

**ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
AFRICAN RAILWAY CENTER OF EXCELLENCE**



**ROLLINGSTOCK MAINTENANCE STRATEGY SELECTION BY APPLICATION
OF THE ANALYTIC NETWORK PROCESS ALGORITHM**

CASE STUDY: ADDIS ABABA LIGHT RAILTRANSIT SERVICE

A Thesis in Railway Engineering (Rolling stock)

BY

CATHERINE ATUHEISE

July 04 2019

Addis Ababa

A Thesis

Submitted in Partial Fulfillment of the requirements for the Degree of Master of Science in

Railway Engineering (Rolling stock)

Declaration

The undersigned have examined the thesis entitled ‘**Rollingstock Maintenance Strategy Selection by Application of the Analytic Network Process Algorithm**’ presented by **CATHERINE ATUHEISE**, a candidate for the degree of **Master of Science in Railway Engineering (Rollingstock)** and hereby certify that it is worthy of acceptance.

Dr. Daniel Tilahun
Advisor’s Name	Signature	Date
Mr. Muluken Assefa
Advisors Name	Signature	Date
Mr. Berhailu Mamo
Internal Examiner	Signature	Date
Mr. Haileleoul Mamo
External Examiner	Signature	Date
.....
Chairperson	Signature	Date

Undertaking

I certify that research work titled “*Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm*” is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

.....

Signature of Student

CATHERINE ATUHEISE

Name of Student

Acknowledgements

First and foremost, I offer my sincerest gratitude to my supervisors Dr. Daniel Tilahun and Mr. Muluken Assefa who have supported me throughout the period of carrying out my thesis research with patience, advice and guidance. I appreciate their vast knowledge and skills in many areas and their assistance in writing reports. Besides my advisors, I would like to thank all my professors and lecturers for their encouragement, and insightful comments during my period of study. I would also like to thank all the maintenance staff and managers from different departments and everyone at AALRT who rendered their support during the data collection phases for my thesis at Ayat, Kality and at the ERC. I would like to thank my husband and family who have been a source of inspiration and determination. My husband who was so patient and supportive throughout my master's studies.

Lastly but definitely not the least, I want to express my most heartfelt thanks to my God almighty up in heaven who has taken me through so many trials and challenges and has seen me to the end of this course. I cannot appreciate Him enough.

Abstract

Industries are facing a lot of challenges such as the optimization of operation and maintenance function due to the continually evolving world of technologies, global competitiveness, environmental and safety requirements. Thus, this study sets out to select an appropriate maintenance strategy with the use of one of the various Multi-Criteria Decision Making (MCDM) methods known as Analytic Network Process (ANP). This study is aimed at selecting an appropriate maintenance strategy to be adopted at AALRTS. This consists of determination of evaluating criteria and maintenance strategies to be used in the study. Thereafter, there is formation of a model, pairwise comparisons based on the model formulated and validation of a model and to achieve this, a survey is carried out in three phases using questionnaires to be filled by a group of experts from the Addis Ababa University, Ethiopian Railway Corporation and Addis Ababa Light Rail Transit depot maintenance and management personnel to narrow down the evaluating criteria that were gotten from the literature review. The model used to analyze and evaluate the data is Analytic Network Process (ANP) and a software, SUPERDECISION is used to assist with the analysis. The results obtained is Total Productive Maintenance as the most recommended suitable maintenance strategies and Corrective maintenance as the least recommended alternative. The strategies currently being utilized at AALRT are preventive maintenance and corrective maintenance. Application of the new recommended strategy (CBM & TPM) can improve company operations, improve the whole system safety, improve company profitability and hence competitiveness.

Keywords: ANP, Maintenance, strategy selection, super-decision

List of Figures

Figure 1: Structural difference between a Hierarchy(a) and a Network(b)	29
Figure 2: a) Hierarchy & b) Network (Momoh and Zhu, 1998; Chung, Lee and Pearn, 2005)	34
Figure 3: An overview of the methodology of selection of an appropriate maintenance strategy	37
Figure 4: Levels of competence of the decision makers	49
Figure 5: ANP Model showing clusters containing sub-criteria.....	65
Figure 6: ANP Model showing clusters and all the interconnections, loops and feedback connections..	66
Figure 7: Pair-wise comparisons in generated questionnaire	69
Figure 8: The final priorities of alternative maintenance strategies	71
Figure 9: The priorities of all the nodes in the model.....	72
Figure 10: Priority vectors stacked on top of each other in the Financial feasibility (N16) node column for children nodes from other clusters and the columns (N17,N18) with their own children nodes.....	81
Figure 11: The local priorities of the economic cluster elements in the CBM column(brown)	82
Figure 12: Screen clip of component (block) for the decision Alternatives	83
Figure 13: The (Decision Alternative, Economic factor) component extracted from the unweighted super-matrix	83
Figure 14: The (Decision alternative, Economic factor) component extracted from the Weighted Super-matrix	84
Figure 15: The (Decision alternative, Economic factor) component extracted from the Limit Super-matrix	85

Figure 16: The Goal (Purple) column extracted from the Limit matrix indicate the final synthesized values (the Raw values) 86

Figure 17: The final synthesized result..... 87

Figure 18: Node Sensitivity graph with original parameter value, p at 0.5 89

Figure 19: Node sensitivity graph with parameter value, p moved to 0.08 90

List of Tables

Table 1: Extracted criteria and source of extraction	44
Table 2: The 42 originally selected factors with explanations	47
Table 3: Comprehensive assessment of competence of Decision Makers	48
Table 4: Distribution of the final selection of the Decision Makers.....	50
Table 5: The Quartile Deviation and the Geometric Mean values for the factors	54
Table 6: The total of the 25 refined factors.....	56
Table 7: The seven leading factors and the sub-factors contained there in	58
Table 8: T the Leading factors selected and the contained coded elements(sub-factors).....	59
Table 9: A final interdependency matrix that integrates all 6/10 opinions demonstrating the influences between sub-criteria	61
Table 10:A final dependency matrix/zero-one matrix demonstrating the influences between sub-criteria	62
Table 11: The priorities of the nodes in the model.	73
Table 12: The unweighted super-matrix	75
Table 13: Weighted super-matrix	77
Table 14: The Limit matrix.....	79
Table 15: The ranks for the different alternatives based on two different parameter values.....	91
Table 16: The Influence analysis	109
Table 17: The Rank Influence analysis.....	111
Table 18: The Marginal Influence analysis	113
Table 19: A table showing the perspective analysis in the perspective of improved company brand ...	113

Table 20: The unweighted super-matrix of the ANP model.....	115
Table 21: The weighted super-matrix of the ANP model.....	115
Table 22: The Limit matrix of the ANP model.....	117

Abbreviations

ANP: Analytic Network Process

AHP: Analytic Hierarchy Process

AALRTS: Addis Ababa Light Rail Transit Service

TPM: Total Productive Maintenance

CBM: Condition Based Maintenance

CM: Corrective Maintenance

MCDM: Multi-Criteria Decision Making

DM: Decision Maker

PCM: Pair-wise Comparison

WMS: World Class Maintenance Systems

TFN: Triangular Fuzzy Number

ERC: Ethiopian Railway Corporation

AAIT: Addis Ababa Institute of Technology

Table of Contents

Declaration	i
Undertaking.....	ii
Acknowledgements.....	iii
Abstract	iv
List of Figures	v
List of Tables	vii
Abbreviations	ix
Chapter one: Introduction	1
1.1 Background.....	1
1.2 Problem Statement	6
1.2.1 Research Questions	7
1.3 Objectives	7
1.3.1 General Objective	7
1.3.2 Specific Objectives	7
1.4 Scope of the work / Delimitations	8
Chapter two: Literature Review	9
2.1 Introduction.....	9
2.2 Multi–criteria Decision Making Models.....	9
2.2.1 MCDMs Applied in Manufacturing plants	9

2.2.2 MCDM approaches carried out at Power Plants.....	14
2.2.3 MCDMs for selecting Equipment.....	15
2.2.4 MCDMs Applied to Building Facilities.....	15
2.2.5 MCDMs Applied to Power Distribution Systems	16
2.2.6 MCDMs For Criticality Analysis.....	16
2.3 Maintenance Strategies	21
2.3.1 Periodic Preventive Maintenance (PPM).....	22
2.3.2 Corrective Maintenance (CM)	25
2.3.3 Condition-Based Maintenance (CBM)	26
2.3.4 Total Productive Maintenance (TPM)	27
2.4 The ANP Process	28
2.4.1 Model Assembly and Problem Construction.....	29
2.4.2 Pairwise Comparison Matrices (PCMs) and Eigen Vector Calculations.....	30
2.4.3 Forming Super-Matrices and calculating weights	32
2.4.4 Selection of the best alternative decision.....	35
Chapter Three: Research Methodology	37
3.1 General Research Design.....	37
3.2 Sample.....	38
3.3 Data Collection Procedure	38

3.4 Data Collection Instrument	39
3.5 Data Analysis	40
Chapter four: Model formulation.....	41
4.1 Identification of potential Maintenance alternatives for the model	41
4.2 Selection of Appropriate Criteria.....	41
4.3 Forming an expert panel.	47
4.4 Questionnaire Design and Investigation	50
4.5 Aggregating Individual Opinions of Expert Panel.....	51
4.5.1 Geometric mean	52
4.6 Setting the standards for unanimity among the expert panel.....	55
4.7 Network construction.....	56
4.8 Assessing dependency among criteria	60
4.9 Construction of The ANP Model.....	62
4.10 ANP Pairwise comparisons.....	67
Chapter five: Results and Discussion	70
5.1 Results.....	70
5.1.1 The final Results: The Priorities of the Alternatives	70
5.1.2 The Priorities of all the nodes	72
5.1.3 Formation of the Unweighted Super-matrix	74

5.1.4 Formation of the weighted Super-matrix	76
5.1.5 Formation of limiting matrix	78
5.2 Discussion of Results	80
5.2.1 Discussion of the Unweighted Super-Matrix.....	80
5.2.2 Discussion of the weighted Super-matrix	84
5.2.3 Discussion of the Limit Super-matrix.....	84
5.2.4 Discussion of the Synthesized values	87
5.3 Sensitivity Analysis of Model.....	88
5.3.1 Sensitivity analysis on the final outcome.....	88
5.3.2 Influence Analysis	91
5.3.3 Rank Influence	92
5.3.4 Marginal Influence.....	92
5.3.5 Perspective Analysis	93
Chapter Six: Conclusions, Recommendations and Future Work.....	94
6.1 Conclusions of the study.....	94
6.2 Recommendations.....	96
6.2.1 Limitations of the ANP-based Framework for Maintenance Strategy Evaluation	97
6.3 Future work.....	98
Bibliography	99

Appendix A..... 107

Chapter one: Introduction

The main purpose of this chapter is to introduce the current situation all over the world in the maintenance sector and use of Multi-Criteria Decision-Making models (MCDMs). Also, it includes the discussion of the problem and the purpose of solving it, the objectives, The scope of work and limitations.

1.1 Background

A large percentage of companies still believe that maintenance costs are minimal or negligible. However, with the growing competitiveness in the business world and the criticality of some elements like product quality, safety, and product reliability, it is increasingly becoming of urgent importance to use an optimum maintenance strategy that keeps maintenance costs to a minimal at the same time ensure improved reliability, safety and quality of the product. Maintenance costs make up an vital part of the operating budget of manufacturing firms. It has been noted by (Moubray, 1997) that over the past twenty years, there has been an alteration in the field of maintenance, and even more so than any other management discipline. These alterations are because of the huge increase in the number and variety of physical assets (Plant, equipment, buildings) which need to be maintained throughout the globe. This has also been due to more compound designs, new maintenance strategies and changing views on maintenance organization and responsibilities. (Moubray, 1997) reported that the changes are testing attitudes and skills in all subdivisions of the industry to the limit. Maintenance personnel have had to utterly adopt to new ways of doing things and acting as engineers and managers. However, the shortcomings of maintenance systems are increasingly becoming clear as much as they are computerized. Moubray went ahead to explain that in face of this massive change, managers everywhere are looking for a novel approach to maintenance in order to avoid wrong starts and dead ends which

cause disruptions. (Mckone and Weiss, 1998) reported that the amount of money Du Pont spent, in 1991, company-wide on maintenance was approximately equal to its net income. Al-Najjar (1997) reported how maintenance expenses vary depending on the type of industry; typically, figures such as 15–40% of production costs may be encountered.

Maintenance plays a key role in keeping availability and reliability levels, product quality, and safety requirements (Mobley, 2002). The economic downturn and the dynamic business environment drive companies to seek more efficient and effective maintenance (Van Horenbeek, Pintelon, & Muchiri, 2010) that industries try to sustain full production capabilities while minimizing capital investment (Eti, Ogaji, & Probert, 2006). As indicated by (Mobley, 2008), one-third of all of the maintenance costs are wasted as a result of inefficient maintenance management methods. The use of inefficient maintenance policies considerably increases the direct maintenance costs (Rastegari and Mobin, 2016). On the other hand, the manufacturing firms are under great pressure to continuously reduce their production costs. One of the main expenditure items for these firms is their maintenance costs, which can comprise up to 15%-70% of the overall production costs according to the type of industry (Bevilacqua and Braglia, 2000); Rastegari and Bengtsson, 2015).

Railway transportation system is experiencing an extensive transformation these days. Over the past few decades, the demand for railway transportation worldwide has increased overwhelmingly. Provision of reliable rolling stock and infrastructure equipment is an important part of achieving high levels of safety. Therefore, the railway industry is looking for ways to improve the performance of subsystems in order to ensure safety and reliability of services, (Rezvanizani *et al.*, 2009). Maintenance activities play a key role to offer these standards of services. (Marten Jr, 2010) reported that, according to the American Public Transportation Association (APTA), heavy rail transit agencies in 2005 disbursed not less than

\$5.2 billion dollars while maintaining rolling stock, which represents a very significant amount of their operating budget. Heavy rail transit agencies rely on their fleet of rolling stock to move their passengers from one point to another. Therefore, the lack of a properly maintained fleet could create service problems that result in a change in ridership at the affected agency. According to (Digital McKinsey, 2017)The rail sector is not exclusive when it comes to warped changes through digitization. In a sector where fleet reliability is a key factor for increasing efficiency and reducing total operation costs, big data and advanced analytics solutions such as condition-based maintenance and predictive maintenance represent a great opportunity to yield the next big efficiency leap in maintenance and that includes reducing the number of failures, the amount of unplanned maintenance and, eventually, the required level of reserve asset capacity for rail operators. The term “light railway” in Britain applies to any rail mode that is scaled down from the usual size of incline railroads. A formal definition was adopted and placed in the Transportation Research Board’s Urban Public Transportation Glossary: “*A metropolitan electric railway system characterized by its ability to operate single cars or short trains along exclusive rights of way at ground level, on aerial structures, in subways, or occasionally, in streets and to board and discharge passengers at track or car floor level*” (Boorse, 2000). The Addis Ababa Light Rail Transit (AALRT) began revenue service on September 20, 2015, after three years of construction and was finalized by China Railway Group Limited (CREC). AALRT has 34km. Two depots were constructed at Kality and Ayat where the trains get maintenance. The Kality depot also serves as the headquarter for the Addis Ababa Light Rail Transit (AALRT). The maintenance strategies carried out at these stations is preventive and corrective maintenance (Addis Ababa Light Rail Transit, 2017). In recent years the need to manage the multiple factors of maintenance more effectively since it has gained a lot of attention because of changing operational technologies and the changing organizational role of

maintenance. In the case of light rail transport organization, maintenance has a wider perspective. In such organizations, the scope of maintenance has shifted from a narrowly-defined operational perspective to an organizational strategic perspective. The main challenges faced by organizations today is selecting efficient and effective strategies to enhance and continually improve operational capabilities, diminish maintenance costs and to achieve a higher level of competitiveness in the industry

In recent years, the importance of maintenance strategy selection has been increased due to the critical role it has for increasing the availability, the safety, and the mean time to failures, improvement of system reliability and product quality, reducing shutdown time of factory, and preventing unnecessary investments, (Wireman, 2005). (Cheng and Tsao, 2010) reported that the selection of a suitable rolling stock maintenance strategy is complicated. The system operator needs to simultaneously consider non-metric evaluation factors (safety, quality) and metric evaluation factors (maintenance cost, inventory cost, shortage cost) to select an appropriate strategy. In addition, the strategy selection should consider important interactions among evaluation factors. There are a lot of research studies that have been made over the years concerning multi-criteria decision-making methods (MCDMs) that have been used for selection purposes. Various methodologies have been used for selecting a suitable maintenance strategy in the literature and these are known as Multi-Criteria Decision-Making Methods (MCDMs). They include examples like; AHP, ANP, Fuzzy Set theory, ELECTRE, TOPSIS. These methods have been used in several research methods in different fields for example; (Zaim *et al.*, 2012) suggested the use of ANP and AHP algorithms for maintenance strategy selection at a local printing newspaper in Turkey, (Rahimi, Sadinejad and Damghani, 2014) proposed the use of ANP incorporated with the fuzzy set theory to determine the most appropriate maintenance strategy at Saipa vehicle industry, (Houria, Besbes and Elaoud, 2015) proposed use of Fuzzy AHP and Fuzzy TOPSIS to select the best maintenance

strategies for hospital equipment.(Borjalilu and Ghambari, 2018) carried out a study using Fuzzy ANP method to select an optimum maintenance strategy for a 5-MW powerhouse. In addition, (Aghae and Fazli, 2012),(Jajimoggala, Rao and Satyanarayana, 2011),(Carnero and Gómez, 2017),(Hemmati *et al.*, 2018),(Fattahi and Askarizadeh, 2013), (Dachyar, Nurcahyo and Tohir, 2018), (Seiti *et al.*, 2017a), (Sankpal, Andrew and Kumanan, 2015), (Sadeghi and Manesh, 2012), (Nezami and Yildirim, 2013) etc. have all made studies concerned with application of MCDM methods. However, all these authors have made their research studies in other fields exclusive of the railway industry.

