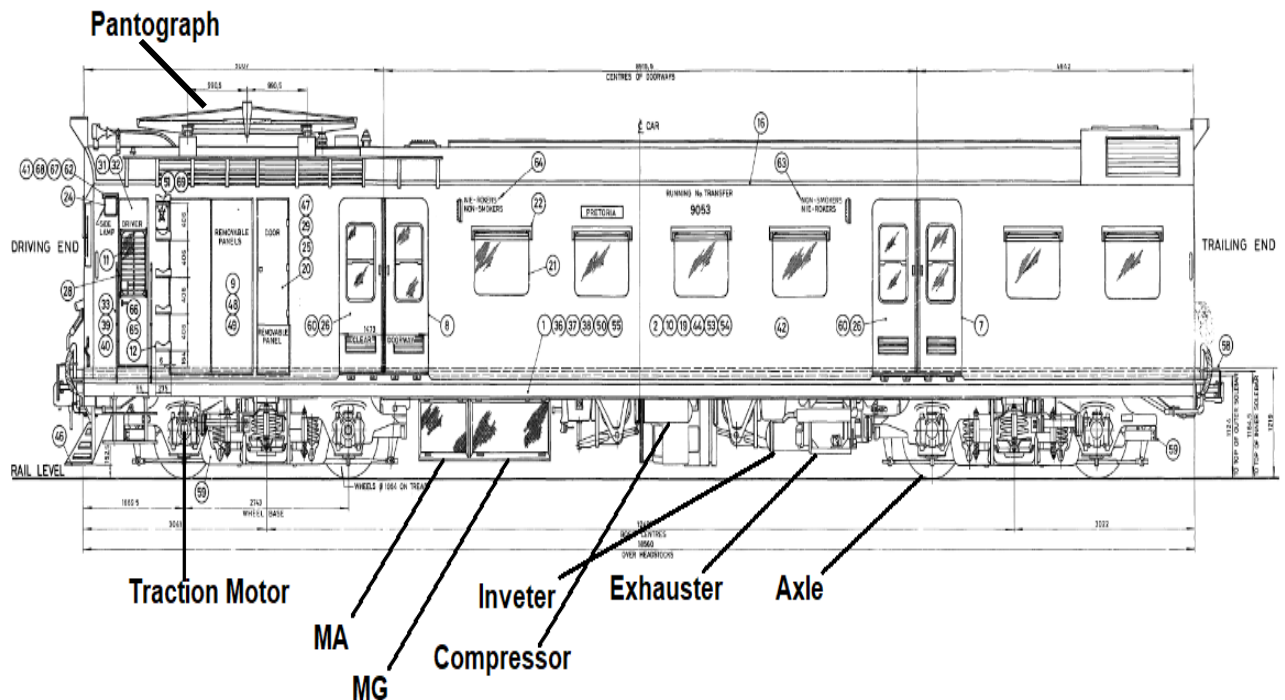


Figure 3: Motor Coach

2.4 Maintenance of Rolling Stock Strategies

The maintenance of rolling stock is characterized in two maintenance strategies: Corrective Maintenance (CM) and Preventative Maintenance (PM). Due to incorrect maintenance work, frequent down time, unnecessary maintenance tasks encountered when executing PM, the rolling stock maintenance companies often revert to CM also known as breakdown maintenance (Asekun & Fourie, 2015). An appropriate maintenance strategy not only mitigates the likelihood of equipment failure but also improves the working condition of assets, resulting in lower maintenance costs, and/or higher product quality. On the other side, an improper selection of strategies may adversely affect the maintenance budget and thereby reducing productivity as well as profitability (Shafiee, 2015). It is important that effective maintenance strategies are developed to deal with rolling stock maintenance tasks. Rail companies focusing in Preventive Maintenance strategy in rolling Stock encounter problems that are not limited to erroneous maintenance work, unnecessary maintenance tasks, etc. (Rezvanizani, et al., 2008).

2.5 Failure data

To meet the needs and expectations of customers and key stakeholders, information on the condition and performance of an asset needs to be gathered consistently (Zhuwaki, 2017). The data collected relating to the characteristics of failure and repair processes and request and service must correspond with the information captured. The data captured for corrective action may include the date, description and duration of an intervention as well as the nature, cause and gravity of the failure (Peres & Noyes, 2003). Failure is a process that takes place in mechanical system/components (Sharma & Pooja, 2010). The 'failure' is the manifestation of an 'error' which follows a 'fault' (Peres & Noyes, 2003). It is further defined as an event that is subjected to reliability analysis as such must be collected as data (Takeshi, 2012). The mathematical and statistical models' techniques require large amount of data; however, this data is often inaccurate, due to poor capturing by those responsible for this task, this results in the lack of adequate data to carry out statistical analysis (Sharma & Pooja, 2010). Accurate corrective action data when correctly captured should include the date, description and duration of an intervention as well as the nature, cause and gravity of the failure (Peres & Noyes, 2003).

2.5.1 Maintenance failure data

A repairable system can produce failure data that are independent and identically distributed (Conradie, et al., 2015) thus, the failure data of a failed or operating system is a very useful quantity in terms of replacement and maintenance strategies (Eryilmaz, 2018). Failure data must correspond with the information captured to include the date, description and duration of an intervention as well as the nature, cause and gravity of the failure (Peres & Noyes, 2003). Improper location and guidance of components constitutes an important mode of failure often ignored in mechanical engineering practice (Eryilmaz, 2018).

2.6 Systems

An effective rail system depends on the seamless integration of several complex systems. The repair or replacement of components that have failed can only be carried out on a repairable system (Conradie, et al., 2015).

2.6.1 Subsystem architecture

The architecture of the subsystems, which defines their interdependence and their common failure modes, plays an important role in mitigating reliability risks. The system should be designed and configured such that failure in one component does not start a chain of failures in other components (Hao, et al., 2015).

2.6.2 Fail safe design

Rolling stock design is critical in addressing maintenance of components during the design of the coaches as such provision for component failure is part of every good design, to avoid collateral damage in case a failure occurs. (Mulder, et al., 2013).

2.7 Decision Making

Railway decision making is complex as it includes huge amount of data, lack of relevant data, data analysis and data integration. Because of its complexity, a need arises to develop an effective maintenance decision-making system to achieve the goals and requirements of railway stakeholders. Decision making can be defined as an activity for solving problems that are eliminated with a satisfactory solution (Kour, et al., 2014). Decisions are made by individuals or groups as a reaction to a problem. The decisions necessitate the interpretation and evaluation of the information received in a form of relevant data (Robbins & Judge, 2015). Decision making that influence more than one individual achieve the following objectives: Compliment one another's knowledge and expertise; Generate more ideas by brainstorming; Generate more information on a problem; and evaluate and correct possible decisions (Reid & Hammersley, 2000). Decision making is achieved when one is evaluating and choosing a solution to a problem. This is done to achieve the following goals in an organization: Product Improvement; Efficiency in production; and Choice of investment (Zey, 1992). AHP method is one of the most popular tools for addressing problems of competing objectives in decision analysis due to the subjective judgements of inputs from decision makers, experts and stakeholders' group decision making. (Lin & Lu, 2012).

2.7.1 Decision Support System

Decision making may be supported by use of methodologies such as the root cause analysis and others, either individually or integrated form. Figure 4 provides an example of an integrated framework for failure analysis of systems which adopted different methodologies such as Root Cause Analysis (RCA), Failure mode and effect Analysis (FMEA) and Fuzzy Methodology (FM) methodologies in the maintenance decision making approach (Sharma & Pooja, 2010). The fact that the framework highlighted the different support systems, whether used individually or in combination can assist decision making in maintenance. Furthermore, the framework suggests the different strategies that can be deployed when there is a failure, which includes optimization of the maintenance decision (repair/replace) and preventative maintenance amongst others. This study considers optimization of maintenance decisions in analyzing maintenance data from a selected company.

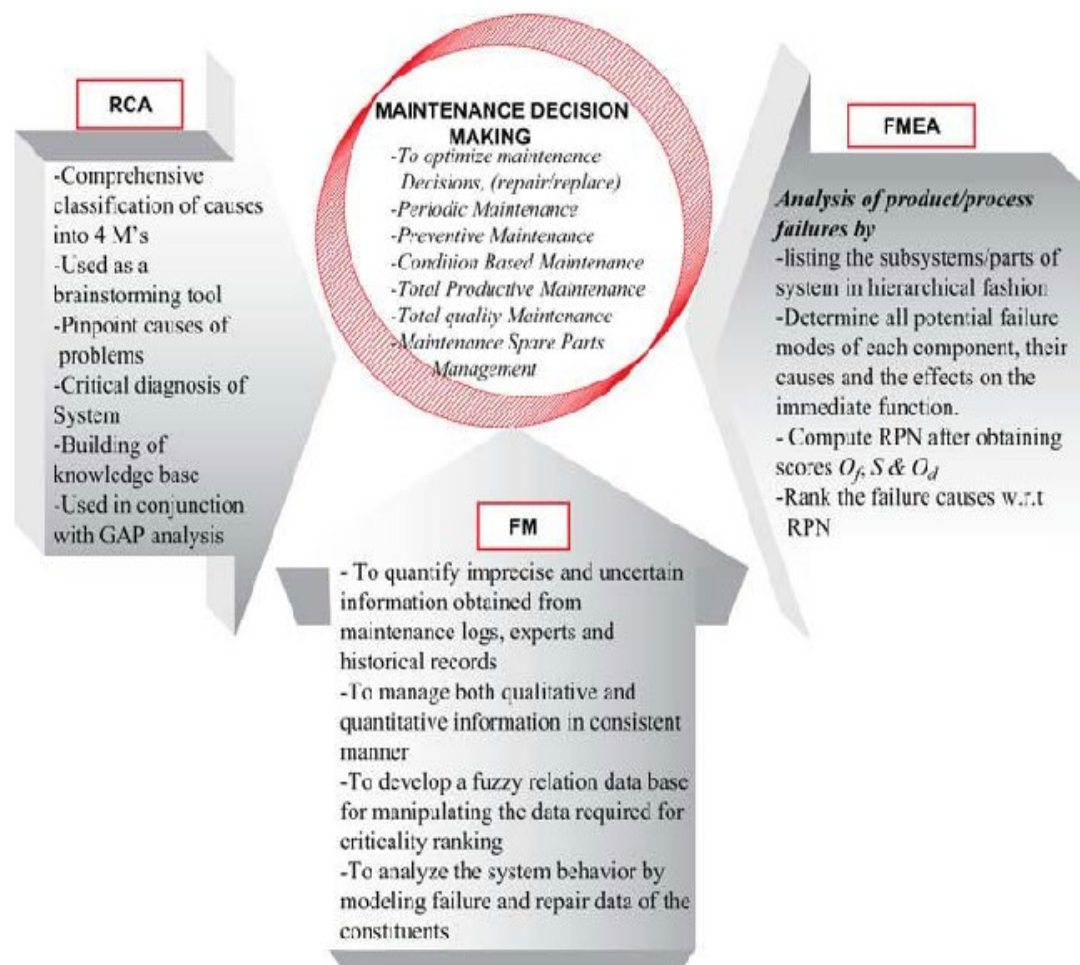


Figure 4: Framework for failure analysis and maintenance decisions (Sharma & Pooja, 2010)

In addition, the framework indicates that in maintenance decision making, one of the decisions to be made about a fault or failure is that of whether to repair or replace (Sharma & Pooja, 2010).