From the literature review carried out, it can be seen that most of the case studies carried out are outside the field of the railway industry. The strategies originally used at the AALRT system were corrective and preventive maintenance but there is a need to achieve a higher level of competitiveness in the industry and diminish maintenance costs since there are changing operational technologies and the changing organizational role of maintenance. The studies carried out in Ethiopia to select a suitable maintenance strategy have never put into consideration the use of the ANP model. The ANP (Analytic Network Process) algorithm creates the possibility of more complex inter-relationships among the criteria/factors. In fact, the ANP method is a mathematical method that can deal with all types of dependencies and this is the main reason for choosing the ANP algorithm as the best alternative for selecting an appropriate maintenance strategy for the proposed case study of this paper. Therefore, this research study answers the question that how can the maintenance strategy be selected while considering multiple criteria to cut down on maintenance costs and still improve ridership quality and company competitiveness. The motivation for this work is the existing need for an appropriate maintenance strategy that can eventually lead to improved machine reliability, company profitability, ridership

quality, and customer satisfaction. Therefore, in this research the algorithm, Analytical Network Process (ANP) will be employed in trying to select an appropriate maintenance strategy.

1.2 Problem Statement

Most organizations today experience a huge amount of maintenance costs that can consist of 15-70% of the total production or operation cost depending on the industry. The main challenges faced by these organizations is selecting an efficient and effective strategies to enhance and continually improve operational capabilities, diminish maintenance costs and to achieve a higher level of competitiveness in the industry.

The maintenance methods currently being used at AALRT are preventive maintenance and corrective (Run-to-failure) maintenance methods which may not be effective enough to ensure company profitability and machine reliability and effectiveness.

An incredible amount of work has been done by previous authors concerning maintenance selection methods. Numerous methods have been used such as AHP, ANP, Fuzzy-set, TOPSIS e,t,c. and they have been done mostly in industries, textile, aircraft, hospitals, manufacturing plants from all sorts of different foreign countries but very few have been done in the field of Railway transport. Furthermore, no such work has been done here in Ethiopia especially using the Analytic Network Process(ANP) algorithm therefore this study sets out to carry out a rolling stock maintenance selection process using the ANP algorithm in order to ensure that the AALRT Rollingstock mechanical system can be able to work to its full competence and this means improved reliability of rolling stock, reduced downtime, improved service quality and at the same time, this ensures the company is competitive enough and operating profitably.

1.2.1 Research Questions

The following main research question was developed to reach the research objective.

How can the most optimum Maintenance Strategy be determined for this case study putting into consideration multiple evaluation criteria/factors?

In order to answer this main research question, the following sub research questions will be posed

How are we going to get expert opinions about the evaluation criteria that affect maintenance strategies at AALRT and their dependencies and interdependencies?

What analysis (model) will be used to evaluate the multiple criteria so as to choose one maintenance strategy?

How will the model be used to determine the most optimum maintenance strategy?

1.3 Objectives

1.3.1 General Objective

To carry out selection of an appropriate maintenance strategy that can be implemented for the AALRT system using a Multi-Criteria Decision Making (MCDM) method known as the Analytic Network Process (ANP) algorithm.

1.3.2 Specific Objectives

The objectives of this project are;

- Identification of the appropriate evaluation criteria, sub-criteria to be considered from the survey

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

- Development of the ANP model through criteria categorization and forming criteria interdependencies and interactions.
- Selection of an appropriate maintenance strategy for AALRT rolling stock through carrying out pairwise comparisons.

1.4 Scope of the work / Delimitations

This research study is constrained to the maintenance strategies of the rolling stock of the AALRT system and hence this is exclusive of the track maintenance. There is a wide range of selection criteria that have been used in Literature review but for this study, only a few selected criteria based on the constraints at AALRT are used. All Technical factors are excluded.

The model to be applied in this study is ANP model. The other various models are not used in this study but are mentioned in the introduction section and discussed as part of previous research studies in the Literature Review section. The experts who are sampled to answer the questionnaires are considered to be in any management position, maintenance engineering position or doing any work or related to the knowledge of maintenance. This study is only limited to the two depots at Ayat and Kality in Addis Ababa and ERC (Ethiopian Railway Commission) headquarters and the study does not include implementation of the selected strategy.

Chapter two: Literature Review

2.1 Introduction

This section is basically a description of what research studies have been done in the previous years that is relevant to the subject of multi-criteria decision making for maintenance strategies. There have been so many authors who have made studies about different strategies using all sorts of Algorithms and all sorts of criteria. The literature review is categorized according to the fields in which the MCDM models have been applied and eventually, it narrows down to what has been done in the railway sector.

2.2 Multi-criteria Decision Making Models

The literature in this section is basically a description of the Multi-Criteria Decision-Making Models (MCDMs) that have been applied in different industrial sectors all over the world. The literature is categorized according to the sectors.

2.2.1 MCDMs Applied in Manufacturing plants

(Fattahi and Askarizadeh, 2013) proposed the methodology of fuzzy AHP (Analytic Hierarchy Process) and fuzzy theory to determine the best ERP system that meets business objectives and goals. In this study, a Likert spectrum was used to screen criteria and the importance of each criterion was ascertained using a pairwise comparison questionnaire. Also, seven expert opinions were used for the selection process of the most optimum software package among the three alternatives (A, B, C) provided and the selection was done based on the criteria, C1-C9. Therefore, from the study, it was found that the best-ranked package was package C.

There has been a research done by (Sadeghi and Manesh, 2012) using a fuzzy group Analytic Network Process. The study was done on a case study of Mobarakeh steel company to determine the best

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

maintenance strategy. The fuzzy set theory was incorporated into the conventional ANP to compensate for the vagueness and ambiguities associated with ANP. There were 5 criteria and 12 sub-criteria used. A Pairwise comparison of main factors was conducted using a triangular fuzzy number (TFN) scale and the best alternative obtained after the selection was World Class Maintenance Systems (WMS). Furthermore, it was discovered from the proposed method that the three most important factors in selection of the maintenance strategies were cost, quality, and feasibility.

(Nezami and Yildirim, 2013) suggested a sustainability approach to select the best maintenance strategy and the methodology used was a fuzzy VICOR framework at a manufacturing industry in wichita. Three main sustainability pillars which cover a wide range of criteria were used which include; social/ethical, business/economic and environmental. This study took into consideration a total of 52 sub-criteria which were then condensed by factor analysis (FA) into 12 leading factors after a rotation method is done to transform the data. As much as the study was comprehensive having considered over 50 variables, there must have been a loss of data while using FA to condense into a few lead factors.

A fuzzy FMEA (Failure Mode and Effect Analysis) incorporated in an Integer programming approach is proposed by (Sankpal, Andrew and Kumanan, 2015) to determine an optimum maintenance strategy. RCM was chosen as an application of FMEA and it was embedded with the integer programming approach. Furthermore, the fuzzy inference system was used for risk assessment to obtain RPN values. This model is based on the assumption that applying a certain maintenance strategy to a failure reduces the RPN value and the whole study was very quantitative therefore the author did not take into consideration any social, environmental factors or feasibility and there was no indication of the best strategy selected since it was based on respective criticalities of failure.

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

(Padial and Marín, 2015) carried out a study in an industrial plant based on a purely strategic approach where the AHP technique was applied in consolidation with the BSC (Balanced score-card) in order to solve a decision problem. The alternatives used in this case were four productive areas from which the best area would be chosen to implement the maintenance action and the key performance indicators were taken to be the criteria. A software package, the Expert choice was used in this case to model the problem and analyze the result.

(Hemmati *et al.*, 2018) proposed a methodology of fuzzy- ANP approach to solving the problem of maintenance policy selection for the new seven equipment of the sulfuric acid production plant i.e. absorption tower, boiler, converter, molten sulfur ponds, cooling towers, sulfur fuel furnace, and heat Exchanger. Four maintenance strategies were selected to be investigated and these include; Corrective maintenance (CM), Time-Based Maintenance (TBM), Condition-Based Maintenance (CBM) and Shutdown maintenance (SM) and the criteria that the selection was based on include; Cost, value-added and risk. From the study carried out, it was found that CBM was good for high risk and high added value equipment and TBM was selected for boiler and converters while SM was selected for molten Sulphur ponds. Furthermore, it was found that CM is appropriate for high-cost, low-risk, and low value-added equipment.

(Vishnu and Regikumar, 2016) conducted a study to determine the most appropriate maintenance strategy in a Process plant that manufactures Titanium dioxide. The AHP model was used by incorporating it into one of the RCM processes which are Logic Tree analysis and Task selection. From the five components selected as maintenance significant items of the calcinatory unit, the appropriate maintenance strategies had to be selected using the AHP model. Therefore, from this study, it was found

that all Class A criticality equipment needed preventive maintenance strategy rather than Scheduled maintenance and breakdown maintenance was enough for all other equipment

(Pariazar *et al.*, 2008), proposed the use of AHP methodology improved with Rough set theory. The methodology was applied to the case study of an industrial unit manufacturing standard units like screw basic, spring nuts, gaskets and many others. The study was aimed at finding the most optimum maintenance strategy used for the machinery at this industrial unit. The machinery include; CNC, lathes, Die and Press etc. and the maintenance strategy originally used was corrective maintenance. There were originally 19 criteria considered for the selection process and then by factor analysis were reduced to 10 subfactors and 4 main factors. It was realized after analysis that predictive maintenance had the most weights and corrective maintenance had the least weight.

(Zaim *et al.*, 2012) suggested the use of both ANP and AHP method to select the best maintenance strategy for the newspaper printing industry “ZAMAN” in Turkey. Three maintenance strategies were considered for analysis in this case study and these include; Corrective, Periodic and Predictive maintenance. A hierarchical model was formed based on four main maintenance policy selection criteria and these include; Cost, Value-added, safety and Implementation. This research showed that predictive maintenance was the most suitable maintenance policy for this newspaper firm in both AHP and ANP analyses.

(Sadeghi, Rashidzadeh and Soukhakian, 2012) suggested the use of ANP for selection of the best supplier in a case study at Fars Gas Company (FGC). FGC obtained gas counters from outside suppliers but the gas counters supplied often failed therefore this study was proposed to select the best supplier for gas counters. A Commercial and Technical Committee (CTC) was delegated with 6 members to assist in the selection process. 13 sub-criteria were selected and 3 main criteria were determined after

categorization. It was discovered after analysis that Gas Suzan had ranked as the best supplier and the technical cluster had the highest priority in all other clusters. Also, within the technical cluster, the financial power factor had the most priority.

(Seiti *et al.*, 2017b) presented a study aimed at developing a model of risk-based AHP (RAHP) which was demonstrated at a steel rolling company in order to select the best maintenance strategy. Critical equipment were initially selected and then the important criteria and applicable strategies were determined to choose a proper maintenance strategy by using the opinions of experts and organizational goals. Pairwise comparisons were carried out using Triangular Fuzzy numbers. The results of AHP and RAHP were compared and the results of the comparison showed that TPM was the best maintenance alternative. With the increasing risk, CBM became more rational and this could have been due to the unexecuted CBM policy in the mentioned company.

2.2.2 MCDMs in Automotive Industry maintenance

(Rahimi, Sadinejad and Damghani, 2014) set out to find the best alternative for the maintenance strategy to be applied at Saipa vehicle industry. A network of 28 sub-criteria was formed and 4 main evaluation criteria. The four main criteria that were considered were; Cost, Safety, Added value and Feasibility. Delphi technique was employed to interview the experts in-order to obtain more quality data. The experts used in this study were Maintenance managers from Saipa company and university professors. From the study carried out, it was discovered that the best maintenance strategy for the case study was corrective maintenance. It was also discovered that Added value had the most influence on optimization

of the maintenance strategy. In this study, the data obtained was of good quality because of the Delphi method utilized but sustainability factors were not put into consideration.

(Aghaee and Fazli, 2012) proposed a study by utilization of a combined approach of ANP and DEMATEL (Decision Making Trial and Evaluation Laboratory) to help vehicle companies that need to evaluate and select the best maintenance strategy. The DEMATEL approach was employed for treatment of inner dependencies of criteria before forming the un-weighted super-matrix. In this paper, six alternative maintenance strategies were put into consideration and four criteria were considered; Security requirements, Cost requirements, strategic requirements and Technical requirements. The calculations were carried out with a professional software known as Super-decision and after analysis, Total Productive Maintenance (TPM) was ranked as the best alternative. Post survey discussions were also carried out with the team of ten experts to realize the reason for the final decision and the usefulness of the proposed solution.

2.2.2 MCDM approaches carried out at Power Plants

(Borjalilu and Ghambari, 2018) proposed a methodology of Analytical Network Process with fuzzy set theory for the selection of an optimal maintenance strategy selection with a case study on a 5MW powerhouse. They were 5 main criteria selected after expert consultation from the firm and the best strategy selected was Preventive maintenance. However much the experts had decided on those five main criteria, they did not consider the cost factor and environmental factor which are usually important factors in any organization.

(Dachyar, Nurcahyo and Tohir, 2018) suggested the methodology of AHP (Analytical Hierarchy Process) and TOPSIS (Technique for order preference by Similarity to Ideal Solution) to obtain the most

appropriate alternative to the ideal solution. The four main criteria considered were; Economic, Social, Technical and Environment factors and several sub-criteria. About 10 experts in the field of steam power plants were used for pairwise comparisons to determine the most dominant criteria that could be used to determine the most suitable maintenance strategies.