2.8 Decision Criteria Analysis

Labib suggests the use of multiple criteria in investigating maintenance problems and proposes the use of hierarchical levels (Aslam-Zainudeen & Labib, 2011). (Aslam-Zainudeen & Labib, 2011) demonstrate its application by investigating maintenance of rolling stock in rail industry. They show maintenance of rolling stock more systematically through the four levels until fault details (level 4) are fully considered. This study covers the details of the fault (level 4) and calls these components subsystems such as MA set fault, Traction motor fault, Circuit breaker fault pictured in Figure 5

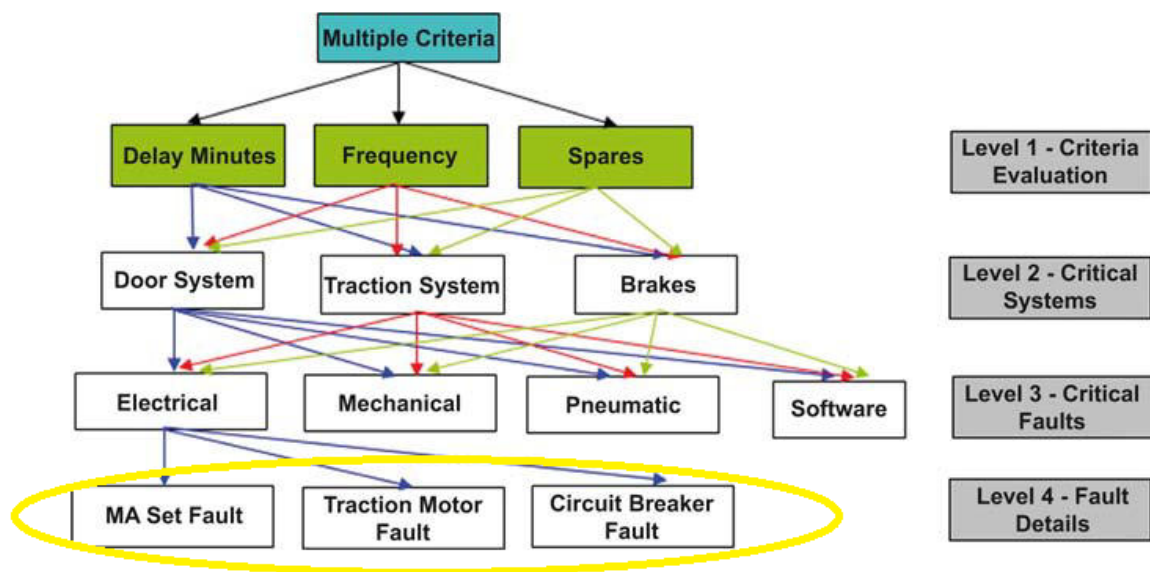


Figure 5: Critical Systems indicating Components under investigation adapted from (Aslam-Zainudeen & Labib, 2011)

2.9 Analytical Hierarchy Process

The Analytical Hierarchy Process (AHP) method is a multiple-criteria decision-making (MCDM) approach that makes it possible to select the best decision for the criterion identified, it is used when making optimum choice in decision making variants. (Sobczyk, 2008). AHP was originally devised by (Saati, 1980) to provide a framework

for solving different types of multi- criterion decision problems based on the relative priorities assigned to each criterion's role in achieving the objective. AHP method takes into consideration all the components and analyses them using hierarchical method ranking. It is a statistical method that has been adopted for analyzing unrelated data, with the main objective to obtain the most viable options. The method develops a matrix that compares attributes in pairs (Handfield & Walto, 2001). AHP considers the hierarchical nature of the defined main goal and this is achieved by creating an association between the available options prior to arriving at the decision. It furthermore identifies the priority of the criteria set (Pour, et al., 2017). The AHP method ensures that the qualitative and quantitative data in decision-making problems are contained such that it is easy to understand its process (Yadav & Sharma, 2015).

2.10 Critical review of literature

Researchers have used AHP methodology for many different purposes, some in isolation and others with combination of other mathematical models, such as the following:

Ratnayake & Tore (2010) used the AHP methodology in measuring the HSE awareness in selecting a maintenance strategy (Ratnayake & Tore, 2010). Similarly, (Roberto & Thomas, 2010) used the AHP approach in identifying improvement areas when implementing green initiatives. (Nikolaos & Panagiotis, 2016) applied the AHP approach to investigate the relationship between regional factors and investment attractiveness of solar energy. (Shivraman, et al., 2011) applied the AHP methodology in selecting the best concept in lean environment thereby improving the leanness of the organization. (Chen & Pei-Ni Huang, 2007) used the AHP with bi-negotiation agents' approach in proposing a new approach for tackling the uncertainty and imprecision of identifying suitable supplier offers, evaluating these offers and choosing the best alternatives in bi-negotiation. (Lo, et al., 2013) adopted the AHP methodology for revealing the preference of tenants on those captioned attributes under a ratio scale. (Singh, 2016) applied the AHP technique to benchmark the competitive service quality in airline industry. (Fong, 2000) applied a similar approach of Analytical Hierarchy Process (AHP) in exploring the final contractor selection. Some writers have combined the AHP methodology with other methodologies, for example (Zaim, et al., 2012) used the combination of AHP and ANP methodology in the selection of maintenance strategy in the printing firm. Similarly, (Shyjith, et al., 2008) also used the

combination of AHP and TOPSIS methodology evaluating the optimum maintenance strategy in textile industry. (Parvaneh & El-Sayegh, 2016) used another combination, AHP and LP methodology in the presentation of a model to select a new construction project for a firm. (Selçuk Perçin, 2006) uses the combination of AHP-PGP methodology in selecting the best suppliers and allocating the optimum order quantities among them by evaluation.

However, in the words of (Lin & Lu, 2012), AHP is one of the most popular tools for addressing problems of competing objectives in decision analysis due to the subjective judgements of inputs from decision makers, experts and stakeholders group decision making. According to (Zaim, et al., 2012), it is clear from the literature that AHP has proven success in maintenance strategy selection, the same way it has proven success in many other decision-making problems. Therefore, this research selects AHP methodology as the preferred tool for the study.

2.11 Summary

This chapter has highlighted the relevant literature for the study to understand the concepts and framework used. Among others, it outlines the concepts of maintenance of rolling stock, AHP, decision criteria analysis and maintenance strategy selection. The chapter paves way for the conceptualization of the research methodology, which is considered in the next chapter.

Chapter 3 - Research Methodology

3.1 Introduction

This chapter discusses the methodology that was implemented in selecting an effective maintenance strategy of motor coach components using the AHP mathematical model. A database of field rail maintenance data was collected for all pieces of the motor coach components to evaluate the appropriate maintenance strategies to be carried out by the maintenance team. The mixed method methodology design is the explanatory sequential method, as it entailed soughting quantitative data first and analyzed, thereafter quantitative data results will be integrated into the survey to be utilized for qualitative data collection. The Data collection techniques were used to obtain data from the maintenance management system and the Delphi technique (Interviews). The motor coach components considered in this study are based on the overall information available on the database which is limited to an axle, compressor, exhauster, inverter, MA, MG, Pantograph (Panto) and a Traction Motor (TM). The subsystems of these components have not been considered. The AHP methodology used for the selection of the effective maintenance strategy of motor coach components is discussed in section 3.2.3.1.

3.2 Research Approach: Mixed Method

The approach used is the mixed method, comprising of both qualitative and quantitative method. Mixed method approach for the study was necessary to validate the data collected with interviews from the owners of the data collected. This approach includes the collection, analysis and integration of both qualitative and quantitative data in a single study (Hesse-Biber, 2010). This was carried out using the sequential mixed method topology which is the collection of data in sequential phases such that the quantitative data collected first contributes to the phase of qualitative data collection (Creswell & Clark, 2018). This study adopted the effective asset management cycle pictured in Figure 6 that was used in a study that assisted engineers in making decisions about what types of maintenance should be done and would also allow maintenance to be adapted to suit the changing real world performance of the fleets (Aslam-Zainudeen & Labib, 2011). Considering that the goal of this study was to highlights the need for a decision-making system in the maintenance of rolling stock particularly the critical functioning of the motor coach to

ensure optimum service quality to the passengers, this cycle was found to be suitable. The steps involved in the methodology are presented in line with Figure 6 and are considered below:

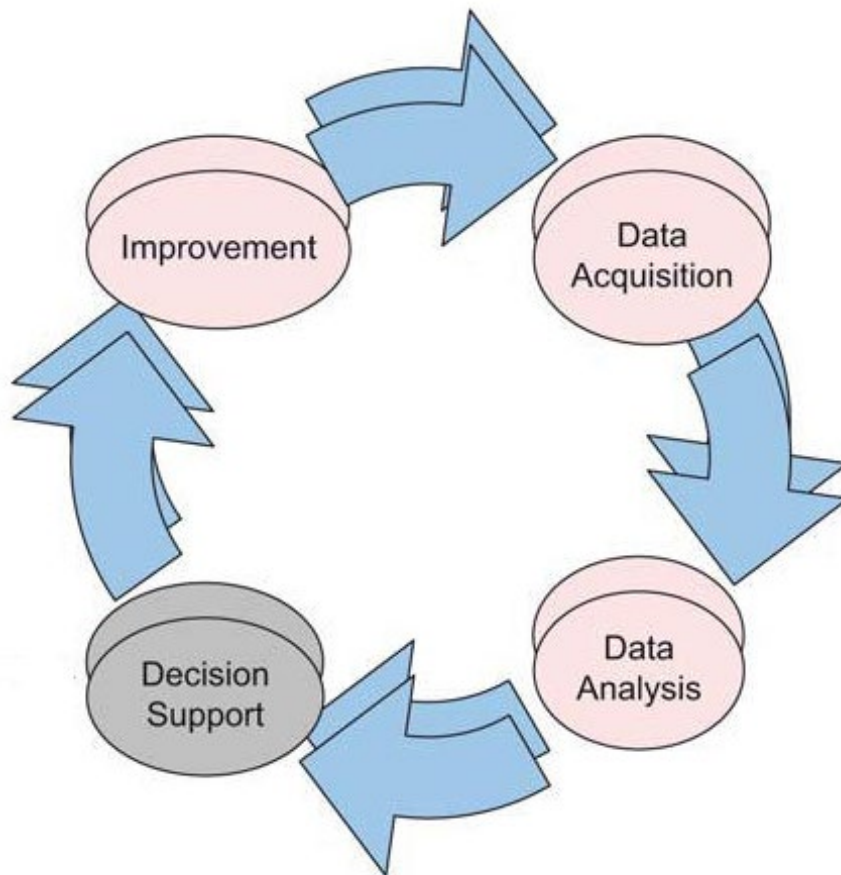


Figure 6: The effective asset management cycle (Aslam-Zainudeen & Labib, 2011)

Figure 6 outlines the four (4) stages in effective management: data acquisition, data analysis, decision support and improvement.

3.2.1 Data Acquisition

The data were acquired from a Rail Company's in-house maintenance database/system, downloaded in Microsoft excel format. This database contains all motor coach maintenance component failures of 551 motor coaches between the year 2014 to 2018. The data collection technique utilized is outlined in the MCDM approach, AHP to ensure that wrong data is not used in evaluating the maintenance strategies or data that is not complete. This entails the application of a Delphi method to counter any gaps in data provided. These data collection approaches ensured that the data is not an infeasible solution to the MSS problem (Shafiee, 2015).

3.2.1.1 Data Classification

The data sought is corrective maintenance data of rail vehicle components.