2.2.3 MCDMs for selecting Equipment

(Houria, Besbes and Elaoud, 2015) proposed the use of the methodologies fuzzy Analytical Hierarchy Process (FAHP) and Fuzzy TOPSIS to determine the most appropriate maintenance strategies for the medical equipment at Habbib Bourguiba Hospital in Sfax. The methodology of Fuzzy AHP was used to determine the criticality of the hospital equipment by determining the criteria weights and Fuzzy TOPSIS was used to rank the maintenance strategies according to criticality. However, this study considered a variety of criteria to determine the strategy but did not consider the cost of the application as a criterion.

(Fazlollahtabar and Yousefpoor, 2008) carried out a study to determine the most optimum maintenance strategy for the different equipment used in a Virtual Learning Environment by use of the Analytic Hierarchy Process (AHP) methodology. There were 4 maintenance strategies were put into consideration; Predictive Maintenance, Time-based Maintenance, Condition Based Maintenance and Corrective Maintenance and there were 4 main evaluation criteria that were also considered in this study; Cost, Safety, Feasibility and Added- Value which had been categorized from 11 sub-criteria. The AHP modeled the problem hierarchically to evaluate the criteria, sub-criteria and alternatives thoroughly

2.2.4 MCDMs Applied to Building Facilities

(Pun *et al.*, 2017) proposed the use of fuzzy AHP Based Decision Support System (FADSS) in maintenance strategy selection in a case study for building facilities maintenance by ABC in Hong King.

FADSS is a cloud-based data management system which was incorporated with AHP and fuzzy set theory. Engineers, technicians and property managers were interviewed to find the most influential criteria and these were considered to be operation flexibility, Reliability, Safety, Installation cost and Operation, and Maintenance cost. From the study made, the proposed effective maintenance strategy was Preventive maintenance, as much as this study was effective having used a cloud-based data management system, there were still some factors that were not put into consideration and this valued addition, social and environmental aspects or feasibility aspects.

2.2.5 MCDMs Applied to Power Distribution Systems

The research conducted by (Carnero and Gómez, 2017) showed that a model incorporated the Measuring Attractiveness by a Categorical Based Evaluation Technique approach with Markov chains to obtain the mean availability for different electric power distribution systems. The multi-criteria decision model used was MACBETH which was used to select the most appropriate maintenance strategy for the electric power distribution system and the main criteria considered were; Maintenance costs (MC), Operativity, Level of the suitability of maintenance actions, Safety of maintenance workers and impact on hospital activity.

2.2.6 MCDMs For Criticality Analysis

(Gupta and Mishra, 2018) did a study on the use of ANP algorithm for criticality analysis of a CNC lathe machine for implementation of RCM (Reliability Centered Maintenance). There were five major variables that were considered that affect the criticality of components; cost, complexity, maintainability, safety impact, functional dependency. The study showed that the functional dependency was the most preferred in all criteria clusters and the limit super matrix indicated that the turret was the most critical and hydraulic system was the least critical component of a CNC machine

2.2.7 MCDMs for selection in other fields

(Coulter and Sarkis, 2006) developed a model for media selection and budget allocation using the (Analytic Network Process) ANP methodology. This study demonstrated how this model may be used to allocate media resources for 2 industries: airlines and financial services. The study considered seven categories of media i.e. direct mail, magazines, newspapers, outdoor, radio, television, and Internet and also considered 5 primary categories and 16 sub-categories. The analysis was done manually by carrying out pairwise comparisons and forming super-matrices. After analysis it was discovered that internet advertising would be the best media choice for advertising followed by Television for both the first participant's product i.e. airlines services and the second participant's product i.e. financial services

(Baby, 2013) proposed the use of ANP/AHP methodology with *Super-decision* to prioritize and optimize the coastal protection policies for coastal areas of Kuwait. The strategies were built by SWOT-QSPM (Quantitative Strategic Planning Matrix). 27 environmental sub-components were put into consideration and 4 major components were formed after categorization. This study would decide better coastal strategies out of 24 coastal management strategies. Sanity check and consistency analysis were carried out to check for incomplete comparisons and consistency in judgements respectively. From the AHP/ANP studies, the optimized and Rationalized policies were sorted in decreasing order of importance and it was discovered that the best policy was "*Involving EIA and its Mandate as supporting resource*"

(Shou and Lin, 2018) presented a study to analyze the factors of relief resources allocation by use of the Analytic Network Process (ANP) Model applied to a case study in Taipei's street trees recovery after a disastrous typhoon had destroyed approximately 20,294 trees. In this study, a group of experts were met with at EOC (Emergency Operations Center) to discuss factors that could affect relief resource allocation and their dependencies. It was found that 3 dimensions and 7 factors influenced decision making. The three dimensions included Loss of citizens properties, Impact on traffic and pressure of execution. The super-decision software was used to draw the network and also to analyze it. After the analysis, it was discovered that the weight of tree fell on house is greater than tree fell on car under the loss of citizens' properties dimension. Also, Under the impact on traffic dimension, the weight of impact on major road traffic is greater than the minor road traffic. In this study, as much as a thorough analysis was done on the factors and dimensions. There was no consideration for the alternatives of relief resource allocation.

Fuzzy algorithm ARAKRI2 with direct aggregation operators Max-Min and Min-Avg were employed by (Ilieva, 2012) to select the best bidding strategy for electronic auction. In this study, there were ten agent bidding strategies; snipping strategy (Snipping), strategy with fixed markup (L), three strategies with different historical prices treatments H1, H2, H3; Zero-Intelligence Unconstrained (ZIU); Zero-Intelligence with budget Constraints (ZIC); Zero-Intelligence Plus (ZIP); Risk-Based strategy (RB) and strategy with a Genetic Algorithm (GA). and 3 strategies were put into consideration for strategies' evaluation and they included; time complexity, price prediction and risk attitude. Based on experts' opinion, ten comparison matrices were filled. After analysis was carried out, it was realized that the first places were reserved for the most adaptive strategies – GA and RB. Last in the rankings come the most “inert” strategies – L, Snip, H1 and H2. In addition, a comparative analysis was carried out with an

algorithm, Fuzzy Techniques and Negotiable Attitude (FTNA) and it was found that there were similarities in the ranking list generated by the FTNA algorithm.

(Liang *et al.*, 2013) proposed a study to determine the best method of engine waste recovery. The methodology employed in this study was Analytic Network Process (ANP) in order to measure the dependencies and inter-dependencies between factors and alternatives. The criteria used were; (1) Weighting(W), (2) Cost (C), (3) Efficiency (EY), and (4) Effect (ET), and six strategies were also put into consideration. Group discussion was very effective to determine important problems and for modeling the network structure through brainstorming. Expert Choice was a software used to compute the eigenvectors from the pairwise comparison matrices to determine the consistency ratios. The super-matrix formation process and the selection of best alternatives was done manually. It was discovered from the analysis carried out that Thermoelectricity technology was the most suitable method for waste energy recovery in future.

The ANP approach was employed by (Velmurugan and Subramanian, 2012) for the selection of the Nano-particle preparation method in the pharmaceutical sector. In this study, there were four main criteria that were considered; process information, operational skill, feasibility, supplier and technical information and 12 sub-criteria. After the goal, criteria and alternatives were completed, then binary comparisons were carried out and the results were entered into the super-decision software for analysis. From the analysis carried out, it was seen that “M5” was chosen as the most reasonable and the most feasible outcome. Then Alternatives; M1, M7, M6, M3, M2 and M4 were ranked to be feasible respectively. In this study, it was recommended that also ANP with fuzzy numbers can be utilized for nanoparticle preparation method selection process, and intelligent programs to assess solutions automatically can be developed.

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

(Voronova and Skvarciany, 2018) proposed a study for the prioritization of competitive strategies based on the ANP approach for the Latvian Telecommunication company. A group of five experts were formed who were to give their preferences on the strategies and factors to be considered in the study. All pairwise comparisons were done with the inputs and guidance of the expert team. The global priorities of criteria, sub-criteria and alternatives were synthesized using the eigenvalue method. A SWOT matrix was generated by determining SWOT factors and sub-factors. There was a total of 32 subfactors that were determined and 18 alternative strategies were selected after the SWOT analysis. It was concluded that Strategy 3 (SO3- Promoting export capability with emphasis to the emergence of new international markets) was in the first/ highest priority. SO3 was ranked higher than the other strategies with a priority value of 0.294.

2.2.7 MCDMs applied to Railway sector

(Cheng and Tsao, 2010), adopted an Analytic Network Process (ANP) for evaluation of an optimum maintenance strategy between CM and PM for rolling stock. This was aimed to help predict spare parts' quantities of the components of the rolling stock. The factors that were based on the selection process were safety, comfort, and cost. From the study which based on the ANP model to get an outcome, indicates that preventive maintenance was preferred to corrective maintenance. This output advertently leads to the possible spare parts' quantities and replacement interval of the rolling stock components.

The research conducted by (Muluken, 2017) demonstrates the use of Analytic Hierarchy Process(AHP) to select the best maintenance strategy for the Light Rail Transit System (LRT). In this study, there were 14 maintenance engineers and technicians used during the survey. The analysis carried out showed that; Safety was the most critical factor on selection of maintenance strategy, Value adding activities,

implementation cost, support system integration, implementation capability, stock & material management and performance measurement are the successive priority factors on implementation of maintenance strategy. The five strategies considered were; Corrective Maintenance, Preventive Maintenance, Condition Based Maintenance, Reliability Center Maintenance and Total Productive Maintenance are identified as a possible maintenance strategy. The analysis discovered that Total productive maintenance is the most suitable strategy to be implemented for Light Rail Transit system and Corrective maintenance is the least to follow.

It can be seen from the literature compiled, that a lot of work has been done in the manufacturing sectors, health sectors, Automotive sector, Electrical sector and so many other sectors. However, there is still a gap in the railway sector concerning use of Multi-Criteria Decision Making Models (MCDMs) to obtain the best maintenance practices for the rollingstock. It is clear that the work done is not satisfactory from the literature that has been compiled. Therefore, this study sets out to apply the Analytical Network Process (ANP) algorithm to select an appropriate maintenance strategy for the AALRTS of Addis Ababa.

2.3 Maintenance Strategies

Maintenance strategy involves identification, investigation, and implementation of several repairs, replaces and/or inspect decisions.(Rastegari and Mobin, 2016) ; Al-Najjar,1997; Kelly, 1997). In this sub-section, there will be a detailed explanation for the maintenance strategies to be considered in this case study and these will include; Periodic Preventive maintenance (PPM), Corrective maintenance (CM), Total Productive maintenance (TPM), Condition Based Maintenance (CBM)

2.3.1 Periodic Preventive Maintenance (PPM)

Preventive maintenance can be defined as the repair, replacement and maintenance in order to avoid unexpected failure during use. (Mann, Saxena and Knapp, 1995). Mann suggested that there are two approaches that evolved for performing PM. The traditional approach which is based on the use of statistical and reliability analysis of equipment failure and the second approach involves the use of sensor-based monitoring of equipment condition in order to predict when machine failure will occur.

According to (AMCP 706-132, 1975), Periodic Preventive Maintenance (PPM) may be described as the care and servicing by individuals involved with maintenance to keep equipment/facilities in satisfactory operational state by providing for systematic inspection, detection, and correction of emergent failures either precedent to their occurrence or precedent to their development into major failure. (Dhillon, 2002)

According to (Moblely, 2008), Preventive Maintenance is a maintenance program that is committed to the elimination or prevention of corrective and breakdown maintenance tasks. A comprehensive preventive maintenance program will utilize regular evaluation of critical plant equipment, machinery, and systems to detect potential problems and immediately schedule maintenance tasks that will prevent any degradation in operating condition.

Preventive maintenance (PM) is based on component reliability characteristic and intended to reduce the chance of the potential failures. This method is carried out at pre-arranged intervals or according to prescribed criteria (Moghaddam and Usher, 2011). In order to keep the equipment in a particular condition, preventive maintenance is performed before machine failure by providing organized check-up, recognition, and prevention of potential failure (Mann, Saxena and Knapp, 1995). This implies that

preventive maintenance strategy is useful in overcoming the hardships associated with the wearing of elements (Tatari and Skibniewski, 2006).

(Nebel, 1994) noted that some of the main objectives of PM are to; Improve capital equipment, productive life, reduce critical equipment breakdowns, allow better planning and scheduling of needed maintenance work, minimize production losses due to equipment failures, and promote health and safety of maintenance personnel. There are seven elements of PM as shown below. Each element is discussed below;

1. *Inspection:*

Periodically inspecting materials/items to determine their serviceability by comparing their physical, electrical, mechanical, etc., characteristics (as applicable) to expected standards

2. *Servicing:*

Cleaning, lubricating, charging, preservation, etc., of items/materials periodically to prevent the occurrence of incipient failures

3. *Calibration:*

Periodically determining the value of characteristics of an item by comparison to a standard; it consists of the comparison of two instruments, one of which is certified standard with known accuracy, to detect and adjust any discrepancy in the accuracy of the material/parameter being compared to the established standard value.

4. *Testing:*

Periodically testing or checking out to determine serviceability and detect electrical/mechanical-related degradation

5. Alignment:

Making changes to an item's specified variable elements for the purpose of achieving optimum performance

6. Adjustment:

Periodically adjusting specified variable elements of material for the purpose of achieving the optimum system performance

7. Installation:

Periodic replacement of limited-life items or the items experiencing time cycle or wear degradation, to maintain the specified system tolerance.

At AALRT, the periodic preventive maintenance carried out includes activities such as;

- i. Daily Inspection
- ii. Monthly Inspection
- iii. Quarterly Inspection
- iv. Annual Inspection

This includes; car body inspection, inspection of bogie and wheelset on both sides, trailer car body and wheelset, coupler system inspection, underneath inspection, drivers cab, drivers cab interior, Inspection of Motor car passenger saloon, Functional Inspection of driver desk.

2.3.2 Corrective Maintenance (CM)

Corrective maintenance may be defined as the restorative action carried out due to failure or deficiencies discovered during preventive maintenance, to restore an equipment/item to its operational state. (McKenna, T. and Oliverson, R., Glossary of Reliability and Maintenance Terms, Gulf Publishing Company, Houston, Texas, 1997.), (AMCP 706-132, 1975)

According to (Dr.Eng.Nappi, 2014), the *failure-driven* approach is a reactive management approach, where the corrective maintenance is often dominated by unplanned events and it is performed only after the occurrence of failures or breakages of the system. Corrective Maintenance actions can recover the malfunctioning part of the system, repairing or replacing the failed component.

(Mobley and Wikoff, 2008) described that the primary difference between corrective and preventive maintenance is that a problem must exist before corrective actions are taken. Preventive tasks are intended to prevent the occurrence of a problem. Corrective tasks correct existing problems.

The principal concept of corrective maintenance is that proper, complete repairs of all incipient problems are made on an as-needed basis. All repairs are well planned, implemented by properly trained craftsmen, and verified before the machine or system is returned to service. Impending problems are not restricted to electrical or mechanical problems. Instead, all deviations from optimum operating condition, that is, efficiency, production capacity and product quality, are corrected when detected.(Mobley and Wikoff, 2008)

Corrective maintenance may be classified into five major categories. These are: fail-repair, salvage, rebuild, overhaul, and servicing. (AMCP 706-132, 1975). These categories are described below;

1.***Fail-repair***: The failed item is restored to its operational state.

2.Salvage: This element of corrective maintenance is concerned with disposal of nonrepairable material and use of salvaged material from nonrepairable equipment/item in the repair, overhaul, or rebuild programs.

3.Rebuild: This is concerned with reinstating an item to a standard as close as possible to original state in performance, life expectancy, and appearance. This is achieved through complete disassembly, examination of all components, repair and replacement of worn/unserviceable parts as per original specifications and manufacturing tolerances, and reassembly and testing to original production guidelines.