3.2.1.2 Data Collection techniques

The research data were gathered mainly using secondary sources (Kumar, 2005). This adopts the document analysis approach whereby the maintenance reports or documents for the rail vehicle components failure is accessed from the rail company and analyzed (Olsen, 2012). Narrative data were gathered using primary sources in a form of structured interviews (Kumar, 2005) which inquire using knowledge questions to obtain respondents information (Patton, 2015). The respondents were randomly selected within the functional area to ensure that the data were not biased (Biggam, 2008). The data collection techniques sought were the following:

3.2.1.2.1 Obtaining data from maintenance management system

The motor coach maintenance data collected were obtained from the Rail Company's rail maintenance management system currently in use, for data between 2014 to 2018 downloaded in an excel format. Permission to use the motor coach maintenance data for study purposes was obtained from the company.

3.2.1.2.2 The Delphi method

The Delphi technique gathers a group of experts' in the field's reliable opinions by allowing them to express their own views on a topic, while considering the other participants' views by means of controlled feedback (Grobbelaar, 2007). When implementing the process of the Delphi method, the human element was found to have the greatest impact on the effectiveness of the process (Crawford & Wright, 2016). Face to face interviews with a panel of maintenance experts was conducted to test the credibility of the data and the research results thereof. An ethics clearance certificate was issued by the university to allow for the interaction to take place is reported in 4.4.5.

3.2.2 Data Analysis

The data analysis was conducted using expert opinion as input into the AHP mathematical modelling knowledge base as recommended by (Sharma & Pooja,

2010). The numerical data analysis gathered was integrated using narrative information (Plowright, 2011). The data analysis model presented in Figure 7 below depicts the typical approach followed in highlighting the 'maintenance related causes', which is in the lack of Maintenance and Maintenance execution:

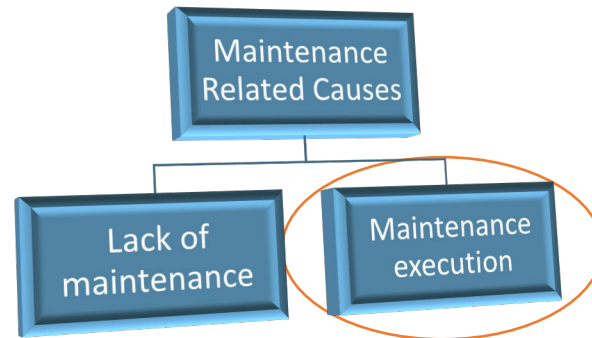


Figure 7: Data Analysis Model (Holmgren, 2005)

Figure 8 represents the maintenance process improvement cycle that breaks down the **maintenance execution** process cycle mentioned in Figure 7. Personnel and material are highlighted as inputs to maintenance execution. The yellow rectangular demarcation in Figure 8 of the PDSA (Plan, Do, Study and Act) approach highlights decision whether to act on fault and which maintenance strategy to deploy as depicted in the oval green circle: the choices available are No maintenance, Preventative maintenance or Corrective maintenance (Soderholm, et al., 2007).

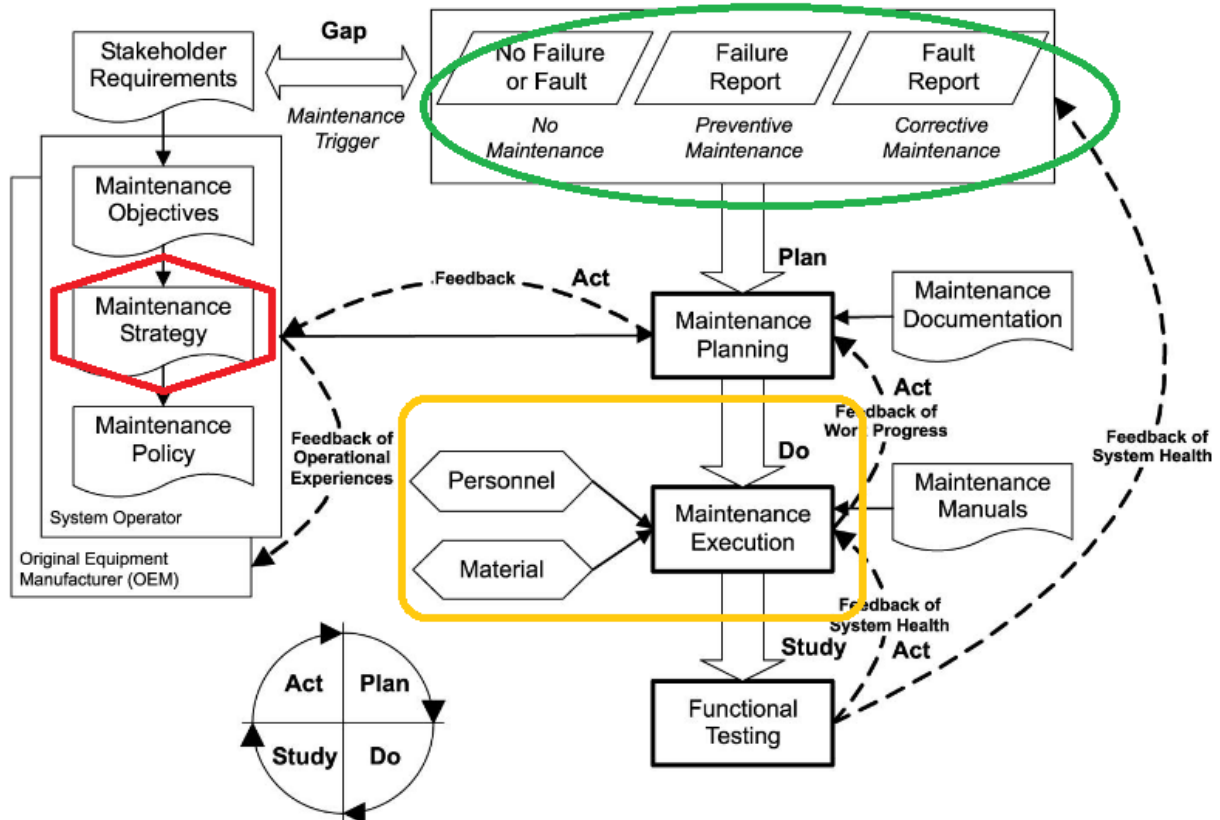


Figure 8: Maintenance Process Improvement Cycle (Soderholm, et al., 2007)

3.2.3 Decision Support - AHP Methodology

AHP methodology was applied in the determination of the best maintenance strategy for rail components.

3.2.3.1 AHP Methodology – steps followed in analysis (Saaty, 2008),

Step 1- Constructing a hierarchal structure of the problem

Stage 2: Formulate the maintenance strategy decision criteria matrix (C) through pair wise comparison

Stage 3: Formulate the criteria weight matrix (CW) from the normalized maintenance decision criteria matrix

Stage 4: Determine the weight vector

$$(W_s) = C \times CW$$

Stage 5: Determine the consistency vector

$$(C) = W_s \times (1/W)$$

Stage 6: Formulate the Consistency Index (CI) using

$$CI = \frac{\lambda - 1}{n - 1}$$

Stage 7: Formulate the Consistency Ratio (CR) using

$$CR = \frac{CI}{RI}$$

Stage 8: Formulate the Optimum maintenance strategy priority weight matrix

$$(F_R)$$

Stage 9: Formulate the transpose of

$$F_R (F_R^T)$$

Stage 10: Formulate the Optimum maintenance strategy selection matrix

Stage 11: Select the alternative Optimum maintenance strategy with the highest priority weight scores

3.2.3.2 The construction of the AHP Hierarchy

The AHP hierarchy is constructed by Identifying the main goal of the hierarchal structure of the problem (Saaty, 2008), this is achieved by decomposing the entire problem into three levels: Goal, Criteria, Alternatives and making a hierarchy of the same (Jagtapa & Bewoorb, 2017) as depicted in Figure 5. The alternative maintenance strategies are: Corrective maintenance, preventative maintenance and No maintenance.

3.2.3.3 The AHP Scale of Importance

Table 1 represents the fundamental scale of importance of absolute numbers:

Table 1: The fundamental scale of importance of absolute numbers (Saaty, 2008);
(Saati, 1980)

Intensity of importance	Definition	Explanation
1	Equal Importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgement slightly favor one element over the other
5	Strong importance	Experience and judgement strongly favor one element over the other
7	Very strong or demonstrated importance	One element is favored very strongly over the other, its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate	Intermediate
Reciprocals of above	-	If activity i is assigned one of the above numbers when compared to activity j, then activity j is assigned the number's reciprocal value when compared to activity i

As elaborated in Table 1: Scale 1 indicates that both elements are relatively equal in contributing to the goal. Scale 2 until scale 9 indicate that one element is relatively more important than the other, in which the bigger the number, the higher the dominance of one element over the other. On the other hand, reciprocals of these numbers indicate inverse relativity (Nur, et al., 2018).

3.2.3.4 The RI table (RI)

The Random index (RI) as tabulated by (Saati, 1980)

Table 2: Values of the RI Table for small problems

n	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.51

3.2.3.5 The Consistency Ratio (CR)

The consistency ratio is calculated using the formula, (Saati, 1980):

$$CR = \frac{CI}{RI}$$

Where **RI** is derived from the RI table depending on the number of things being compared and the consistency index (CI), (Saati, 1980)

$$CI = \frac{\lambda - 1}{n - 1}$$

3.2.4 Improvement

This is done by collecting information on objects and building library database – Information like failure mode, failure cause, failure condition, MTTF, MTTR among others are gathered for each component and introduced to the library database

3.3 Validity and Reliability

The reliability of the data collected was tested by calculating the Consistency ratio of the data input in accordance with the AHP methodology step. When the value of the consistency ratio (CR) is < 0.10 , it indicates that there is enough consistency for a decision/judgement to be made (Saaty, 1980). Structured interviews were carried out with maintenance personnel for verification purposes. (Benedetto, et al., 2007)..

3.4 Ethics

Ethical clearance for purposes of data collection, protection and good practice was sought to conform to the professional ethical standards expected by the University and generally required (Olsen, 2012), this Ethical Clearance was granted by the institution of study.

3.5 Summary

This chapter discussed the research approach undertaken and justification for the approach selected. It outlines the data collection techniques deployed, the classification of data and the steps involved in undertaking the AHP methodology for selecting an effective maintenance strategy of motor coach components. The validation and reliability aspects of the research and ethical considerations are also mentioned. This chapter paves the way for critical analysis of data collected, results and discussions.

Chapter 4 – Results and Analysis

4.1 Introduction

This chapter outlines the research results: the data compilation, analysis and application of the AHP methodology in selecting the best maintenance strategy which is informed by identifying the most critical component using motor coach reliability data provided by the Rail Company and application of AHP methodology in ranking the most critical component. The global priorities obtained are used for ranking of the alternatives and selection of the best maintenance strategy to be deployed and most critical component. There are four (4) different factors which were taken into consideration: data reliability, quality of spare parts, component frequency of failure and the impact of component failure. These attributes were used in determining the criticality of the components identified in the study. There are three different maintenance strategies that were taken into consideration: Preventative maintenance, Corrective maintenance and No maintenance as depicted in Figure 8. Upon completion of the application thereof results are gathered and interpreted accordingly in the next chapter. Similarly, the component taken into consideration were 8 components.

4.2 Data Collection

Quantitative data were collected from the Rail Company Maintenance database; this database consisted of component failure data covering the period 2014 to 2018. On the other hand, Qualitative data were collected from relevant literature on online databases and from the Rail Company personnel through the interview process.