4.Overhaul: Restoring an item to its total serviceable state as per maintenance serviceability standards, using the “inspect and repair only as appropriate” approach.

5.Servicing: Servicing may be needed because of the corrective maintenance action, for example, engine repair can lead to crankcase refill, welding on, etc. Another example could be that the replacement of an air bottle may require system recharging.

2.3.3 Condition-Based Maintenance (CBM)

According to Dr. Eng. Roberto Nappi, this maintenance is a method that reduces unpredictability of maintenance activities. The results obtained from condition monitoring can be used to determine the activities involved. The main aim of condition-monitoring is to exterminate the failures and broaden the preventive maintenance intervals. The condition-based maintenance assumes that the existence of indicative prognostic parameters can be identified and used to quantify potential system failures before they occur.

Condition based maintenance is the maintenance that is carried out in response to a significant deterioration in a machine unit as indicated by a change in a monitored parameter of the unit condition or performance. It utilizes the machine condition monitoring tools and these include; vibration monitoring tools, thermal monitoring tools, sound monitoring tools, acoustic emission monitoring tool, shock pulse monitoring tools, strain load monitoring tool, lubricant monitoring tools, corrosion monitoring tools, crack detection tools, ultrasonic tools and flux monitoring tools. All these are aimed at giving good indication whenever a machine is functioning well and efficiently or otherwise for failed condition; giving an early signal of warning when fault is noticed and providing diagnoses for developed faults. (Kanisuru, 2018)

2.3.4 Total Productive Maintenance (TPM)

(Ahuja, 2007) recommended that one approach to improving the performance of maintenance activities is to develop and implement strategic Total Productive Maintenance (TPM) programs. According to (Nakajima, 1988) vice-chairman of Japan Institute of Plant Maintenance, TPM is a combination of American preventive maintenance and Japanese concepts of total quality management and total employee involvement. According to (Ahuja, 2007), TPM is a Japanese concept developed in the 1970s by adapting preventive maintenance to become approximately like productive maintenance. Ahuja also noted that, Total Productive Maintenance (TPM) as the name suggests consists of three words: **Total:** Implies that every aspect is considered and including everybody from top to bottom; **Productive:** emphasis on trying to do it while production goes on and reducing troubles for production; and **Maintenance:** means equipment upkeep in good condition autonomously by production operators—repair, clean, grease, and accept to spend necessary time on it.

(Willmott, 1994) portrays TPM as an approximately new and practical application of Total Quality Management (TQM) and suggests that TPM aims to cultivate a culture in which technicians develop 'ownership' of their machines, specialty in the machines, learn much more about them, and in the process realize skills based on diagnostic and equipment improvement projects.

2.4 The ANP Process

According to (Dağdeviren, 2007), studies in literature identify the multi-criteria decision technique known as the Analytic Hierarchy Process (AHP) to be most appropriate for solving complicated problems. AHP was proposed by Saaty (1980) as a method of solving socioeconomic decision-making problems and has been used to solve a wide range of problems. (Saaty, 1996), proposed the use of the ANP method, which is a supplement of the AHP method. Specifically, a feedback mechanism was initiated to the AHP method and the feedback is presented in network form to offer a solution to interdependence between criteria.

(Saaty, 1996) pointed out that many decision problems cannot be structured hierarchically because they involve the interaction and dependence of dominant-level elements on a dominated-level element. Structuring a problem involving functional dependence allows for feedback among clusters. This is a network system. Saaty (1996) suggested the use of AHP to solve the problem of independence on alternatives or criteria, and the use of ANP to solve the problem of dependence among alternatives or criteria.

(Saaty, 1991) describes that a network is a set of nodes (each of which consists of a set of elements). Nodes are equivalent to components or levels, and the arcs indicate the interaction among the components and the direction of these arcs signify dependence (Saaty 1996). The elements in a node

may influence some or all of the elements in other components. In a network, there can be source nodes, intermediate nodes and sink nodes. Interdependency between two nodes, termed as outer dependence, is represented by a two-way arrow, and inner dependencies among elements in a node are represented by a looped arc(Sarkis, 2003)

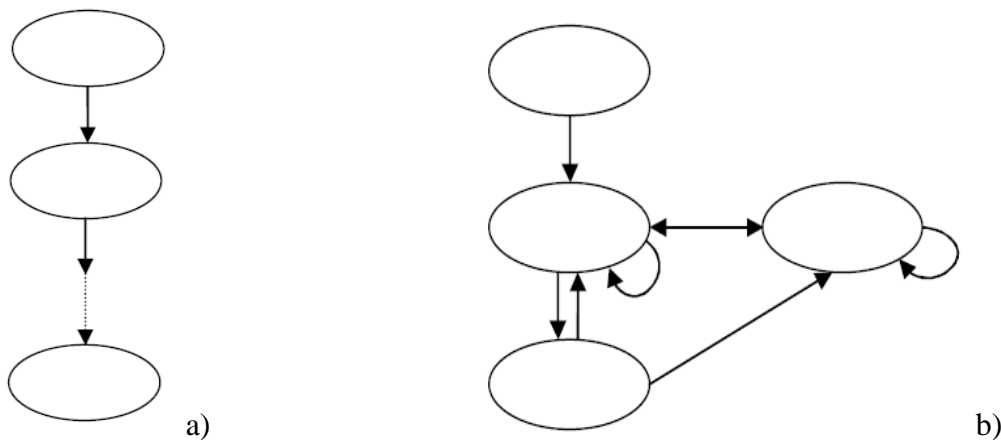


Figure 1: Structural difference between a Hierarchy(a) and a Network(b)

The ANP process will be summarized in four major steps with some adaptations from (Meade and Sarkis, 1999), (Chung, Lee and Pearn, 2005) (Cheng and Li, 2005) and these include; (1) Model assembly and Problem structuring, (2) Pairwise comparison matrices and eigen vector calculations, (3) Forming super-matrices and calculating weights & (4) Selection of the best alternative solution.

2.4.1 Model Assembly and Problem Construction

The model to be constructed based on the goals in this study and the nature of the problem. The problem should be stated clearly and decomposed into a rational system like a network. The structure can then be

obtained by the opinion of decision makers through brainstorming or other appropriate methods. This means that the evaluations can then be determined together with the criteria and sub-criteria. If the criteria are influenced by each other, there is an outer dependence among them. If the sub-criteria are influenced by each other, there is an interdependence among them. This is very different from AHP where there is a hierarchy and there is only dependence of lower level components on higher level components.

2.4.2 Pairwise Comparison Matrices (PCMs) and Eigen Vector Calculations

In ANP, like AHP, decision elements at each component are compared pairwise with respect to their importance towards their control criterion, and the *components* themselves are also compared pairwise with respect to their contribution to the *goal*.

Therefore, in this step, decision makers are requested to respond to a series of pairwise comparisons. where two *elements* or two *components* at a time will be compared in terms of how they contribute to their particular upper level criterion (Meade and Sarkis, 1999). The relative impacts or strength of the impact on a particular element can be measured by a ratio scale similar to AHP.(Meade and Presley, 2002)

For ANP, a scale of 1 to 9, was suggested by (Saaty, 1980) to determine relative importance values when comparing two elements/ components, where a score of 1 represents equal importance between the two elements and a score of 9 indicates the extreme dominance of one element (row component in the matrix) compared to the other one (column component in the matrix) (Meade and Sarkis, 1999)

If a component has some level of weaker impact the range of scores will be from 1 to 1/9, where 1 represents indifference and 1/9 being an overwhelming dominance by a column element over the row element. When scoring is conducted for a pair, a reciprocal value is automatically assigned to the reverse comparison within the matrix. That is, if a_{ij} is a matrix value assigned to the relationship of component i to components, then a_{ji} is equal to $1/a_{ij}$ (or $a_{ij}a_{ji} = 1$)

In addition, if there are interdependencies among elements of a component, pairwise comparisons also need to be created, and an eigenvector can be obtained for each element to show the influence of other elements on it. Like AHP, pairwise comparison in ANP can be made in the framework of a matrix, and a local priority vector (w) can be computed as an estimate of relative importance associated with the elements (or components) being compared, and it can be solved as a unique solution to:

$$Aw = \lambda_{max}w,$$

Where λ_{max} is the largest eigen value of matrix, A . w is the eigen vector and A is an $n \times n$ comparison matrix. Saaty (1980) proposes several algorithms for approximating w : In this study, the following three-step procedure is used to synthesize priority vectors ((Meade and Presley, 2002) Saaty, 1980).

- 1) Sum the values in each column of the pairwise comparison matrix.
- 2) Divide each element in a column by the sum of its respective column. The resultant matrix is referred to as the *normalized pairwise comparison matrix (PCM)*
- 3) Sum the elements in each row of the normalized pairwise comparison matrix, and divide the sum by the n elements in the row. These final numbers provide an estimate of the relative priorities for the elements being compared with respect to its upper level criterion. Priority vectors must be derived for all comparison matrices.

This is referred to as the process *of averaging over normalized columns*. This is represented as

$$w_i = \frac{\sum_{i=1}^I \left(a_{ij} / \sum_{j=1}^J a_{ij} \right)}{J}$$

2.4.3 Forming Super-Matrices and calculating weights

According to (Saaty, 1996), The super matrix concept is similar to the Markov chain process. To obtain global priorities in a system with interdependent influences, the local priority vectors are entered in the appropriate columns of a matrix, known as a super matrix.

As a result, a super matrix is actually a partitioned matrix, where each matrix segment represents a relationship between two levels in the graphical model (Meade and Sarkis, 1999). Three types of relationships may be encountered in this model: (1) independence from succeeding components, (2) interdependence among components, and (3) interdependence between levels of components.

It is assumed that the decision- making system, C_i comprises ($i = 1, 2 \dots n$) and each criterion, C_i comprises n_i sub-criteria. The local priority vectors obtained in Step 2 are grouped and located in appropriate positions in a super-matrix based on the flow of influence from a component to another component, or from a component to itself as in the loop. A standard form of a super-matrix shown in matrix below. (Saaty,1996)

The figure (Figure 2) below shows a graphical representation of the hierarchy and network in terms of vector representation.

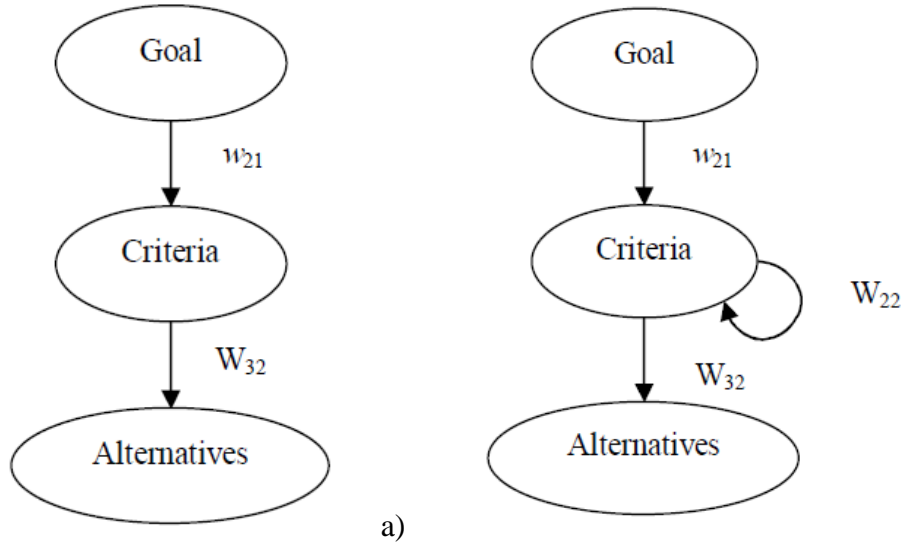


Figure 2: a) Hierarchy & b) Network (Momoh and Zhu, 1998; Chung, Lee and Pearn, 2005)

The super matrix representation of a hierarchy with three levels is shown as an example in the figure below, follows (Saaty, 1996).

$$W_h = \begin{bmatrix} 0 & 0 & 0 \\ w_{21} & 0 & 0 \\ 0 & W_{32} & I \end{bmatrix}$$

where w_{21} is a vector that represent the impact of the goal on the criteria, w_{32} is a matrix that represents the impact of criteria on each of the alternatives, I is the identity matrix, and entries of zeros corresponding to those elements that have no influence.

If the criteria are interrelated among themselves, the hierarchy is replaced by a network such as the graphical representation shown in the figure 2(b) above. The entry of \mathbf{W}_n given by w_{22} would indicate the interdependency among criteria, and the super-matrix would be as shown below (Saaty,1996).

$$\mathbf{W}_n = \begin{bmatrix} 0 & 0 & 0 \\ w_{21} & W_{22} & 0 \\ 0 & W_{32} & I \end{bmatrix}$$

Note that any zero “0” in the super-matrix can be replaced by a matrix if there is an inter-relationship of the elements in a component or between two components. Since there usually is interdependence among clusters in a network, the columns of a super-matrix usually sum to more than one. Such a super-matrix is then referred to as an unweighted super-matrix.

The super-matrix must be transformed first to make it stochastic (must be normalized), that is to say that each column of the matrix sums to unity (equal to one). Such a super-matrix is then referred to as a weighted super-matrix.

2.4.4 Selection of the best alternative decision

A recommended approach by Saaty (1996) is to determine the relative importance of the clusters in the super-matrix with the column cluster (block) as the controlling component (Meade and Sarkis, 1999). That is, the row components with nonzero entries for their blocks in that column block are compared according to their impact on the component of that column block (Saaty,1996). With pairwise comparison matrix of the row components with respect to the column component, an eigenvector can be obtained. This process gives rise to an eigenvector for each column block.

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

For each column block, the first entry of the respective eigenvector is multiplied by all the elements in the first block of that column, the second by all the elements in the second block of that column and so on. In this way, the blocks in each column of the super matrix is weighted, and the result is known as the weighted super-matrix, which is stochastic.

Raising a matrix to powers gives the long-term relative influences of the elements on each other. To achieve a convergence on the importance weights, the weighted super-matrix is raised to the power of $2k+1$; where k is an arbitrarily large number, and this new matrix is called the limit super-matrix (Saaty, 1996). The limit super-matrix has the same form as the weighted super-matrix, but all the columns of the limit super-matrix are the same. By normalizing each block of this super-matrix, the final priorities of all the elements in the matrix can be obtained. It is from these priorities that the alternatives can then be ranked according to the final priorities assigned. The alternative with the highest priority is ranked as the best and the alternative with the least priority is ranked as the least alternative.