4.3 Data Analysis

Data analysis was carried out on the data collected and the results are broken down into the following categories:

4.3.1 Availability of Spare Parts (Motor Coach Components)

Figure 9 presents the component data from the Rail Company's motor coach maintenance database between the years 2014 and 2018. The total number of components under scrutiny was 9,922 which included the unknown components where data is missing and thus cannot identify component captured.

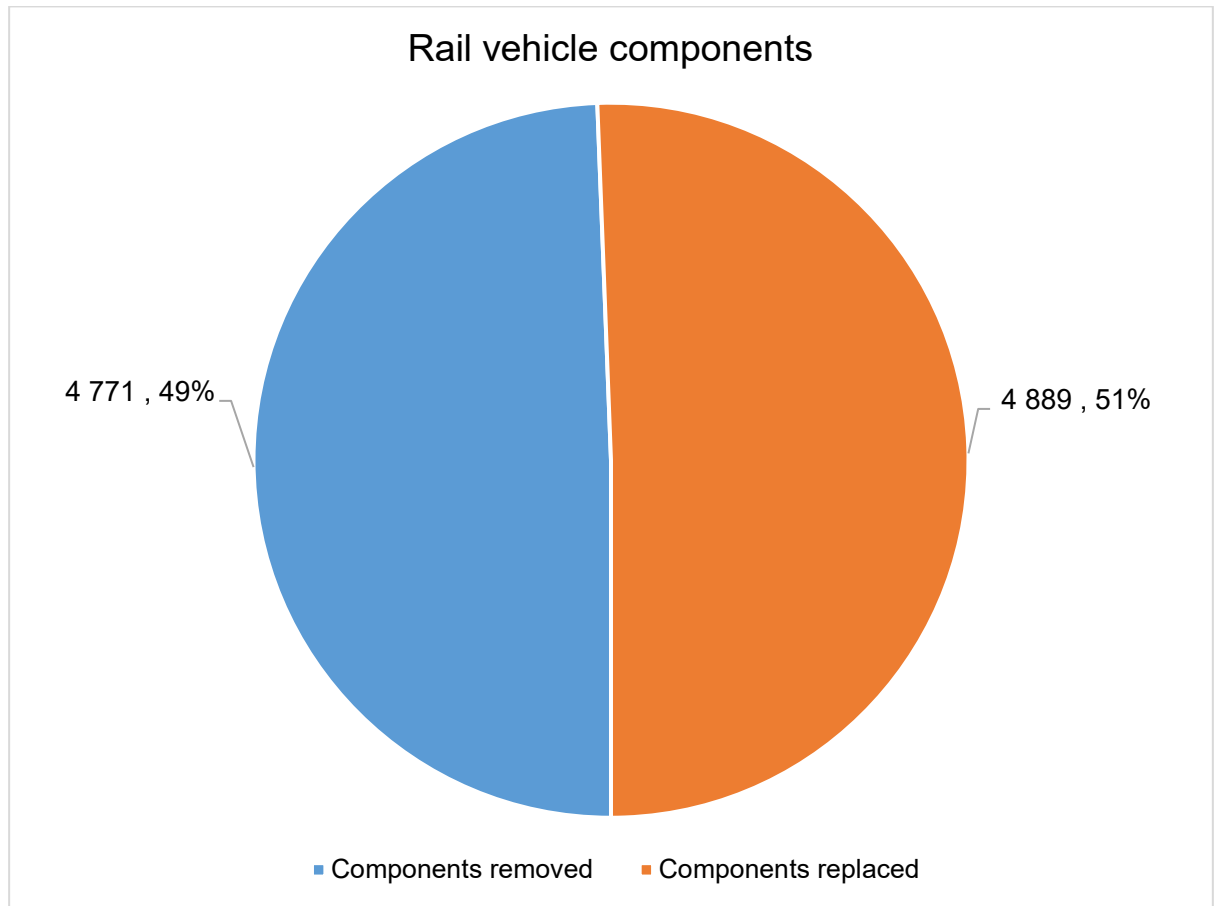


Figure 9: Motor coach components composition

Figure 9: Motor coach components composition Figure 9 depicts the components data retrieved from the database, namely: components removed, and components replaced. Removed components are components that are removed from a motor coach and are either refurbished or discarded. Replaced components are components that are used as spares/replacement part, these components can either be new components or refurbished components. Refurbished components are components that were removed from a motor coach due to failure or fault, refurbished for re use. There was a total of 4771 components that were removed from motor coach for failure, and a total of 4889 components that were replaced overall. These components are captured on the rail company database using unique serial numbers for ease of audit trail of a component lifespan. It should be noted that a component which is removed, then refurbished and replaced will have the same serial number and hence can be traced.

4.3.2 Impact of Component failure on Rail Vehicle

Table 3 tabulates the impact of component failures. The ratings were obtained using expert opinion due to data unavailability that allows computation of such ratings.

Table 3: Impact of component failure on motor coach

Components	Impact of Component Failure
Axle	3
Compressor	1
Exhauster	1
Inverter	1
MA	1
MG	1
Panto	1
TM	1

Key: 1 - Motor coach is operational (Has back up TM); 2- Operational loss < 50% (No Backup component); 3- Motor coach is stationery

4.3.3 Frequency of failure of the component

Figure 10 tabulates the frequency of failure for the different components affected in a motor coach. The number of components presented in Appendix 5 exclude the unknown components that did not have any data identification captured on the system.

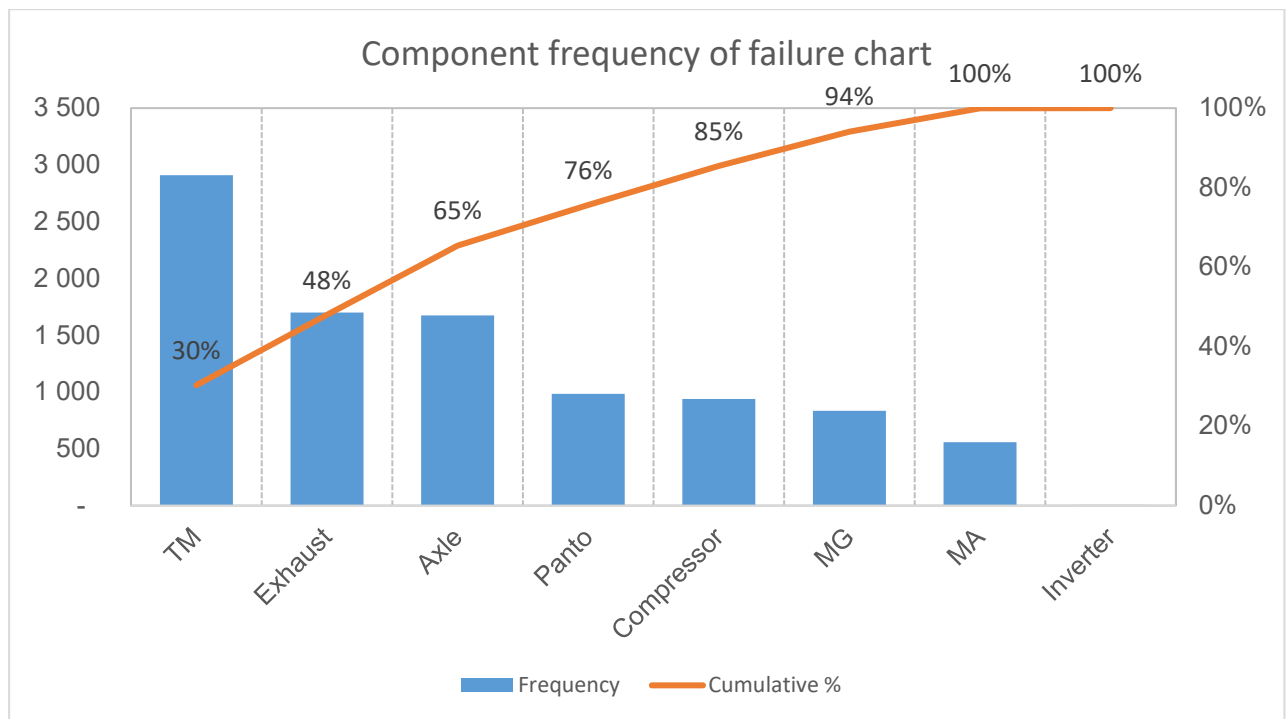


Figure 10: Pareto analysis for Component frequency of failure

The Pareto analysis shows that 80% of the coaches affected fall between the frequency of 1 to 20 failures. Figure 10 depicts the components frequency of failure, it outlines the traction motor, exhauster and axle as having the most frequent failures and thus these components have been selected for the AHP analysis to be carried out in the study.

4.4 AHP Analysis

The AHP analysis was carried out on the three (3) maintenance strategies using the following selection criteria (attributes): data reliability, quality of spare parts, component failure frequency and the impact of component failure. A hierarchical structure was developed and presented in Figure 11 to outline the different levels in achieving the goal of the study in accordance with the first step of carrying out an AHP analysis. A pairwise comparison was then carried out for the attributes to determine the data consistency suitability. Once the desired consistency value was achieved, analysis was carried out for each of the attributes and results presented of the preferred strategy. The same phenomenon was applied using the same attributes in determining the most critical component by applying the AHP methodology and results are presented in 4.4.6.

4.4.1 The AHP hierarchal structure

Figure 11 below presents the hierarchical structure of the decision-making criteria broken down into four (4) levels:

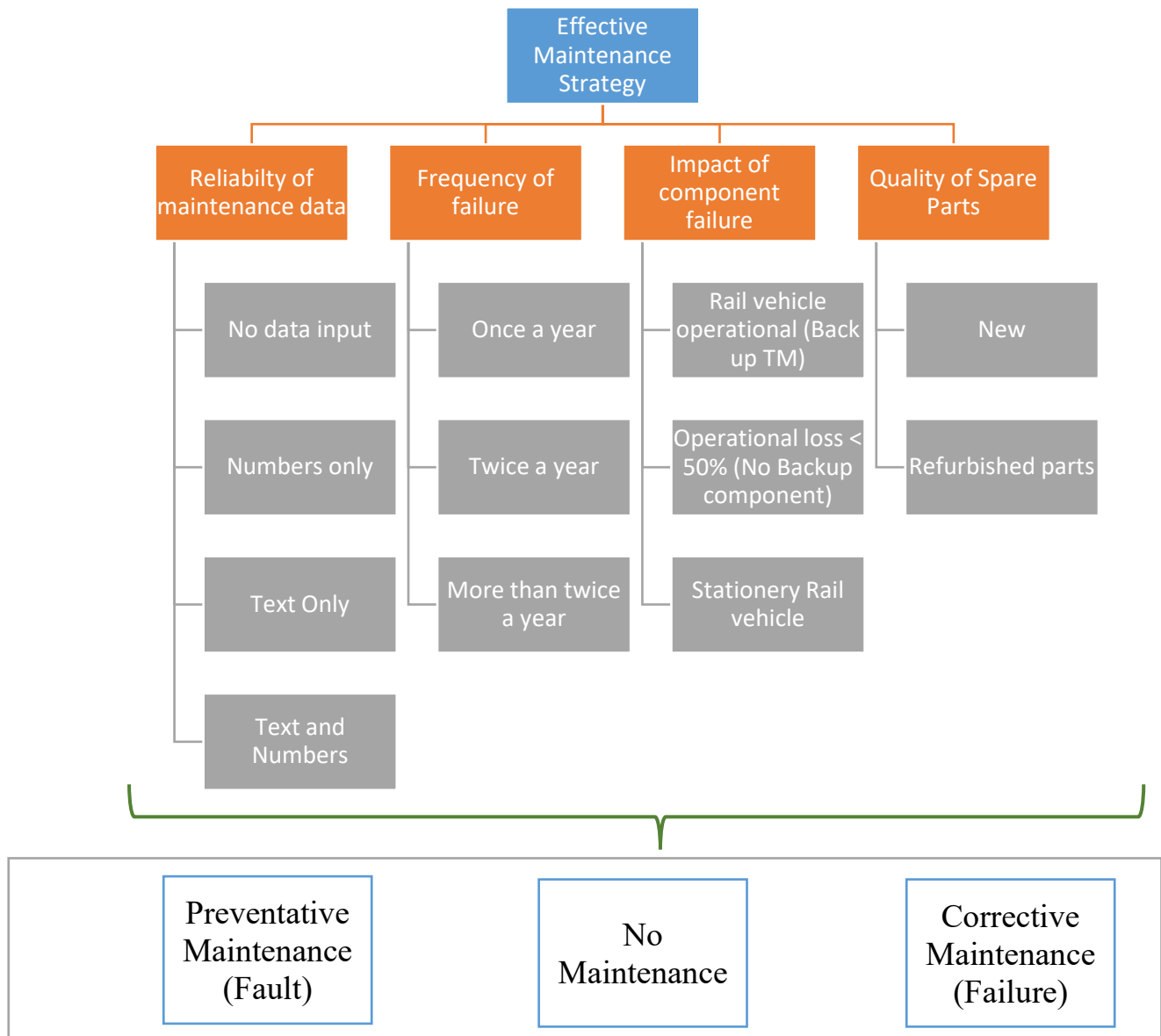


Figure 11: Hierarchical Structure of the Maintenance Strategy Problem

Level 1 of the hierarchy represents the overall goal of the study, level 2 of the hierarchy lists the attributes of each of the rail vehicle components to be evaluated and level 3

outlines the paired comparison of each criteria and level 4 shows maintenance strategy choices within each criterion.

4.4.2 Comparison of the criteria (attributes) with respect to the goal

The comparison of the attributes was carried out by executing the following steps:

4.4.2.1 Pairwise Comparison of the criteria with respect to the goal

A pairwise comparison of the criteria with respect to the goal was carried out by applying the AHP methodology in selecting the best strategy for the rail components and selecting the most critical component of the rail components presented. The selected factors for the study are:

- ✚ Impact of failure on rail vehicle
- ✚ Availability of Spare Part
- ✚ Frequency of failure of the component
- ✚ Reliability of maintenance data

These factors were looked at by experts and expert Judgement was used for scoring which of the factors are more important and its intensity thereof, this is presented in

Table 4. The scoring was based on the Pairwise comparison values presented in Table 1: The fundamental scale of importance of absolute numbers and the outcomes are outlined in Table 4.

Table 4: Expert Judgement

Criteria		More important	Intensity
A	B		
Frequency of failure of the component	Spare Parts (Motor Coach Components)	B	1

Criteria		More important	Intensity
A	B		
Frequency of failure of the component	Effect of failure on rail vehicle	B	3
Frequency of failure of the component	Reliability of maintenance data	A	1
Spare Parts (Motor Coach Components)	Frequency of failure of the component	A	3
Spare Parts (Motor Coach Components)	Effect of failure on rail vehicle	B	5
Spare Parts (Motor Coach Components)	Reliability of maintenance data	A	7
Effect of failure on rail vehicle	Frequency of failure of the component	A	1/1
Effect of failure on rail vehicle	Spare Parts (Motor Coach Components)	A	1/3
Effect of failure on rail vehicle	Reliability of maintenance data	B	1/1
Reliability of maintenance data	Frequency of failure of the component	A	1/3

Criteria		More important	Intensity
A	B		
Reliability of maintenance data	Spare Parts (Motor Coach Components)	B	1/5
Reliability of maintenance data	Effect of failure on rail vehicle	B	1/7

A pairwise comparison of relative importance was carried out between the selected factors that present the rating criteria as presented in Table 5.

Table 5: AHP Pairwise Comparison

Criteria Pairwise Comparison Matrix				
	Impact of failure on rail vehicle	Availability of Spare Part	Frequency of failure of the component	Reliability of maintenance data
Impact of failure on rail vehicle	1.0	1.0	3.0	1.0
Availability of Spare Part	1.0	1.0	3.0	3.0
Frequency of failure of the component	0.3	0.3	1.0	1.0
Reliability of maintenance data	1.0	0.3	1.0	1.0

The inputs into the matrix are informed by expert judgement presented in Table 5

4.4.2.2 AHP Normalized Comparison

The pairwise comparison matrix depicted in Table 5 was then normalized as per AHP methodology and presented in Table 6.

Table 6: AHP Normalized

Normalized Criteria Pairwise Comparison matrix				
	Impact of failure on rail vehicle	Availability of Spare Part	Frequency of failure of the component	Reliability of maintenance data
Impact of failure on rail vehicle	0.300	0.375	0.375	0.167
Availability of Spare Part	0.300	0.375	0.375	0.500
Frequency of failure of the component	0.100	0.125	0.125	0.167
Reliability of maintenance data	0.300	0.125	0.125	0.167
Total	1.0	1.0	1.0	1.0

4.4.2.3 AHP Criteria Weights

The results of the criteria weight highlight which factor/s is the most important when compared to one another: Availability of Spare parts with a weighted value of 0,388 was found to be the most critical factor. The second priority of the factors under consideration being the Impact of failure on rail vehicle with a weighted score of 0,304 followed by the Reliability of maintenance with a weighted score of 0,179 and lastly, Frequency of failure of the component with a weighted score of 0,129. The criteria weight summed up to 1.000 (0.304+0.388+0.129+0.179) for this study.

4.4.2.4 The Consistency of Data

AHP calculations of weighted scores were carried out to determine the consistency ratio of the data to decide presented in Table 7.

Table 7: AHP Weighted score

	Impact of failure on rail vehicle	Availability of Spare Part	Frequency of failure of the component	Reliability of maintenance data	Weighted Sum Value
Impact of failure on rail vehicle	0.304	0.388	0.388	0.179	1.258
Availability of Spare Part	0.304	0.388	0.388	0.538	1.617
Frequency of failure of the component	0.101	0.129	0.129	0.179	0.539
Reliability of maintenance data	0.304	0.129	0.129	0.179	0.742

The weighted sum values were multiplied by the criteria weights to get the ratio of each factor to input in the calculation of the consistency ratio. These ratios are then averaged to get the Eigen max value. The Eigen max value was calculated to be 4,155. This value was then used to calculate the Consistency index using the formula $CI = \frac{\lambda - 1}{n - 1}$ and the value as presented in Appendix 7 was 0,052. The Random index used for the study is 0.900 informed by the number of factors under consideration which is $N = 4$ as per the Table 2. The consistency ratio was calculated using the formula $CR = \frac{CI}{RI}$ and the result presented in Appendix 7. The consistency ratio (CR) is 0.057, it indicates enough consistency for a decision/judgement as its value is < 0.10 (Saati, 1980) as depicted in Appendix 7.

4.4.2.5 The critical weights with respect to goal

The critical weights with respect to goal were computed and the results are presented in Table 8.

Table 8: AHP Criteria Weights

Attributes	Criteria Weights
Impact of failure on rail vehicle	0.304
Availability of Spare Part	0.388
Frequency of failure of the component	0.129
Reliability of maintenance data	0.179

4.4.2.6 Data consistency

The consistency of data results indicated enough consistency for a decision/judgement as its value is < 0.10 (Saati, 1980) as consistency ratio (CR) is 0.057.

4.4.2.7 Attribute Ranking

The attribute ranked as most critical is the availability of spare parts, followed by Impact of failure on rail vehicles, reliability of maintenance data and frequency of component failure respectively.

4.4.3 Comparison of alternatives - application of AHP methodology in selecting the best maintenance strategy

The following steps outline comparison of the alternatives:

4.4.3.1 The critical weights with respect to attributes - selecting the best maintenance strategy

The critical weights with respect to attributes were computed and the results are as follows:

Criteria 1 - AHP for the Impact of Component failure on rail vehicle

Corrective maintenance strategy is the most preferred strategy when dealing with impact of component failure of a rail vehicle, followed by preventative maintenance and no maintenance, with the consistency ratio for the Impact of Component failure on rail vehicle of $0.025 < 0.100$ @ $RI = 0.058$, $n=3$ meaning that the judgement is consistent.

Criteria 2 - AHP for Availability of Spare Parts

Preventative maintenance strategy is the most preferred strategy when looking at the availability of spare parts attribute, with consistency ratio for spare parts of $0.011 < 0.1$ @ $RI = 0.058$, $n=3$ therefore the judgement is consistent.

Criteria 3 - AHP for Frequency of failure of the component

Preventative maintenance strategy is the most preferred strategy when looking at the frequency of failure of the component attribute. The consistency ratio for frequency of failure attribute is $0.033 < 0.1$ @ $RI = 0.058$, $n=3$ therefore the judgement is consistent.

Criteria 4 - AHP for Reliability of maintenance data

Reliability of maintenance data, all the maintenance strategy objectives were found to be equally important. The consistency ratio is $0.000 < 0.1$ @ $RI = 0.058$, $n=3$ therefore the judgement is consistent for this attribute.

4.4.3.2 AHP decision result - Strategy Ranking

The overall comparison of strategies result found that the most is preventative maintenance, the AHP has shown that the preventative maintenance best satisfies all the criteria and judgement. This strategy is followed by the corrective maintenance and No maintenance strategy being the least in the ranking.

4.4.4 Comparison of alternatives - application of AHP methodology in selecting the most critical Component

The following steps in comparison of alternatives in selecting the most critical components of AHP methodology is outlined:

4.4.4.1 The critical weights with respect to attributes

The critical weights with respect to attributes were computed and the results are as follows:

Criteria 1 - AHP for the Impact of Component failure on rail vehicle

The axle was found to be the most critical component followed by the panto, Traction Motor, Compressor, Inverter, MA, MG and Exhauster respectively when looking with impact of component failure of a rail vehicle. The consistency ratio for the Impact of Component failure attribute on rail vehicle of $- 0.442 < 0.100$ @ $RI = 1.41$, $n=8$ meaning that the judgement is consistent.

Criteria 2 - AHP for Availability of Spare Parts

The axle was found to be the most critical component followed by panto, Traction Motor, Compressor, Inverter, MA, MG and Exhauster respectively when looking at the availability of spare parts of a rail vehicle. The consistency ratio for the Impact of Component failure attribute on rail vehicle of - $0.459 < 0.100$ @ $RI = 1.41$, $n=8$ meaning that the judgement is consistent.

Criteria 3 - AHP for Frequency of failure of the component

The axle was found to be the most critical component followed by Traction Motor, panto, Compressor, MA, MG Inverter, and Exhauster respectively when looking at Frequency of failure of the component of a rail vehicle. The consistency ratio for the Impact of Component failure attribute on rail vehicle of - $0.703 < 0.100$ @ $RI = 1.41$, $n=8$ meaning that the judgement is consistent.

Criteria 4 - AHP for Reliability of maintenance data

The axle was found to be the most critical component followed by Traction Motor, panto, Inverter, MA, Compressor, MG and Exhauster respectively when looking at reliability of maintenance data of a rail vehicle. The consistency ratio for the Impact of Component failure attribute on rail vehicle of - $0.616 < 0.100$ @ $RI = 1.41$, $n=8$ meaning that the judgement is consistent.

4.4.4.2 AHP decision – Component Ranking

The most important component ranked in the study is the Axle, followed by the Panto, Traction Motor, Compressor, Inverter, MA, MG and Exhauster respectively.

4.4.5 Validation of the Results (Delphi Method)

The results of the study were validated using the Delphi method, this was carried out through structure interviews with the rail company senior personnel responsible for the

maintenance of the database. The following questions were asked to the rail company personnel and their comments thereof through structured interviews:

1. What are your general comments on the data analysis report submitted?
2. Is there a policy, process or procedure in place that outlining the data capturing requirements?
3. Are there controls in place to ensure that data is captured correctly on the system?
4. Do you report on the data captured on the rail company maintenance system?
5. Were the personnel trained in capturing the data required?
6. A component like a Panto, appears more than 900 times in a period of 4 years in corrective maintenance data, does that raise any alarms in the business?
7. Is a prescribed format that data needs to be captured in?

The responses from the respective personnel were as follows:

1. Frequency of Component Failure

A root cause analysis needs to be carried out on the frequency of failure for TM, this could be due to artisan incompetence and thus may need to train

2. Reliability of maintenance data

The depot needs to distribute failure report and analyze it on a frequent basis to carry out the root cause analysis of component failures. The rail company needs to further investigate the quality of data captured and request the Non-conforming Report (NCR) from supplier of part for analysis. Engineering technicians need to start monitoring the failure rate of Traction Motors

3. Availability of Spare parts

The issue of spare parts that are used more than once as replacement parts cause a major concern as general lifespan of a part once refurbished is 5 years, this will need to be looked at. A process to manage the issue of serial numbers also needs to be looked at for ease of tracking the parts. This will include but not limited to looking as to why spare parts serial numbers are removed and how to manage the process better.

4. Pantographs

The procedure in place for pantographs is such that when a coach leaves the depo and when it returns to the depo, pantograph needs to be check and measured and adjusted by the artisans as a preventative maintenance measure. The high failure of panto over the period is alarming and a course for concern and thus will need to revise the rail company's maintenance strategy.

5. General Concerns

The data analysis report has shown gaps in the daily operations of carrying out the maintenance of components of rail vehicles in the business. The potential cost saving that can be achieved if tasks are carried out correctly and the competence of the artisans in carrying out their duties. The rail company needs to consider capacitating the business to ensure continuous improvement once all the processes, procedures are in place and artisans are trained in the work. The system inputs will need to be revised to suite operational needs and reduce manual input.

Chapter 5 – Discussion

5.1 Introduction

This chapter discusses the outcomes of the study that are presented in Chapter 4 – Results and Analysis. The discussion is limited to the data analysis carried out and the application of AHP methodology results.

5.2 Discussion on the data analysis results

Data analysis of component failure data was carried out on the following components: axle, compressor, exhauster, inverter, Motor Alternator (MA), Motor generator (MG), Pantograph (panto) and a Traction motor (TM). The attributes considered were: Reliability of the maintenance data sourced from the Rail Company database the and overview of the data analysis:

5.2.1 Reliability of Maintenance Data (captured on the Rail Company system)

The data collected for analysis were downloaded directly from the Rail Company database in an excel format after getting permission to use for scholarly advances from a representative of the organization. Other information sought was from literature and was collected from referenced journals and books to meet the reliability of data and information collected in this study. The reliability of maintenance data was grouped into the capturing of reliability of motor coach data and reliability of component data:

5.2.1.1 Reliability of Motor Coach data captured

The reliability of motor coach data captured in the Rail Company database pertaining to the category of motor Coaches can be ascertained in Appendix 3. The number that appears in the category “Vehicle number” which identifies the coaches affected is 551, however 136 inserts were found to be blank which can translate to added number of coaches. These 136 blank inserts in the “Vehicle number” category only had information of components replaced/removed in the data analyzed. In these motor

coaches represented in 551, maintenance of components was carried out more than once a year on either same component or different components.

5.2.1.2 Reliability of Component data captured

The reliability of component data that was by the rail company's personnel is ascertained from information broken down and analyzed in Appendix 4. The components name is captured in different formats and so is not clean data. This data were cleaned over a period and have been reduced to these common parts names for uniformity, however there were components which could not be classified (unknown) into what category they belong as the data captured gave no indication of its component name.

The data in Appendix 4 is broken down into four (4) categories:

1. Where there is no information provided on the field (Blank Information)
2. Where there is a combination of text and numbers as unique identifier (Combination (Text and Numbers))
3. Where there is text only as a unique identifier (Text)
4. Where there are numbers only as unique identifiers (Numbers only)

5.2.2 Overview of the data analysis results

Data reliability results show that there is poor data capturing of the maintenance data in the maintenance system. The frequency of component failure is not consistent considering that in a period of 4 years, components appear as refurbished parts more than once even though the lifespan of a refurbished part is given as 5 years. In addition, some component appearing in this data are not supposed to be reported under corrective maintenance as the company standard is such that preventative maintenance is the strategy deployed to monitor them, for example, a panto. Clearly the standard of capturing data in the rail company's maintenance system is not adhered to. This anomaly is highlighted by (Eryilmaz, 2018) that by Improper location and guidance of components constitutes an important mode of failure often ignored in

mechanical engineering practice. This is evident in that the data captured is not consistent and, in some cases, missing. This could be due to lack of training for the personnel capturing the data and lack of monitoring of the quality of data entered into the system. Components that do not get refurbished such as the panto and inverter should not have high failure rates enlisted in corrective data maintenance database. This can be enforced by following preventative maintenance procedures.

5.3 Discussion on the AHP methodology results

5.3.1 Application of AHP methodology in selecting the best maintenance strategy

The results of the AHP methodology carried out in selecting the best maintenance strategy found that the preventative maintenance strategy is the best approach when dealing with rail vehicle components overall. This is generally accepted considering that the rail vehicles always need to be in service as down times has major cost impact on the business if maintenance is not planned. However, in that approach, one cannot eliminate failure completely that informs the deployment of corrective maintenance strategy. Data is critical in analyzing trends and pointing out areas of improvement and the results support that statement in ranking all the strategies as equally important when it comes to reliability of data captured. The availability of spare parts is critical in the business to minimize downtime when encountered with a failure or fault. The AHP methodology first ranked the factors under consideration and found the analysis to be consistent in decision making as per value of consistency ratio calculated.

This showed that the most important factor was the availability of spare parts; followed by impact of failure on rail vehicle, reliability of maintenance data and the frequency of failure respectively. These findings are consistent with the main task of the maintenance team as they need parts to be available to carry out the work. If this is done then the least ranked factor, frequency of failure can be avoided as it will be maintained according to maintenance schedule. These factors where used in ranking the overall strategy, preventative maintenance strategy. Implementation of the AHP approach can assist in prioritizing the strategy to be deployed to stay productive and avoid any financial losses in the business. The results of the AHP methodology are

consistent with other literature in rating preventative strategy as the best approach for rail vehicle components.

The following computations were presented to arrive at decision:

1. Pairwise Comparison of the criteria with respect to the goal
2. Pairwise comparison, comparing the alternatives with respect to the goal - Selection of the best maintenance strategy.
3. Pairwise comparison, comparing the alternatives with respect to the goal - Selection of the best maintenance strategy.

5.3.1.1 Pairwise comparison, comparing the alternatives with respect to the goal - Selection of the best maintenance strategy. There criteria's that were considered in the study are:

Criteria 1 - AHP for the Impact of Component failure on rail vehicle

The expert judgements that informed the comparisons of criteria used in the AHP computations are presented as input in Appendix 8 using Table 1 for the selected alternatives. The vector of criteria weights was computed, and the results are pulled from the computations and the results are presented in Appendix 1, and finally Appendix 2 that shows Corrective maintenance strategy is the most preferred strategy when dealing with impact of component failure of a rail vehicle, followed by preventative maintenance and no maintenance. The Consistency ratio for the Impact of Component failure on rail vehicle is $0.025 < 0.100$ @ $RI = 0.058$, $n=3$ meaning that the judgement is consistent.

Criteria 2 - AHP for Availability of Spare Parts

The expert judgements that informed the comparisons of criteria used in the AHP computations for Spare Parts are presented as input in Appendix 11 using Table 1 for the selected alternatives. The vector of criteria weights was computed and the results are pulled from the computations presented in Appendix 11, Appendix 12 and finally Appendix 13 that depicts that Preventative maintenance strategy is the most preferred

strategy when looking at the availability of spare parts attribute. The consistency ratio for spare parts is $0.011 < 0.1$ @ $RI = 0.058$, $n=3$ therefore the judgement is consistent.

Criteria 3 - AHP for Frequency of failure of the component

The expert judgements that informed the comparisons of criteria used in the AHP computations for the Frequency of failure of the component are presented as input in Appendix 14 using Table 1 for the selected alternatives. The vector of criteria weights was computed and the results are pulled from the computations presented in Appendix 14 and finally Appendix 16 that illustrates that Preventative maintenance strategy is the most preferred strategy when looking at the frequency of failure of the component attribute. The consistency ratio for frequency of failure attribute is $0.033 < 0.1$ @ $RI = 0.058$, $n=3$ therefore the judgement is consistent.

Criteria 4 - AHP for Reliability of maintenance data

The expert judgements that informed the comparisons of criteria used in the AHP computations for Spare Parts are presented as input in Appendix 17 using Table 1 for the selected alternatives. The vector of criteria weights was computed and the results are pulled from the computations presented in Appendix 17, and finally Appendix 19 that illustrates that comes to the reliability of maintenance data, all the maintenance strategy objectives are equally important. The consistency ratio for frequency of failure attribute is $0.000 < 0.1$ @ $RI = 0.058$, $n=3$ therefore the judgement is consistent.

5.3.2 Making the decision (Best Maintenance Strategy)

In this comparison the sub criteria were used to compare the maintenance strategy rankings. The PV factors calculated for all the criteria are then used as inputs in the AHP results presented in Appendix 20. The weighted scores are calculated using the formula $MMult$ (PV factors) in excel to get the values presented in Appendix 20 that inform the ranking of each strategy. The Final criticality rank of the maintenance strategies obtained by the by AHP methodology highlighted in Appendix 20 shows that the most important strategy with the weighted score of 0.468 is preventative

maintenance, the AHP has shown that the preventative maintenance best satisfies all the criteria and judgement. This strategy is followed by the corrective maintenance with the weighted score of 0.40 and No maintenance strategy with weighted score of 0.13. The decision is to prioritize the strategy that best satisfies all the criteria and judgements in these attribute factors.

5.3.3 Application of AHP methodology in selecting the most critical component

The Final criticality rank of equipment was obtained by applying the AHP methodology and it was found that the most important component with the weighted score of 0.433 is the Axle, as it best satisfies all the criteria and judgement. This component is then followed by the Panto with the weighted score of 0.264; followed by the Traction Motor at 0,216; Exhauster with the score of 0.215; MA with the score of 0,124; Inverter with the lowest score of 0,121; Compressor with the lowest score of 0,118; MG with the lowest score of 0,106. The decision is to prioritize the component that best satisfies all the criteria and judgements using the maintenance strategy expectation index weights with the best maintenance strategy Preventative Maintenance. The global priorities obtained *were* used for ranking of the alternatives and selection of the best maintenance strategy to be deployed.

The following computations were presented to arrive at decision:

1. Pairwise comparison, comparing the alternatives with respect to the goal - Selection of the most critical Component.

5.3.3.1 Pairwise Comparing the alternatives with respect to the goal - Selection of the critical rail vehicle component. There four (4) criteria considered in the study are the same as the ones considered in the selection of best maintenance strategy.