Chapter Three: Research Methodology

The figure below shows a flow chart of the methodology utilized for this study;

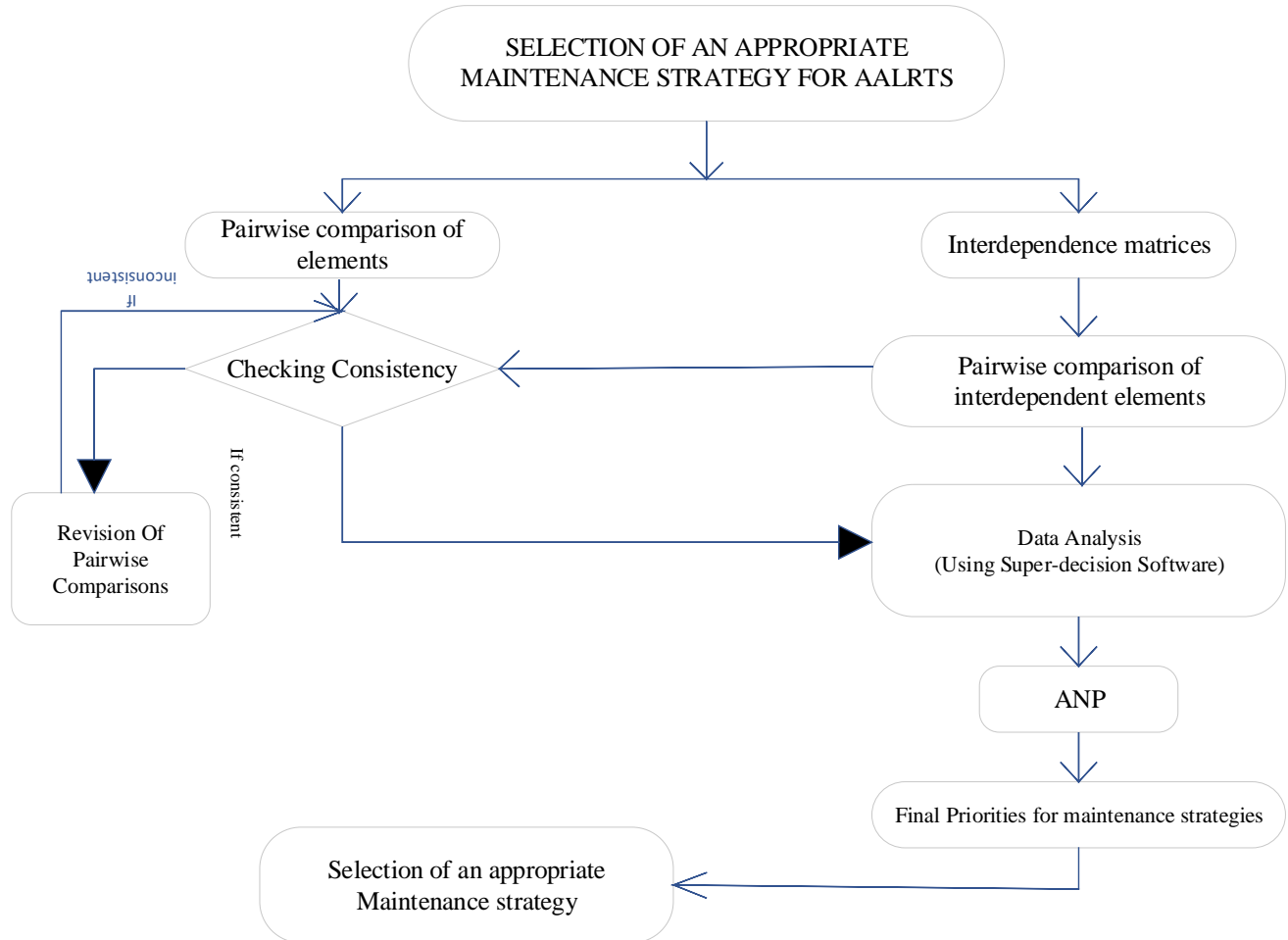


Figure 3: An overview of the methodology of selection of an appropriate maintenance strategy

3.1 General Research Design

In this study, the research approach used is a *decision-oriented research* approach and *explanatory* research. According to (Lin and Yang, 2016), employing both *qualitative* and *quantitative* analysis, ANP provides a systematic process of analysis that can determine the weight of each criterion, which

also determines the relevance of each criterion and the potential for successfully reaching the objective. Apart from its hierarchical analysis function, ANP can also be used to analyze feedback relationships between different levels and interdependent relationships among elements on the same level.

3.2 Sample

Comparisons between maintenance alternatives are usually performed by experts in the field, or by users themselves according to previous studies carried out. In some cases, however, it is difficult for ordinary users to make comparisons because of their lack of expertise. It is for this reason that the sampling technique used is a *non-random sampling* approach. The type of sample used is a *judgmental sample*. Furthermore, although expert opinion is highly valuable in many cases, it can be subjective, and not every expert may have expertise in every alternative. Therefore, the *population* in this case study will be experts who may be professors from the university or experts from AALRT top management positions and also low management positions in the rollingstock maintenance department.

The *sample size* considered for this case study is *ten* (10) in number. This is to ensure that there is a large enough sample space to carry our pairwise comparisons and to get enough expertise about the inter-dependencies of different factors/criteria.

3.3 Data Collection Procedure

Data collection instrument used in this study is a *questionnaire* which was taken to the site where these (Decision Makers) DMs work, and that includes the Addis Ababa Institute of Technology for the professors, also the AALRT depots; Ayat and Kality for the maintenance personnel and maintenance managers and at the Ethiopian Railway Corporation (ERC).

The questionnaires are given out to the respondents and they fill out the questionnaires while being monitored in case there are inquiries about the questionnaire or in case there is a need for guidance about the process of filling out the questionnaire. The respondents are required to fill the form in an environment that is most comfortable for them and that is most likely their offices or workshops.

The respondents are also be required to sign for their proof of participation after they have finished to successfully fill the form. Data collection took place in a period of three months as it was challenging to get some of the experts to make time out of their busy schedules to dedicate it to the survey. After all the questionnaires have been collected from all the respondents then the data can be extracted and analyzed. The questionnaire seems like the most appropriate method because there is a need to extract quantitative data from the survey.

3.4 Data Collection Instrument

In this study, a sample survey is carried from which the Primary data is collected. A group of Decision Makers (DMs) is selected and these will include 10 experts and data will be collected through the use of one main data collection instrument namely; questionnaires.

The questionnaire format used for the first phase is *System Usability Scale* (SUS) questionnaire and the question format will be *Likert scale format* (Degree of Agreement). This is because with this format, it is much easier to quantify the qualitative data and to measure perceptions of usability. The main aim for carrying out this survey is to fulfill the first objective.

3.5 Data Analysis

In the data analysis stage, Once the pairwise comparisons are completed, the *geometric means* are computed in order to aggregate individual judgments into a representative group judgment for each pairwise question (Forman and Peniwati, 1998).

According to (Feldman, 2002), The geometric average of two numbers is the middle term in a geometric progression of three terms including the two given numbers. Thus, for example, the geometric mean of 1 and 9 is 3, since the geometric progression from 1 to 9 occurs in two equal *ratios* of 3. In simpler terms, **Geometric mean** takes several values and multiplies them together and take the root of the number of them together. This is known as a geometric mean. The geometric mean permits that an impartial average that does not put as much weight on one or two numbers that are different from the rest used to calculate the final number. The geometric mean formula can be written as shown below;

$$\sqrt[n]{X1.X2.X3.X4 \dots Xn}$$

The Geometric mean is calculated to accumulate the results (importance) given by the Likert scale in the phase I questionnaire and the phase III questionnaire.

After accumulation of data collected from the expert group, the data is placed into a software, super-decision through construction of the model. The model used in this study is a simple structure. The system structure of the upkeep methodology choice issue and the associations between the bunches have been mimicked utilizing Super Decisions 2.6.1-RC1 Software, planned by Bill Adams and the Creative Decisions Foundation. Introduced on windows 10. It has a tcl version 8.5. It makes a rundown of the pairwise correlations expected to run the evaluation. The chosen criteria for the choice issue are selected as appeared in the next chapter and are bunched into five fundamental gatherings (groups).

Chapter four: Model formulation

In this section, there is a detailed description of the steps that are followed in order to formulate the model. These included the data collection process which involved selection of experts and the process of obtaining data from them, extraction of factors and sub-factors according to the experts' opinion. The maintenance strategies have already been selected from the literature review that was done in the previous section. The section also includes the detailed process of how the ANP model is structured and the inter-relations considered among factors and sub-factors.

4.1 Identification of potential Maintenance alternatives for the model

In order to identify potential maintenance alternatives, the reviewed published literature e.g. (Sankpal, Andrew and Kumanan, 2015), (Rahimi, Sadinejad and Damghani, 2014), (Hemmati *et al.*, 2018), Mechefske and Wang (2003), Al-Najjar and Alsyouf (2003), Bertolini and Bevilacqua (2006), Garg and Deshmukh (2006) is used to identify four maintenance alternatives that can be best suited for maintenance of rolling stock. The maintenance strategies that were eventually selected for evaluation include; Preventive Maintenance, Corrective Maintenance, Total Productive maintenance and Condition-Based Maintenance.

4.2 Selection of Appropriate Criteria

Successful implementation of an effective maintenance strategy entails incorporation of some pre-determined criteria. These sub-criteria address the concepts of cost, efficiency, quality and technical aspects of a maintenance strategy and are obtained through a comprehensive literature review [e.g. (Nezami and Yildirim, 2013), (Borjalilu and Ghambari, 2018), (Zaim *et al.*, 2012), (Sadeghi,

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

Rashidzadeh and Soukhakian, 2012), (Sankpal, Andrew and Kumanan, 2015), (Rahimi, Sadinejad and Damghani, 2014), (Hemmati *et al.*, 2018), Mechefske and Wang (2003), Al-Najjar and Alsyouf (2003), Bertolini and Bevilacqua (2006), Garg and Deshmukh (2006)].

From this literature, there were a variety of studies that were made using Multi-Criteria Decision-Making methods and there are also a variety of criteria and sub criteria that had been put into consideration in these studies. Therefore, it is from this intensive literature survey that it was possible to extract the following comprehensive criteria as the preliminary criteria to be considered in this particular study and they include;

The References	The Extracted Criteria
Rollingstock maintenance strategy selection, spare parts' estimation and replacements' interval calculation. Yung-Hsiung Cheng, Hou-Lei Tsao, (2010)	Safety, Comfort and Cost
Maintenance policy selection: a fuzzy-ANP approach by Narges Hemmati, Masoud Rahiminezhad Galankashi (2018)	Cost, Risk, added value
Maintenance Strategy Selection in Electric Power Distribution Systems by María Carmen Carnero, Andrés Gómez (2017)	Maintenance costs, Operativity, safety of maintenance workers, level of suitability of maintenance actions, impact on hospital activity
Reliability Based Maintenance Strategy Selection in Process Plants: A Case Study by Vishnu C. R., Regikumar V (2016)	Impact on production, Impact on safety, Availability of standby Cost Equipment, Criticality
"Maintenance strategy selection using AHP &	On time delivery, Profit, Quality, Image,

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

<p>ANP algorithms: casestudy" Selim Zaim,A. Turkyilmaz, M.F.Acar, U.A.Turki, O.F.Demirel. (2013)</p>	<p>Hardware costs, Software costs, Training costs, Inventory of spare parts, cost of advising and consulting, personnel safety, internal and external environment safety, Return on Investment cost</p>
<p>Selection of Optimum maintenance strategies in a virtual Learning Environment based on Analytic Hierarchy Process</p>	<p>Personnel safety, facilities safety, Environmental safety, fault identification, user capability/ acceptability, reliability, spare-parts cost.</p>
<p>Using the analytic network process to determine the method of waste energy recovery from engine by Xingyu Liang, Xiuxiu Sun, Gequn Shu (2013)</p>	<p>Cost, weighting, efficiency, Risk Level of system</p>
<p>Odeyale, S.O, Alamu. O.J. (2013)The analytical hierarchy process concept for maintenance strategy selection in manufacturing industries. 223-233</p>	<p>Improved reliability of machine, improved safety, minimum inventory, return on investments, acceptance/compliance of personnel, competitiveness.</p>
<p>Lazakis .I. and Olcer .A.(2016). Selection of the best maintenance approach in the maritime industry under fuzzy multiple attributive group decision-making environment. 297-309</p>	<p>Managerial willingness/commitment, personnel/ crew training, human willingness, system compatibility</p>
<p>Maletic et al. (2014). An application of analytic hierarchy process (AHP) and sensitivity analysis for maintenance policy selection.</p>	<p>Equipment and process related measures, financial measures and health, safety and environment measures (diminishing of ecological systems</p>
<p>Lerace and Cavalieri (2008). Maintenance strategy selection: A comparison between fuzzy logic and analytic hierarchy process.</p>	<p>Damages, added-value, cost, System compatibility / applicability</p>
<p>Farnaz.G.N. and Mehmet.B.Y.(2013). A sustainability approach for selecting maintenance strategy</p>	<p>Applied technology complexity, customer satisfaction, return on investment, spare-parts availability, risk level of system, time</p>

	effectiveness of strategy used, personnel wages, health and safety, personnel acceptance, toxic emissions, energy consumption, waste production
Eddie .W.L. Cheng and Heng Li (2005) Contractor selection using the analytic network process.	Managerial competence, Government regulation, Technical knowhow, Quality of service, customer satisfaction, Severity of failure of the machine, availability of resources

Table 1: Extracted criteria and source of extraction

In total, there are extracted are **42 criteria** extracted for this study. These criteria were then further refined (narrowed down) through interactions with experts in the field of maintenance.

The initial criteria listed are then explained in detail for ease of understanding in the table below (Table 2). It must be noted that these are just the preliminary criteria that were originally extracted from the literature that has already been Identified above. The next step is to collect and review the decision-makers' viewpoints. This is achieved through the design and investigation of questionnaires. This is discussed in detail in the next sub-section.

No.	SUB-CRITERIA	EXPLANATION
1	Employment wages	Issues concerned with the wages paid to the maintenance personnel may affect which level of complexity of the maintenance strategy is introduced;
2	Materials and spareparts management	The availability of a proper spareparts and materials management system may dictate which maintenance strategy is selected
3	Personnel training cost	The cost incurred to train the technicians on the new maintenance strategy may impact the choice of strategy selected
4	Availability of the rolling stock	The level of availability of the rolling stock required may dictate the maintenance strategy selected
5	Personnel capability(Ease of understanding and Implementation)	The ease with which the technicalities of a maintenance strategy can be understood and implemented can affect the maintenance strategy
6	Reduced energy consumption	The energy consumed should be minimized and this includes choosing an optimum maintenance strategy
7	Modifiability of strategy	The ability to modify the strategy may affect the maintenance strategy selected
8	Passenger safety	The safety of the passengers may dictate the maintenance strategy selected
9	Mental attitude of maintenance staff	Attitude of staff towards adopting the new maintenance strategy
10	Loss of ridership	If there is a chance of reduction in the number of passengers using the rail transport, this can affect the maintenance strategy selected
11	Convenience to fix Failure	The ease with which a failure can be corrected by the users who are using that particular maintenance strategy
12	Financial feasibility	The financial feasibility of employing a particular maintenance strategy for example very expensive strategies with expensive technology and high-tech equipment may not be considered
13	Land wastes from Maintenance	The wastes from maintenance carried out like machine parts and scrap for disposal may affect the maintenance strategy selected
14	Right person in the right place	Ability to assign the right person for the right job who is appropriately skilled to use the equipment for maintenance
15	Human health	The maintenance strategy being used should not be detrimental or risky to the health of the users
16	System safety	The safety of the equipment, the system infrastructure and rollingstock may dictate which maintenance strategy is to be selected
17	Fault identification	The ability of a maintenance strategy selected to identify where the fault has occurred or will occur is an addition that could favor which maintenance strategy to be selected
18	Diminishing of capacity of ecological systems	Ecological systems like lake or river water used to create electricity from dams should not be affected in capacity by the maintenance chosen which if not appropriate can lead to numerous failures hence more energy consumed
19	Human safety	The maintenance strategy being used should be safe enough for the users
20	Environmental safety	The safety of the environment may affect the decision of the maintenance strategy selected