Criteria 1 - AHP for the Impact of Component failure on rail vehicle

The expert judgements that informed the comparisons of criteria used in the AHP computations are presented as input in Appendix 21 using Table 1 for the selected alternatives. The vector of criteria weights was computed and the results are pulled

from the computations presented in Appendix 21, Appendix 22, and finally Appendix 23 that shows Axle as the most critical component when considering the impact of component failure of a rail vehicle followed by Panto, TM, Compressor, Invertor, MA, MG, and exhauster respectively. The Consistency ratio for the Impact of Component failure on rail vehicle is $-0.442 < 0.100$ @ $RI = 1.41$, $n=8$ meaning that the judgement is consistent.

Criteria 2 - AHP for Availability of Spare Parts

The expert judgements that informed the comparisons of criteria used in the AHP computations for Spare Parts are presented as input in Appendix 12 using Table 1 for the selected alternatives. The vector of criteria weights was computed and the results are pulled from the computations presented in Appendix 12, Appendix 13 and finally Appendix 14 that depicts that the Axle as the most critical component when considering availability of spare parts attribute followed by Panto ,TM , Compressor, Invertor, MA, MG, and exhauster respectively. The consistency ratio for spare parts is $-0.459 < 0.1$ @ $RI = 1.41$, $n=8$ therefore the judgement is consistent.

Criteria 3 - AHP for Frequency of failure of the component

The expert judgements that informed the comparisons of criteria used in the AHP computations for the Frequency of failure of the component are presented as input in Appendix 25 using Table 1 for the selected alternatives. The vector of criteria weights was computed, and the results are pulled from the computations presented in Appendix 25, Appendix 28 and finally Appendix 29 that illustrates that depicts that the Axle as the most critical component when considering frequency of failure of the component attribute followed by TM, Panto, Compressor, MA, MG, Invertor and exhauster respectively. The consistency ratio for frequency of failure attribute is $-0.703 < 0.1$ @ $RI = 1.41$, $n=8$ therefore the judgement is consistent.

Criteria 4 - AHP for Reliability of maintenance data

The expert judgements that informed the comparisons of criteria used in the AHP computations for Spare Parts are presented as input in Appendix 30 using Table 1 for the selected alternatives. The vector of criteria weights was computed and the results are pulled from the computations presented in Appendix 30, Appendix 29 and finally Appendix 32 that the Axle is the most critical component when considering the reliability of maintenance data attribute followed by TM, Panto, Invertor , MA, Compressor and MG respectively. The consistency ratio for frequency of failure attribute is $0.616 < 0.1$ @ $RI = 1.41$, $n=8$ therefore the judgement is consistent.

5.4 Overview of results

Microsoft Excel 2010 was used to analyze the compiled AHP data set. The expert judgement table was compiled informed by the AHP scale of importance table and expert advice; these values were used to construct pairwise comparison matrices for the factors. The critical weights were calculated for the factors and the results shows its priority in the ranking of critical factors can be identified that the most important factor is the availability of spare parts with the criteria weight of 0.388, followed by the impact of failure on rail vehicle with 0.304 and the reliability of maintenance data with 0.179. The least important factor is the frequency of failure of the component with 0.129. The criteria weight summed up to 1.000. The CR calculated is lower than the acceptable limit of 1.0 at 0.057, thus the pairwise judgment was found to be consistent.

The Final criticality rank of alternatives obtained by the by AHP methodology is highlighted in Appendix 20 with preventative maintenance being the best strategy overall: When considering the availability of spare parts factor, preventative maintenance strategy is the best strategy to be implemented. When considering the impact of failure on rail vehicle factor, corrective maintenance strategy is the best strategy to be deployed. Whilst the reliability of maintenance data factor has shown equal importance for all strategies under investigations. And finally, the frequency of failure of the component factor, corrective maintenance strategy is the best strategy to be implemented. The Final criticality rank of alternatives obtained by the by AHP

methodology is highlighted in Appendix 33 with the axle being the most critical component overall and including when considering all attributes.

Chapter 6 – Conclusion and Recommendations

6.1 Introduction

This chapter concludes the study outcomes; outlines research limitations, states significance of the study and recommends future work.

6.2 Conclusion

The research conducted in this study promotes the use of the AHP methodology when selecting the best maintenance strategy for a rail vehicle component and in determining the most critical component. The results in the selection of the best maintenance strategy are presented as it was found that preventative maintenance strategy is the best overall strategy together with the results of the AHP analysis conducted on rail components which were represented in the Rail Company data collected and the ranking of the most critical component being the axle using AHP methodology. The objectives of the research were met in that:

Objective 1 sought to select the most appropriate maintenance strategies for the motor coaches' components and the most critical component using AHP methodology

✚ the most appropriate maintenance strategy for the motor coaches' components was identified as the preventative maintenance strategy and the most critical component was also identified as the Axle using AHP methodology.

Objective 2 sought to develop the general framework based on AHP for the selection of optimum maintenance strategy for motor coach components

✚ The general framework based on AHP for the selection of optimum maintenance strategy for motor coach components was developed and used to select the most appropriate maintenance strategies for selecting the motor coaches' critical component.

Objective 3 sought to validate the AHP algorithm results using the Delphi methodology

✚ The results of the study were validated using the Delphi method, this was carried out through structured interviews with the rail company senior personnel responsible for the maintenance of the database.

On the other hand, the research question was: How AHP algorithm can be used in selecting the best maintenance strategies for motor coach components?

The research question was addressed as AHP methodology was carried out in selecting the best maintenance strategies for motor coach components. The purpose of the study to address decision making ability in the selection of an optimum maintenance strategy for motor coach components was reached and results presented that preventative maintenance strategy is the most appropriate maintenance strategies for the selection of motor coaches' components. The results of the study are consistent with literature as the study by (Cheng, et al., n.d.) adopted the Analytical network Process (ANP) methodology in concluding that preventative maintenance strategy was superior than the other two maintenance strategies with maintenance strategy index values of 0.607; 0.244 and 0.149 respectively.

6.3 Significance of the Study

The significance of the study is that it supports other studies that preventative maintenance is the best maintenance strategy and axle ranked as most critical component in a rail vehicle. This contributes in developing knowledge in the field of study as AHP methodology has been demonstrated as a necessary tool in selecting the best maintenance strategy and determining the criticality of components in question.

6.4 Research Limitations

The maintenance data provided by the rail company did not have a clear indication of the maintenance strategy deployed for each component removed. The data captured were not consistent and did not include timelines of when a coach was scheduled for the removal of a given part and when it was replaced and sent back to production. The data presented needed to be cleaned up before it could be used for analysis with a lot

of unknowns presented. The components data provided were limited to corrective maintenance data, this was indicated by the maintenance personnel only when presenting the data analysis report to the rail company personnel. The quality of data provided therefore could not be used directly as inputs in the AHP methodology and thus limited the ability to answer effectively to the research question without using expert advice. Poor data capturing results in poor methods of data collection. The proposed methodology in selecting the best maintenance strategy could be even more relevant if the inputs in judgement were based wholly on maintenance data rather than expert judgement, hence it may need validation by implementation.

6.5 Further Research

Further research is needed in addressing the limitations of this study. The following studies are proposed in particular: The correlation of failure data and reliability analysis of maintenance schedule within preventative maintenance strategy and reliability centered maintenance.

6.6 Recommendations

The AHP methodology provides an effective guide for the rail company operations to adopt when making maintenance strategy decisions to set priorities and thus making the best decision. It is recommended that the model be introduced to the responsible personnel for consideration in implementation in the business. The rail company will need to review their processes, procedures and align to the system requirements to ensure it guides improvement and cost saving for the business. It is further recommended that the rail company offers training to the data capturing personnel on what to capture and how to capture. The system in use needs to be further developed such that it produces production reports on the data captured for effective monitoring of parts removal and replacement on rail vehicles. AHP methodology can also be used to rank the critical components in the business using the data presented

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Appendixes

Appendix 3: Motor Coach data Composition

Range	Number of times a motor coach was affected (Known)
Range between 1 to 10 failures (2014-2018)	203
Range between 11 to 20 failures (2014-2018)	130
Range between 21 to 30 failures (2014-2018)	131
Range between 31 to 40 failures (2014-2018)	62
Range between 41 to 70 failures (2014-2018)	53
Unknown	136

Appendix 4: Component Data Composition

Components	Blank information	Combination (Text and Numbers)	Text only	Numbers only
Axle	33	840	169	2
Compressor	81	261	392	392
Exhauster	135	781	850	233
Inverter	0	0	7	0
MA	30	567	143	3
MG	82	704	335	14
Panto	59	200	637	23
TM	116	925	516	1249
Unknown	116	12	11	4
Total	652	4290	3060	1920

Appendix 5: Component Frequency of Failure

Component	Frequency of failure of the component	Spare Parts/Components	Impact of failure on rail vehicle	Reliability of maintenance data
Traction Motor	2 909	1 673	1	1 044
Exhauster	1 701	1 048	1	1 126
Axle	1 675	915	3	1 999
Panto	983	637	1	7
Compressor	938	542	1	743
MG	834	517	1	1135
MA	558	339	1	919
Inverter	7	6	1	2806

Appendix 6: AHP Consistency Calculations

	Weighted Sum Value	Criteria Weights	Ratio
Impact of failure on rail vehicle	1.258	0.304	4.14

	Weighted Sum Value	Criteria Weights	Ratio
Availability of Spare Part	1.617	0.388	4.17
Frequency of failure of the component	0.539	0.129	4.17
Reliability of maintenance data	0.742	0.179	4.14

Appendix 7: AHP Consistency Ratio

	EigenMax	4.155
Consistency index (CI)	$E-n/(n-1)$	0.052
Random Index	RI	0.900
Consistency ratio (CR)	CI/RI	0.057

Appendix 8: Pairwise comparison of alternatives: AHP for the Impact of Component failure on rail vehicle

Pairwise Comparison			
	Corrective Maintenance	Preventative Maintenance	No Maintenance
Corrective Maintenance	1.00	1.00	5.00
Preventative Maintenance	1.00	1.00	3.00
No Maintenance	0.20	0.33	1.00
Total	2.20	2.33	9.00

Appendix 9: Normalized table of alternatives: AHP for the Impact of Component failure on rail vehicle

Normalized			
Strategy	Corrective Maintenance	Preventative Maintenance	No Maintenance
Corrective Maintenance	0.45	0.43	0.56

Preventative Maintenance	0.45	0.43	0.33
No Maintenance	0.09	0.14	0.11
Total	1.00	1.00	1.00

Appendix 10: PV factors table of alternatives: Impact of Component failure on rail vehicle

Strategy	Alternative Priority Vector
Corrective Maintenance	0.48
Preventative Maintenance	0.41
No Maintenance	0.11
Total	1.00

Appendix 11: Pairwise comparison of alternatives: Availability of Spare Parts

Pairwise Comparison			
Strategy	Corrective Maintenance	Preventative Maintenance	No Maintenance
Corrective Maintenance	1.00	1.00	5.00
Preventative Maintenance	1.00	1.00	7.00

Pairwise Comparison			
Strategy	Corrective Maintenance	Preventative Maintenance	No Maintenance
No Maintenance	0.20	0.14	1.00
Total	2.20	2.14	13.00

Appendix 12: Normalized table of alternatives: Availability of Spare Parts

Normalized			
Strategy	Corrective Maintenance	Preventative Maintenance	No Maintenance
Corrective Maintenance	0.45	0.47	0.38
Preventative Maintenance	0.45	0.47	0.54
No Maintenance	0.09	0.07	0.08
Total	1.00	1.00	1.00

Appendix 13: PV factors table of alternatives: Availability of Spare Parts

Strategy	Alternative Priority Vector
Corrective Maintenance	0.44
Preventative Maintenance	0.49
No Maintenance	0.08
Total	1.00

Appendix 14: Pairwise comparison of alternatives: Frequency of failure of the component

Pairwise Comparison			
Strategy	Corrective Maintenance	Preventative Maintenance	No Maintenance
Corrective Maintenance	1.00	0.33	3.00
Preventative Maintenance	3.00	1.00	5.00
No Maintenance	0.33	0.20	1.00

Pairwise Comparison			
Strategy	Corrective Maintenance	Preventative Maintenance	No Maintenance
Total	4.33	1.53	9.00

Appendix 15: Normalized table of alternatives: Frequency of failure of the component

Normalized			
Strategy	Corrective Maintenance	Preventative Maintenance	No Maintenance
Corrective Maintenance	0.23	0.22	0.33
Preventative Maintenance	0.69	0.65	0.56
No Maintenance	0.08	0.13	0.11
Total	1.00	1.00	1.00

Appendix 16: PV factors table of alternatives: Frequency of failure of the component

Strategy	Alternative Priority Vector
Corrective Maintenance	0.26
Preventative Maintenance	0.63
No Maintenance	0.11

Appendix 17: Pairwise comparison of alternatives: Reliability of maintenance data

Pairwise Comparison			
Strategy	Corrective Maintenance	Preventative Maintenance	No Maintenance
Corrective Maintenance	1.00	1.00	1.00
Preventative Maintenance	1.00	1.00	1.00
No Maintenance	1.00	1.00	1.00

Appendix 18: Normalized table of alternatives: Reliability of maintenance data

Normalized			
Strategy	Corrective Maintenance	Preventative Maintenance	No Maintenance
Corrective Maintenance	0.33	0.33	0.33
Preventative Maintenance	0.33	0.33	0.33
No Maintenance	0.33	0.33	0.33
Total	1.00	1.00	1.00

Appendix 19: PV factors table of alternatives: Reliability of maintenance data

Strategy	Alternative Priority Vector
Preventative Maintenance	0.33
Corrective Maintenance	0.33
No Maintenance	0.33

Appendix 20: Summary of AHP results (Strategy Ranking)

Final criticality rank of Strategy by AHP methodology					
Selection Criteria	Impact of failure on rail vehicle	Availability of Spare Part	Reliability of maintenance data	Frequency of failure of the component	Ranking
Corrective Maintenance	0.480	0.435	0.333	0.260	0.40
Preventative Maintenance	0.405	0.487	0.333	0.633	0.47
No Maintenance	0.115	0.078	0.333	0.106	0.13

Critical Component Ranking Tables

Appendix 21: Pairwise comparison of alternatives: AHP for the Impact of Component failure on rail vehicle

Pairwise Comparison								
	Panto	Traction Motor	Axle	Compressor	Inverter	MA	MG	Exhauster
Panto	1.0	2.0	5.0	4.0	3.0	2.0	3.0	2.0
Traction Motor	0.5	1.0	5.0	2.0	3.0	3.0	2.0	5.0
Axle	0.2	0.2	1.0	8.0	7.0	7.0	7.0	9.0
Compressor	0.3	0.5	0.1	1.0	4.0	3.0	4.0	5.0
Inverter	0.3	0.3	0.1	0.3	1.0	3.0	3.0	5.0
MA	0.5	0.3	0.1	0.3	0.3	1.0	4.0	5.0
MG	0.3	0.5	0.1	0.3	0.3	0.3	1.0	4.0
Exhauster	0.5	0.2	0.1	0.2	0.2	0.2	0.3	1.0

Appendix 22: Normalized table of alternatives: AHP for the Impact of Component failure on rail vehicle

Normalized								
	Panto	Traction Motor	Axle	Compressor	Inverter	MA	MG	Exhauster
Panto	0.3	0.4	0.4	0.2	0.2	0.1	0.1	0.1
Traction Motor	0.1	0.2	0.4	0.1	0.2	0.2	0.1	0.1
Axle	0.1	0.0	0.1	0.5	0.4	0.4	0.3	0.3
Compressor	0.1	0.1	0.0	0.1	0.2	0.2	0.2	0.1
Inverter	0.1	0.1	0.0	0.0	0.1	0.2	0.1	0.1
MA	0.1	0.1	0.0	0.0	0.0	0.1	0.2	0.1
MG	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1
Exhauster	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Appendix 23: PV factors table of alternatives: Impact of Component failure on rail vehicle

Component	Criteria Weights
Panto	0.224
Traction Motor	0.178
Axle	0.244
Compressor	0.114
Inverter	0.082
MA	0.076
MG	0.050
Exhauster	0.032

Appendix 24: Pairwise comparison of alternatives: Availability of Spare parts

Pairwise Comparison								
	Panto	Traction Motor	Axle	Compressor	Inverter	MA	MG	Exhauster
Panto	1.0	3.0	4.0	3.0	2.0	3.0	2.0	2.0
Traction Motor	0.3	1.0	4.0	2.0	3.0	2.0	3.0	2.0
Axle	0.3	0.3	1.0	8.0	7.0	8.0	8.0	9.0
Compressor	0.3	0.5	0.1	1.0	3.0	2.0	3.0	1.0
Inverter	0.5	0.3	0.1	0.3	1.0	2.0	2.0	2.0
MA	0.3	0.5	0.1	0.5	0.5	1.0	3.0	2.0
MG	0.5	0.3	0.1	0.3	0.5	0.3	1.0	3.0

Exhauster	0.5	0.5	0.1	1.0	0.5	0.5	0.3	1.0
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Appendix 25: Normalized table of alternatives: Availability of Spare parts

Normalized								
	Panto	Traction Motor	Axle	Compressor	Inverter	MA	MG	Exhauster
Panto	0.3	0.5	0.4	0.2	0.1	0.2	0.1	0.1
Traction Motor	0.1	0.2	0.4	0.1	0.2	0.1	0.1	0.1
Axle	0.1	0.0	0.1	0.5	0.4	0.4	0.4	0.4
Compressor	0.1	0.1	0.0	0.1	0.2	0.1	0.1	0.0
Inverter	0.1	0.1	0.0	0.0	0.1	0.1	0.1	0.1
MA	0.1	0.1	0.0	0.0	0.0	0.1	0.1	0.1
MG	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1
Exhauster	0.1	0.1	0.0	0.1	0.0	0.0	0.0	0.0

Appendix 26: PV factors table of alternatives: Availability of Spare parts

Component	Criteria Weights
Panto	0.224
Traction Motor	0.161
Axle	0.287
Compressor	0.087
Inverter	0.071
MA	0.065
MG	0.056
Exhauster	0.050

Appendix 27: Pairwise comparison of alternatives: Reliability of maintenance data

Pairwise Comparison								
	Panto	Traction Motor	Axle	Compressor	Inverter	MA	MG	Exhauster
Panto	1.0	1.0	3.0	1.0	1.0	1.0	1.0	3.0
Traction Motor	1.0	1.0	5.0	1.0	1.0	1.0	1.0	3.0
Axle	0.3	0.2	1.0	4.0	4.0	4.0	4.0	7.0
Compressor	1.0	1.0	0.3	1.0	2.0	1.0	1.0	3.0
Inverter	1.0	1.0	0.3	0.5	1.0	1.0	1.0	3.0
MA	1.0	1.0	0.3	1.0	1.0	1.0	1.0	3.0
MG	1.0	1.0	0.3	1.0	1.0	1.0	1.0	3.0
Exhauster	0.3	0.3	0.1	0.3	0.3	0.3	0.3	1.0

Appendix 28: Normalized table of alternatives: Reliability of maintenance data

Normalized								
	Panto	Traction Motor	Axle	Compressor	Inverter	MA	MG	Exhauster
Panto	0.2	0.2	0.3	0.1	0.1	0.1	0.1	0.1
Traction Motor	0.2	0.2	0.5	0.1	0.1	0.1	0.1	0.1
Axle	0.1	0.0	0.1	0.4	0.4	0.4	0.4	0.3
Compressor	0.2	0.2	0.0	0.1	0.2	0.1	0.1	0.1
Inverter	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1
MA	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1
MG	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1
Exhauster	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0

Appendix 29: PV factors table of alternatives: Reliability of maintenance data

Component	Criteria Weights
Panto	0.137
Traction Motor	0.162
Axle	0.248
Compressor	0.114
Inverter	0.097
MA	0.103
MG	0.103
Exhauster	0.035

Appendix 30: Normalized table of alternatives: Frequency of failure of the component

Pairwise Comparison								
	Panto	Traction Motor	Axle	Compressor	Inverter	MA	MG	Exhauster
Panto	1.0	1.0	3.0	4.0	1.0	1.0	1.0	3.0
Traction Motor	1.0	1.0	5.0	3.0	2.0	1.0	3.0	1.0
Axle	0.3	0.2	1.0	8.0	8.0	7.0	7.0	7.0
Compressor	0.3	0.3	0.1	1.0	4.0	1.0	1.0	3.0
Inverter	1.0	0.5	0.1	0.3	1.0	1.0	3.0	5.0
MA	1.0	1.0	0.1	1.0	1.0	1.0	1.0	3.0
MG	1.0	0.3	0.1	1.0	0.3	1.0	1.0	3.0
Exhauster	0.3	1.0	0.1	0.3	0.2	0.3	0.3	1.0

Appendix 31: Normalized table of alternatives: Frequency of failure of the component

Normalized								
	Panto	Traction Motor	Axle	Compressor	Inverter	MA	MG	Exhauster
Panto	0.2	0.2	0.3	0.2	0.1	0.1	0.1	0.1
Traction Motor	0.2	0.2	0.5	0.2	0.1	0.1	0.2	0.0
Axle	0.1	0.0	0.1	0.4	0.5	0.5	0.4	0.3
Compressor	0.0	0.1	0.0	0.1	0.2	0.1	0.1	0.1
Inverter	0.2	0.1	0.0	0.0	0.1	0.1	0.2	0.2
MA	0.2	0.2	0.0	0.1	0.1	0.1	0.1	0.1
MG	0.2	0.1	0.0	0.1	0.0	0.1	0.1	0.1
Exhauster	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0

Appendix 32: PV factors table of alternatives: Frequency of failure of the component

Component	Criteria Weights
Panto	0.148
Traction Motor	0.179
Axle	0.285
Compressor	0.081
Inverter	0.098
MA	0.091
MG	0.071
Exhauster	0.046

Appendix 33: Summary of AHP results (Component Ranking)

Final criticality rank of equipment by AHP methodology						
Components	Impact of failure on rail vehicle	Availability of Spare Part	Reliability of maintenance data	Frequency of failure of the component	Weighted Overall Score	Ranking
Panto	0.22	0.22	0.14	0.15	0.199	2
Traction Motor	0.18	0.16	0.16	0.18	0.169	3
Axle	0.24	0.29	0.25	0.29	0.268	1
Compressor	0.11	0.09	0.11	0.08	0.098	4
Inverter	0.08	0.07	0.10	0.10	0.082	5
MA	0.08	0.06	0.10	0.09	0.078	6
MG	0.05	0.06	0.10	0.07	0.063	7
Exhauster	0.03	0.05	0.04	0.05	0.042	8