No.	SUB-CRITERIA	EXPLANATION
21	Environmental damage from accidents	The damage of the environment most likely to happen when an accident happens may dictate the type of maintenance strategy selected.
22	Improved company brand	The brand of the company is improved if there are no accidents attached to its name and this could dictate the maintenance strategy to be selected
23	prioritization of maintenance activities	High returns (profits) may affect the maintenance strategy much more than low returns
24	Worker safety	The safety of the technicians using the maintenance strategy may dictate which maintenance strategy is to be used
25	Availability of Technnology	The technology needed to implement a particular maintenance strategy should be available
26	Severity of failure of the machine	A high severity of failure of a machine or part could mean a high financial loss and this could dictate the maintenance strategy taken on.
27	Regulation compliance of personnel	The technicians using the particular maintenance strategy should be doing so in-line with the government regulations and policies or regulations binding that railway line
28	Health damage from accidents	The damage of health of people may affect the maintenance strategy selected
29	Time effectiveness of strategy used	A strategy that consumes less time to produce results may be preffered to one that consumes more time
30	Human and Managerial willingness to support the strategy	The willingness for the company staff and management to aid and support a maintenance strategy may affect the decision of which strategy is taken.
31	customer satisfaction	The satisfaction of the customer would improve company profit therefore this may affect the maintenance strategy selected
32	Reliability of the rollingstock	The level of reliability of the rollingstock needed can dictate the maintenance strategy selected
33	Spare parts availability	The availability of the spare-parts may have an impact on the maintenance strategy selected
34	Training Requirements for personnel	The requirements for the training of the technicians in line with the maintenance strategy being taken should be attainable
35	Spare parts cost	The cost incurred to buy new spare parts may affect the choice of strategy selected
36	Prioritization of maintenance activities	The strategy used should be having a quality of prioritizing to fix failures that are most crucial first and continue in a descending order
37	Employment issues	Issues concerned with the employment status of the personnel; permanent or temporary may affect the maintenance strategy selected
38	Reliability level of the strategy used	A more reliable strategy may be preffered more to a less reliable one
39	Availability of resources	Resources should be available that support the use of a particular maintenance strategy
40	Cost of maintenance equipment	The cost incurred while purchasing the maintenance equipment required for a particular maintenance strategy may dictate which one is taken on.
41	Risk Level of the system	The level of Risk is considered like high risk or low risk level systems.
42	System compatibility	The compatibility of the strategy with the specific system in the case the AALRT system and this may affect the strategy selected

Table 2: The 42 originally selected factors with explanations

4.3 Forming an expert panel.

This study utilized the principle of Gestalt (Merton, Fiske & Kendall, 1990) which states that the number of experts in accordance with the principles of Gestalt (Merton, Fiske, & Kendall, 1990) should be in the limit of 10 people (usually 7 +/- 2). Selection of candidates for a group of experts can be carried out by various methods (Ivlev, Kneppo and Barták, 2015). In this study, a simple method of self-assessment and calculation of the competence based on criteria is proposed and utilized. The results of the survey of candidates for experts and calculation of the competence of experts and a group of experts are given in (Table 4) below and a corresponding graph in (figure 5) below.

The method of selecting the most suitable experts for the task of selecting an appropriate maintenance strategy for the AALRT was based on; 1) the expert's overall work experience, 2) experience in solving tasks, 3) level of education and scientific record, 4) interest in solving the particular task, 5) current position, 6) awareness of how to solve the task, 7) relevance of the expert's knowledge and 8) the overall self-evaluation concerning their total competence in solving the task. A comprehensive assessment of competence is carried out using the above stated criteria on a scale of 0 to 10 and they are elaborated in the table (table 4) as shown below;

The best selected candidates are ten out of the total, based on the scores out of 80. The candidates selected are from the academic department and experts from the organization. One of them are selected from the railway departments at the institution of AAIT and the rest (the 9) are experts from the organizations.

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

#	Competence Criteria	DM1	DM2	DM3	DM4	DM5	DM6	DM7	DM8	DM9	DM10	DM11	DM12	DM13	DM14	DM15
1	The experts overall work experience	7	8	9	6	1	6	10	6	5	7	3	5	10	6	6
2	experience in solving tasks	8	8	8	7	2	7	8	3	7	7	6	7	8	4	4
3	Level of education and scientific record	7	9	8	8	3	10	7	5	4	10	7	6	9	5	5
4	Interest in solving the particular task	7	7	7	8	7	9	7	5	6	8	7	2	9	4	4
5	Current position	9	8	8	9	5	9	8	6	1	7	6	7	7	4	1
6	Awareness of how to solve the task	9	10	6	8	4	9	10	7	4	9	8	6	9	6	5
7	Relevance of the expert's knowledge.	10	10	9	6	2	8	9	4	5	8	8	7	9	5	6
8	The overall self-evaluation concerning their total competence in solving the task.	11	9	9	9	0	6	8	4	0	9	9	10	9	6	6
	TOTAL (OUT OF 80)	68	69	64	61	24	64	67	40	32	65	54	50	70	40	37
	TOTAL PERCENTAGES (%)	85	86.3	80	76.3	30	80	83.8	50	40	81.3	67.5	62.5	87.5	50	46.25

Table 3: Comprehensive assessment of competence of Decision Makers

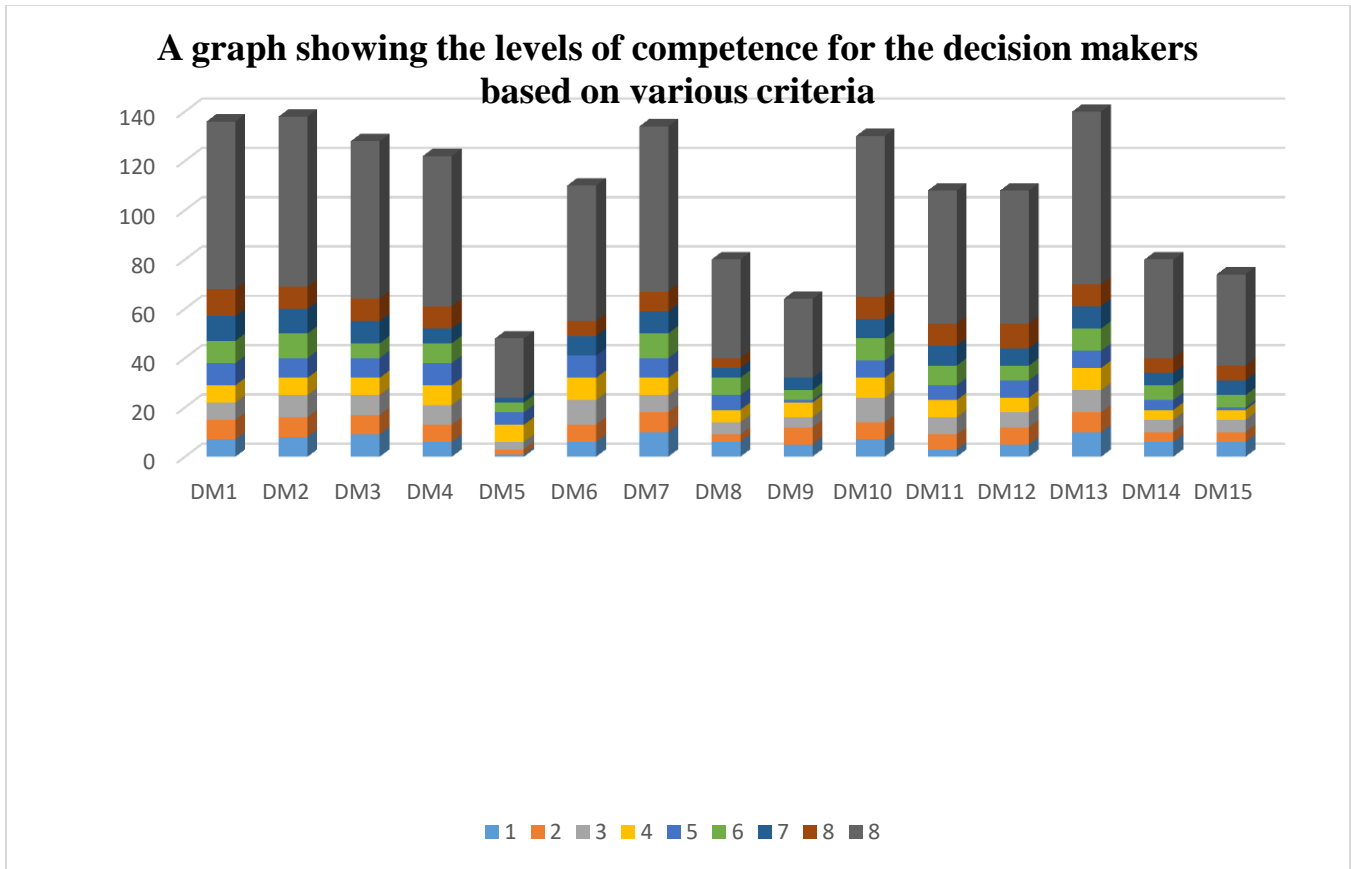


Figure 4: Levels of competence of the decision makers

Therefore, a total of 10 available experts is selected, including 9 from the organizational circle (leaders at the AALRT, maintenance, Safety and Rolling stock departments of the organization, the ERC), and 1 from the academic circle (professors of Railway engineering) at Addis Ababa Institute of Technology.

The ones from the organization that filled in the questionnaire were 9 out of the ten. Then from the academic circle, there is 1 out of the ten. Among the 10 experts selected, 6 of them answered via email and the rest answered the questionnaires manually and collected when they were finished. From the organizational circles, there is the staff at AALRT, this includes, two low-level maintenance engineers. In addition to that, two safety and security directors, Rolling stock director at Ayat, Rolling stock manager at Kality and then two expatriates from the Ethiopian Railway Commission (ERC). From the

Academic circles, there is 1 lecturer in the Railway Engineering Department. They are distributed as shown in the table (table 2) below;

Decision maker	Description
DM1	Transport Director at Kality
DM2	Project Manager at ERC
DM4	Safety Manager at Kality
DM6	Rolling stock Manager at Kality
DM10	Rolling stock Director at Ayat
DM13	Safety and Security Director
DM11	Low-level Maintenance manager
DM12	Low-level Maintenance Manager
DM3	Railway Engineering lecturer
DM7	Director Operations dept at ERC

Table 4: Distribution of the final selection of the Decision Makers

4.4 Questionnaire Design and Investigation

The data collection tool utilized in this study is a questionnaire. This study adopts a three-phase questionnaire design. The first phase of the questionnaire is designed by considering all the preliminary factors in the sub-section above. Questionnaires are distributed on-site with the maintenance staffs who work for the AALRT depots at Ayat and at Kality. The questionnaire format that is used for this phase is the *System Usability Scale* (SUS) questionnaire and the question format is *Likert scale format* (Degree of Agreement).

A total number of 10 questionnaires is returned and they are all proved to have content which is valid and could be used to extract the needed information. The opinions of all the 10 experts is aggregated to give one opinion and this is done as described in the sub-section below. The number of criteria obtained from the previous sub-section is 40 which is a large number of criteria and therefore there is need for them to be reduced to reasonable number and this would depend on the standard of consensus among the experts that is described in the next section below.

4.5 Aggregating Individual Opinions of Expert Panel

According to (Forman and Peniwati, 1998), When individuals are each acting in his or her own right, with different value systems, we are concerned about each individual's resulting alternative priorities. An accumulation of each individual's resulting priorities can be calculated using either a geometric or arithmetic mean.

When several individuals provide judgments with the Analytic Network Process, one may use *Average of individual judgments (AIJ)* or *Average of individual Priorities (AIP)*. The selected method depends on whether the group is considered to act together as a unit or as separate individuals. In the former case, the geometric *Average of individual judgments (AIJ)* satisfies the reciprocity requirement, implying a synergistic aggregation of individual preferences in such a way that the group becomes a new 'individual' and behaves like one. Individual identities are lost with every stage of aggregation and the Pareto principle is irrelevant. When group members act as individuals (AIP), one may take either a geometric mean (representing an average ratio) or an arithmetic mean (representing an average interval) of their resulting priorities. While the Pareto principle will not be violated in either case, the geometric mean is more consistent with the meaning of both judgments and priorities.

Therefore, in this study, it is assumed that group members act as individuals (AIP), hence a geometric mean (representing an average ratio) is utilized to accumulate each individual's (Decision Maker's) opinion into one single opinion.

4.5.1 Geometric mean

According to (Feldman, 2002), The geometric average of two numbers is the middle term in a geometric progression of three terms including the two given numbers. Thus, for example, the geometric mean of 1 and 9 is 3, since the geometric progression from 1 to 9 occurs in two equal *ratios* of 3. In simpler terms, **Geometric mean** takes several values and multiplies them together and take the root of the number of them together. This is known as a geometric mean. The geometric mean permits that an impartial average that does not put as much weight on one or two numbers that are different from the rest used to calculate the final number. The geometric mean formula can be written as shown below;

$$\sqrt[n]{X1.X2.X3.X4 \dots Xn}$$

The Geometric mean is calculated to accumulate the results (importance) given by the Likert scale in the phase I questionnaire. The Geometric Mean is calculated in the Microsoft Excel sheet using the command “=GEOMEAN” and the cells with the numbers to be selected were selected in a parenthesis. The results are as shown in the table (Table 5) below;

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

No.	SUB-CRITERIA	DECISION MAKERS										GEOMETRIC MEAN	QUARTILE DEVIATION		
		DM1	DM2	DM3	DM4	DM5	DM6	DM7	DM8	DM9	DM10		Q1	Q3	(Q3-Q1)/2
1	Employment wages	5	4	3	4	4	5	5	5	4	4	4.249424553	4	5	0.5
2	Materials and spareparts management	4	2	2	1	5	3	4	5	3	5	3.060083306	2.25	4.75	1.25
3	Personnel training cost	2	5	5	5	4	4	5	4	5	5	4.266807006	4	5	0.5
4	Availability of the rolling stock	1	5	5	4	3	4	3	4	4	4	3.437543855	3.25	4	0.375
5	Personnel capability(Ease of understanding and Implementation)	5	3	3	5	5	4	4	5	5	3	4.102356296	3.25	5	0.875
6	Reduced energy consumption	3	3	4	4	5	5	4	5	5	5	4.222087704	4	5	0.5
7	Modifiability of strategy	2	3	4	4	4	3	4	5	5	4	3.68426828	3.25	4	0.375
8	Passenger safety	5	4	5	5	4	5	4	5	3	3	4.222087704	4	5	0.5
9	Mental attitude of maintenance staff	4	4	5	4	5	5	4	4	5	4	4.373448296	4	5	0.5
10	Loss of ridership	4	5	5	4	3	5	5	4	5	5	4.443366388	4	5	0.5
11	Convenience to fix Failure	5	4	3	4	5	3	4	5	5	5	4.222087704	4	5	0.5
12	Financial feasibility	4	4	5	4	5	4	3	4	5	5	4.249424553	4	5	0.5
13	Land wastes from Maintenance	3	5	4	3	4	3	3	3	3	2	3.211328629	3	3.75	0.375
14	Right person in the right place	2	1	2	2	3	2	1	4	2	5	2.129757336	2	2.75	0.375
15	System safety	4	5	5	5	5	4	4	5	4	5	4.573050519	4	5	0.5
16	Fault identification	4	5	3	5	3	4	4	5	3	5	4.01182865	3.25	5	0.875
17	Diminishing of capacity of ecological systems	2	3	2	2	2	2	4	5	1	2	2.282617394	2	2.75	0.375
18	Human Health & safety	5	5	4	3	4	5	5	5	4	4	4.345313594	4	5	0.5
19	Environmental safety	3	3	5	4	5	3	5	5	5	5	4.194926715	3.25	5	0.875

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

No.	SUB-CRITERIA	DM1	DM2	DM3	DM4	DM5	DM6	DM7	DM8	DM9	DM10	GEOMETRIC MEAN	Q1	Q3	(Q3-Q1)/2
20	Environmental damage from accidents	5	4	3	5	5	4	5	4	5	5	4.443366388	4	5	0.5
21	Improved company brand	4	3	5	5	4	5	4	3	5	5	4.222087704	4	5	0.5
22	prioritization of maintenance activities	3	4	3	5	1	3	4	2	3	3	2.877217053	3	3.75	0.375
23	Worker safety	5	4	5	4	4	5	5	2	5	5	4.266807006	4	5	0.5
24	Availability of Technnology	2	5	5	5	4	3	5	5	4	5	4.145807434	4	5	0.5
25	Severity of failure of the machine	5	4	4	4	3	5	5	5	5	5	4.443366388	4	5	0.5
26	Regulation compliance of personnel	1	2	2	3	4	4	3	3	3	3	2.625298103	2.25	3	0.375
27	Health damage from accidents	2	3	3	3	3	3	3	4	5	4	3.211328629	3	3.75	0.375
28	Time effectiveness of strategy used	4	5	5	4	4	4	4	3	5	5	4.249424553	4	5	0.5
29	Human and Managerial willingness to support the strategy	5	5	5	5	4	4	3	4	3	5	4.222087704	4	5	0.5
30	customer satisfaction	5	3	5	5	5	5	3	4	4	3	4.102356296	3.25	5	0.875
31	Reliability of the rollingstock	4	5	5	5	4	4	2	5	5	4	4.172650389	4	5	0.5
32	Spare parts availability	2	2	4	3	3	3	3	3	4	5	3.083724883	3	3.75	0.375
33	Training Requirements for personnel	5	4	3	3	5	5	5	5	4	5	4.317359884	4	5	0.5
34	Spare parts cost	1	2	3	3	5	4	3	3	3	5	2.942141981	3	3.75	0.375
35	Employment issues	3	5	5	4	4	3	5	5	5	5	4.317359884	4	5	0.5
36	Reliability level of the strategy used	4	5	3	5	4	5	5	4	5	5	4.443366388	4	5	0.5
37	Availability of resources	1	3	5	3	3	4	4	3	3	3	2.996275558	3	3.75	0.375
38	Cost of maintenance equipment	4	5	5	5	4	4	4	5	4	3	4.249424553	4	5	0.5
39	Risk Level of the system	4	5	4	5	2	4	3	5	5	5	4.054320941	4	5	0.5
40	System compatibility	4	5	4	4	5	5	4	5	4	4	4.373448296	4	5	0.5

Table 5: The Quartile Deviation and the Geometric Mean values for the factors

4.6 Setting the standards for unanimity among the expert panel.

In this study, unanimity among the expert panel was measured in terms of the importance of the criteria (a value of 5 means “very important” and 1 means “very unimportant”) under Likert’s five-point scale and the quartile method proposed by (Faherty, 2013). The expert panel reaches a harmonized decision when quartile deviation regarding an opinion towards an item is less than 0.50 and the importance measured by the Likert Scale is less than 4.00. The item that fulfills the required standard should then be deleted. According to the outcome of the first questionnaire survey, criteria or sub-criteria that the expert panel reached a concurrence on, were deleted. The factors that were deleted are outlined using color red. As a result, 28 criteria are retained.

Furthermore, The Factors 1&35 are combined as “Employment issues and wages”. Factors 15 & 19 are combined as “Human health & safety” and coded as factor 18. Factor 36 (Reliability level of the strategy used) is eliminated because of its similarity to factor, 31(Reliability of Rollingstock). Factor 19 (Environmental safety) is eliminated because of its similarity to factor 20, (Environmental damage from accidents). Factor 18 (Human health and safety) was eliminated because of its similarity to Factors 8&23 (Passenger safety, worker safety). Therefore, there were 25 factors in total that were considered as shown in the Table 6 below;

No.	SUB-CRITERIA
1	Employment wages
2	Personnel training cost
3	Personnel capability(Ease of understanding and Implementation)
4	Reduced energy consumption
5	Passenger safety
6	Mental attitude of maintenance staff
7	Loss of ridership
8	Convenience to fix Failure
9	Financial feasibility
10	System safety
11	Fault identification
12	Environmental damage from accidents
13	Improved company brand
14	Worker safety
15	Availability of Technnology
16	Severity of failure of the machine
17	Time effectiveness of strategy used
18	Human and Managerial willingness to support the strategy
19	customer satisfaction
20	Reliability of the rollingstock
21	Training Requirements for personnel
22	Employment issues
23	Cost of maintenance equipment
24	Risk Level of the system
25	System compatibility

Table 6: The total of the 25 refined factors

4.7 Network construction

This is the first step for developing the ANP network model. As can be noticed from the variety of colors from the table (Table 6) above, different colors represent the different categories in which the factors were grouped. Therefore, in this section, the criteria are grouped according to their correlation.

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

This implies that all criteria that seemed to be similar by certain aspects have been grouped into one category(cluster) and this is done before determining the interdependences among the criteria. Some criteria are grouped according to their connection to “cost” and these are the criteria, 2,7,16,23. These criteria were all grouped into one category and under one main criterion which is the “**Economic**” factor. Then, the criteria labelled; 6,21,22,1 are all categorized to be associated with Human or social aspects therefore they are placed under the main criterion, “**Social**” factors. The criteria labelled; 11,13,19,20 are all categorized into one group based on their similarity with value- addition therefore they are placed under one main evaluation criteria known as, “**Value-Addition**” factors. The criteria labelled; 5,10,14 are all categorized in the same group since they have aspects associated with safety and they are all placed under the main evaluation factor known as, “**Safety**” factors. The criteria labelled; 3,9,15,18,25 are all categorized in the same group as they have aspects concerning feasibility. They are all placed under one main criterion known as, “**Feasibility**” factors. The criteria labelled; 4&12 are categorized into one group based on their similarities of environmental and sustainability aspects. Therefore, they are all placed under a single main evaluation criterion known as “**Environmental**” factors. The factors labelled; 8,17,24 are categorized based on their similarities with technical aspects and placed under a main criterion known as, “**Technical**” factors

The leading factors that are formed are represented in the table as shown below;

LEADING FEACTORS	No.	SUB-CRITERIA/ SUB-FACTORS
SOCIAL FACTORS	9	Mental attitude of maintenance staff
	21	Training Requirements for personnel
	22	Employment issues
	1	Employment wages
OPERATIONAL FACTORS	24	Risk Level of the system
	17	Time effectiveness of strategy used
	8	Convenience to fix Failure
ECONOMIC FACTORS	2	Personnel training cost
	7	Loss of ridership
	16	Severity of failure of the machine
	23	Cost of maintenance equipment
VALUE ADDITION FACTORS	20	Reliability of the rollingstock
	11	Fault identification
	13	Improved company brand
	19	customer satisfaction
SAFETY FACTORS	5	Passenger safety
	14	Worker safety
	10	System safety
FEASIBILITY FACTORS	9	Financial feasibility
	18	Human and Managerial willingness to support the strategy
	15	Availability of Technology
	3	Personnel capability (Ease of understanding and Implementation)
	25	System compatibility
ENVIRONMENTAL FACTORS	12	Environmental damage from accidents
	4	Reduced energy consumption

Table 7: The seven leading factors and the sub-factors contained there in

From the second section of the phase I questionnaire, the DMs are again requested to select which of the Leading factors should be removed. Using the *Likert Scale format* questions, the DMs filled the questionnaires again and from the results, it is seen that the *Environmental* and *Technical* factors have

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

the least importance after applying Geometric mean. Therefore, they are selected by consensus to be eliminated as having less influence on the maintenance strategies to be selected.

Therefore, a total of 20 sub-factors remained and there was a total of five Leading factors which were to be used for the evaluation process. The remaining leading factors and sub-factors are represented in the Table (Table 8) as shown below and they are coded using numbers from N1-N20;

LEADING FEACTORS	CODE NO.	SUB-CRITERIA/ SUB-FACTORS
SOCIAL FACTORS	N1	Mental attitude of maintenance staff
	N2	Training Requirements for personnel
	N3	Employment issues
	N4	Employment wages
ECONOMIC FACTORS	N5	Personnel training cost
	N6	Loss of ridership
	N7	Severity of failure of the machine
	N8	Cost of maintenance equipment
VALUE ADDITION FACTORS	N9	Reliability of the rollingstock
	N10	Fault identification
	N11	Improved company brand
	N12	customer satisfaction
SAFETY FACTORS	N13	Passenger safety
	N14	Worker safety
	N15	System safety
FEASIBILITY FACTORS	N16	Financial feasibility
	N17	Human and Managerial willingness to support the strategy
	N18	Availability of Technnology
	N19	Personnel capability(Ease of understanding and Implementation)
	N20	System compatibility

Table 8: T the Leading factors selected and the contained coded elements (sub-factors)

4.8 Assessing dependency among criteria

This study intends to investigate how the decision making is influenced if the existence of interdependencies among the sub-criteria is considered. Thus, the decision-making experts were required to vote for the interdependencies between each pair of sub-criteria through a checklist and the interdependent sub-criteria were then determined based on their votes. This checklist which is shown in the figure below includes blocks which were marked if any of the left column elements influenced any of the elements on the top row. The whole matrix is a **20 × 20** interdependency matrix. In order to examine the influence among criteria, a new survey questionnaire is distributed to experts, who are asked to assess the strength of dependency among criteria.

The ten completed questionnaires are collected. The '*majority rule*' is then used to aggregate the responses into a single matrix, where a majority condition of **6 out of 10 (6/10)** experts' consensus (i.e. 60%) is considered as a minimum requirement for any entry to confirm the existence of a direct relationship between any pair of criteria. The final interdependency matrix is shown in the table (Table 9) below and the final dependency matrix is developed using a zero-one matrix of criteria against criteria using a binary value of 1 to designate reliance of one criterion on another, and zero otherwise (Saaty, 2006). This matrix is demonstrated in the table (Table 10) below;

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14	N15	N16	N17	N18	N19	N20
N1			X			X			X		X			X		X	X		X	
N2				X	X				X		X					X				
N3	X	X		X							X						X		X	
N4	X	X	X		X	X	X	X	X	X	X	X			X	X	X		X	
N5				X						X		X	X	X		X	X			
N6	X		X	X							X	X							X	
N7		X	X			X									X				X	
N8				X					X			X				X				
N9				X	X	X					X	X				X	X			
N10					X		X		X		X				X					
N11	X			X		X													X	
N12				X		X					X								X	
N13	X	X		X	X	X				X	X	X							X	
N14	X	X	X	X	X			X		X	X								X	
N15	X	X		X	X	X		X		X	X								X	
N16		X			X								X						X	
N17	X	X		X	X	X			X		X				X					
N18		X		X	X		X		X	X	X	X	X	X	X	X	X		X	X
N19	X								X		X			X						
N20							X								X					

Table 9: A final interdependency matrix that integrates all 6/10 opinions demonstrating the influences between sub-criteria

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

	N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14	N15	N16	N17	N18	N19	N20
N1	0	0	1	0	0	1	0	0	1	0	1	0	0	1	0	1	1	0	1	0
N2	0	0	0	1	1	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0
N3	1	1	0	1	0	0	0	0	0	0	1	0	0	0	0	0	1	0	1	0
N4	1	1	1	0	1	1	1	1	1	1	1	1	0	0	1	1	1	0	1	0
N5	0	0	0	1	0	0	0	0	0	1	0	1	1	1	0	1	1	0	0	0
N6	1	0	1	1	0	0	0	0	0	0	1	1	0	0	0	0	1	0	0	0
N7	0	1	1	0	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0
N8	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	1	0	0	0	0
N9	0	0	0	1	1	1	0	0	0	0	1	1	0	0	0	1	1	0	0	0
N10	0	0	0	0	1	0	1	0	1	0	1	0	0	0	1	0	0	0	0	0
N11	1	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0
N12	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0	1	0	0	0
N13	1	1	0	1	1	1	0	0	0	1	1	1	0	0	0	0	1	0	0	0
N14	1	1	1	1	1	0	0	1	0	1	1	0	0	0	0	0	1	0	0	0
N15	1	1	0	1	1	1	0	1	0	1	1	0	0	0	0	0	1	0	0	0
N16	0	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0	1	0	0	0
N17	1	1	0	1	1	1	0	0	1	0	1	0	0	0	1	0	0	0	0	0
N18	0	1	0	1	1	0	1	0	1	1	1	1	1	1	1	1	1	0	0	0
N19	1	0	0	0	0	0	0	0	1	0	1	0	0	1	0	0	0	0	0	0
N20	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0

Table 10:A final dependency matrix/zero-one matrix demonstrating the influences between sub-criteria

4.9 Construction of The ANP Model

To develop an ANP model, it is necessary to identify the problem, define criteria and sub-criteria and alternatives and then specify the relations between them and their interactions. A network model has a criteria cluster and an alternative cluster and there is no goal cluster. The network model has one single objective and that is to try and select an appropriate maintenance strategy by taking into consideration the maintenance characteristics and attributes that affect and contribute to the selection of an appropriate

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

maintenance strategy. These are represented as clusters, nodes and influence links in a network. The decision alternatives are the *maintenance strategies*.

In the present application, the model has been created by the '*simple (straight-forward)*' system structure. A simple system contains groups, hubs/components and associations or connections(links) which are altogether contained in a solitary window. This implies that there are no sub-networks. The "basic" arrangement is a free-displaying approach, which isn't bolstered by any guide or pre-decided structure (complex system structure). The system structure of the upkeep methodology choice issue and the associations between the bunches have been mimicked utilizing Super Decisions 2.6.1-RC1 Software, planned by Bill Adams and the Creative Decisions Foundation. Introduced on windows 10. It has a tcl version 8.5. It makes a rundown of the pairwise correlations expected to run the evaluation. The chosen criteria for the choice issue are selected as appeared in the segment above (section.3.6) and are bunched into five fundamental gatherings (groups) as illustrated previously. The figure underneath showcases the model with the bunches and their individual components.

A straightforward system contains bunches(clusters), hubs(nodes), and associations or connections(links). At the point when a parent hub(node) is connected to hubs in another group, these are known as its children hubs(nodes). The kids(children) hubs are to be contrasted with reference to the parent hub. At the point when a parent hub is connected to children hubs in another bunch, a line or connection shows up between the groups with an arrow on it from the bunch containing the parent hub. At the point when the parent hub and children are in a similar group there will be a self-circle on that bunch.

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

As indicated by the ANP system, when the system has been recognized, it is important to represent the impacts (or between connections) among the components (hubs). This undertaking is drawn closer in the accompanying way. Above all else, the objective is to have an impact on every one of the components in the groups. Furthermore, the components in the bunches should have an effect on the choices (see Figure 5). Thirdly, further connections are distinguished concerning the potential impacts among the components of each (unique) group (external reliance); for example between the Cost and monetary bunch (cluster) is spoken to by the link from the cost group to the financial/social group in (Figure 5). Fourthly, connections are considered between components of a similar group (inner-dependence) which is which is represented by a loop arrow as appeared (Figure 6) for example in the monetary bunch(cluster). Lastly, a feedback structure was introduced whereby options (alternatives) were connected with the criteria so as to contrast them for inclination to discover what set of criteria or components contributes more to an appropriate maintenance strategy (see Figure 6)

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

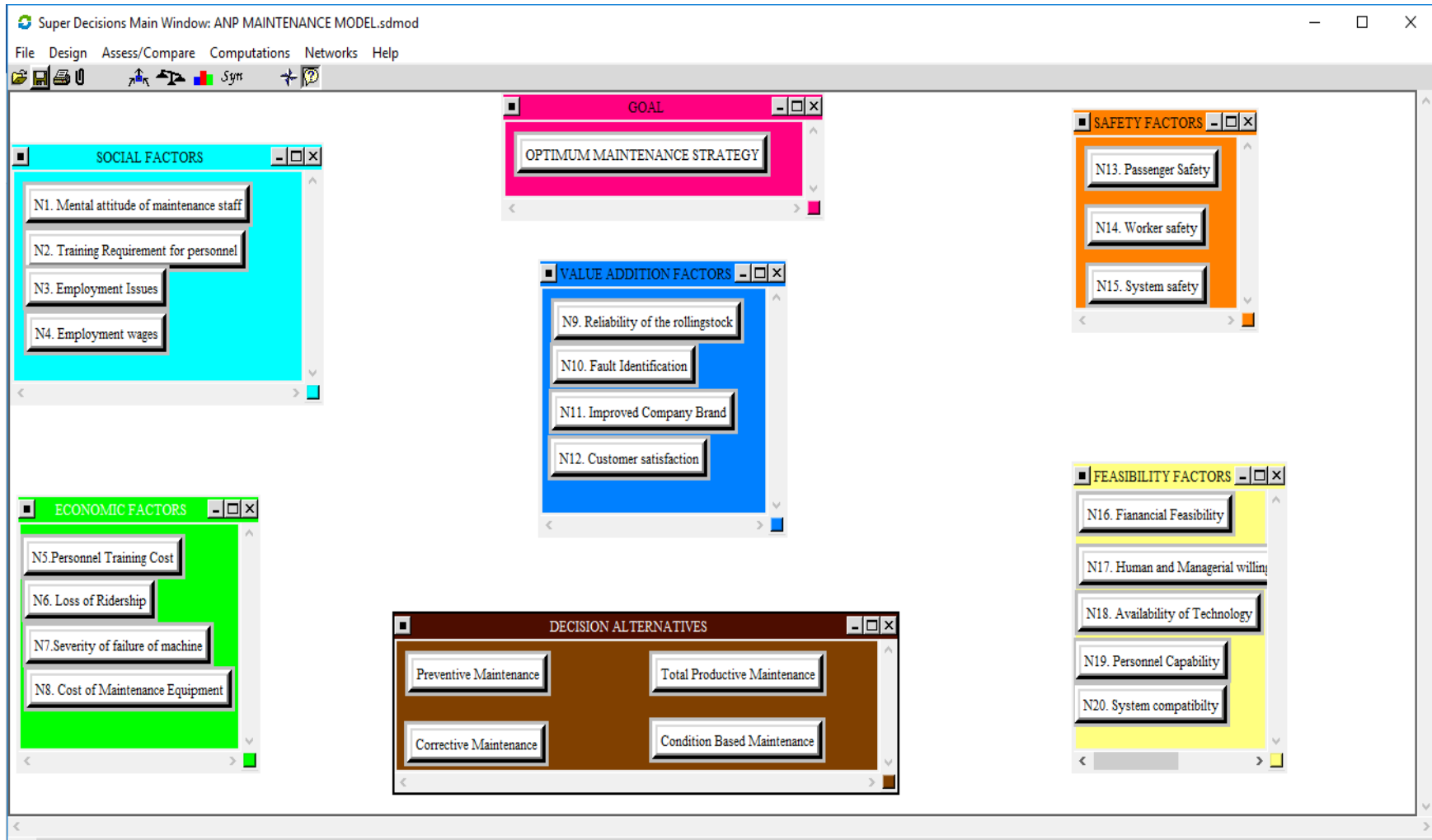


Figure 5: ANP Model showing clusters containing sub-criteria

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

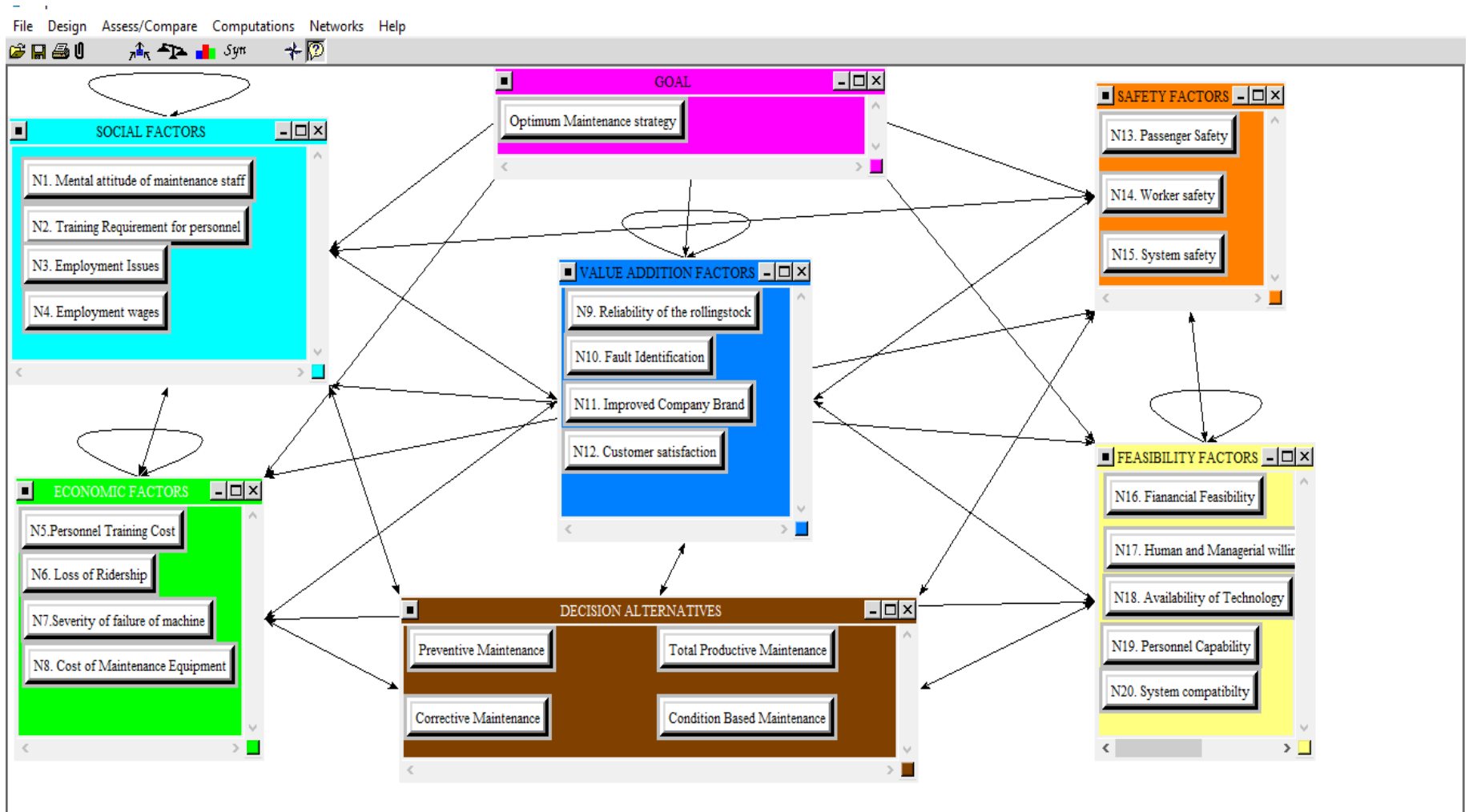


Figure 6: ANP Model showing clusters and all the interconnections, loops and feedback connections

4.10 ANP Pairwise comparisons

After constructing the ANP model, the next phase is carrying out pairwise comparisons, which involves obtaining judgements from experts for pairwise comparison questions created according to the ANP structure that was modeled. A pairwise comparison is a numerical representation of the relationship between two elements that discerns which element is more important than the other with respect to a higher criterion.

This process requires a series of pairwise comparisons where the decision maker will compare two components at a time with respect to a control/parent criterion based on the nine-point scale suggested by Saaty (1988). A score of 1 indicates the equality between the two elements whereas score 9 represents the dominance of row element in the matrix over the column element. A reciprocal value is automatically assigned in the opposite position in the matrix. In this model, there were **474** pairwise comparison questions. It is obvious that the task of asking such a large number of questions would be very enormous and would require intensive efforts and extended time. The questionnaires included all required pairwise questions to assess expert judgments in relation to the relative influence of affecting elements on the affected ones.

According to the ANP methodology, the comparison and evaluation phase is based on the pairwise comparison of the elements under consideration which involves comparison between clusters which is more general and the comparison between nodes which is more detailed. The generic question of the pairwise comparisons has the following form: given an element in any component, how much more does a given element of a pair influence that element with respect to a control sub-criterion (criterion)? The same kind of question is asked about the comparison of clusters. Cluster comparison is done to establish

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

their importance with respect to each cluster they are linked from. The linked nodes in a given cluster are pairwise compared for their influence on the node they are linked from (the parent node) to determine the priority of their influence on the parent node. All the comparison questions are asked from the perspective of what is contributing more to the selection of an appropriate maintenance strategy. Each comparison has a respective question; for example, “with respect to Passenger safety in the economic factors cluster,

which indicator is more important: Personnel training or loss of ridership, and to what degree?” The same question is made for all elements that have an impact on other elements, whether they belong to the same cluster (inner dependence) or to another cluster (outer dependence). The point in doing the comparisons is to obtain their relative weights; i.e. each element/cluster has a certain importance in the network/model, which is represented by weights. During the pairwise comparison process of all the factors, the consistency of the responses must be checked by calculating the Consistency Ratio (CR). A consistency less than 0.1 is acceptable. In this study the consistency ratio is calculated automatically by the Super Decisions software.

An example of such posed pairwise questions is of the following kind: In selecting an appropriate maintenance strategy, which influences more in the safety factors cluster, Passenger safety or worker safety? And with what strength. Once the pairwise comparisons questionnaires were completed and collected from the decision makers, the geometric means were computed in order to aggregate individual judgments into a representative group judgment for each pairwise question. The Assess/Compare command of the *Super-Decisions* was then used to enter the obtained group judgments and Pairwise comparison process was then initiated. An example of the used comparison questionnaire

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

mode is shown in the figure below; The whole questionnaire is shown in the Appendix section of the report.

	Graphical	Verbal	Matrix	Questionnaire	Direct																		
Comparisons wrt "OPTIMUM MAINTENANCE STRATEGY" node in "ECONOMIC FACTORS" cluster																							
N5.Personnel Training Cost is ?????? more important than N6. Loss of Ridership																							
1. N5.Personnel Tr~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	N6. Loss of Rid~		
2. N5.Personnel Tr~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	N7.Severity of ~		
3. N5.Personnel Tr~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	N8. Cost of Mai~		
4. N6. Loss of Rid~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	N7.Severity of ~		
5. N6. Loss of Rid~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	N8. Cost of Mai~		
6. N7.Severity of ~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	N8. Cost of Mai~		

Figure 7: Pair-wise comparisons in generated questionnaire

Chapter five: Results and Discussion

This chapter discusses the results of the empirical analysis of selection of an appropriate maintenance strategy for the Addis Ababa Light Rail Transit Service rollingstock. The results of the ANP models are presented and examined. After collection of data by using the questionnaire generated in the super-decision software, the combined rating of all experts' opinion was transferred in the super-decision software and analyzed. Each set of pair wise comparisons was checked for consistency and revised where necessary until the maximum inconsistency was below ten percent (<0.1), which is considered the minimum standard level. The results were synthesized throughout the model to yield the overall priorities of the strategic alternatives. The results are demonstrated in the subsequent figures below; Condition-Based Maintenance (CBM) is the most suitable maintenance strategy to be implemented on the light rail transit system. CM is the least preferable maintenance strategy to be implemented in light rail transit system.

5.1 Results

5.1.1 The final Results: The Priorities of the Alternatives

After collection of data by using the super-decision generated questionnaire, the combined rating of all experts' opinion is then transferred to super-decision software and analyzed. Each set of pair wise comparisons is checked for consistency and revised by using the matrix mode of the software until the inconsistency is below ten percent, which is considered the minimum standard level(Saaty, 1991). The results are synthesized throughout the model to yield the overall priorities of the strategic alternatives. The results that are obtained from the super-decision software are as shown below;

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

The figure below (Figure 10) presents the final results ‘global preferences’ for alternatives which are obtained using *Super-Decisions* ‘Synthesis’ command. These results indicate that the Condition Based Maintenance (CBM) is the most preferred alternative with a priority of 34.42%, Total Productive Maintenance (TPM) is ranked second but almost as equally preferred as CBM with a priority has 33.22%, Preventive maintenance is ranked third with a priority of 20.15% and the least preferred maintenance strategy among others is Corrective maintenance with a priority of 12.20%.

The Priorities of the alternatives are obtained by selecting computations on super-decision software window, then selecting synthesise. Alternatively, the priorities can be obtained from clicking on the icon ‘syn’.

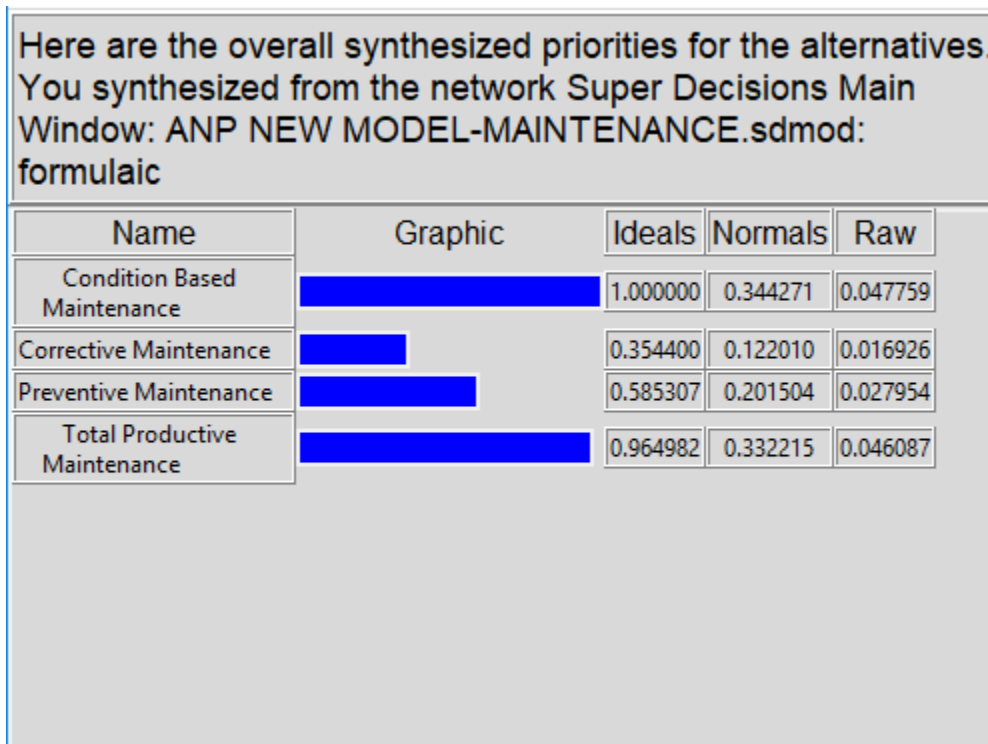


Figure 8: The final priorities of alternative maintenance strategies

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

5.1.2 The Priorities of all the nodes

The priorities for all the criteria are obtained by selecting the *computations >priorities* command. This generates the priorities of all the criteria (nodes) in the model. The priorities obtained are extracted (generated) from the software as shown in the figure (figure 11) below;

Icon	Name	Normalized by Cluster	Limiting
No Icon	Condition Based Maintenance	0.34427	0.047759
No Icon	Corrective Maintenance	0.12201	0.016926
No Icon	Preventive Maintenance	0.20151	0.027954
No Icon	Total Productive Maintenance	0.33222	0.046087
No Icon	N5. Personnel Training Cost	0.43987	0.072299
No Icon	N6. Loss of Ridership	0.32857	0.054006
No Icon	N7. Severity of failure of machine	0.05923	0.009735
No Icon	N8. Cost of Maintenance Equipment	0.17233	0.028325
No Icon	N16. Financial Feasibility	0.19384	0.033760
No Icon	N17. Human and Managerial willingness to support t-	0.71249	0.124090
No Icon	N18. Availability of Technology	0.03119	0.005432
No Icon	N19. Personnel Capability	0.06146	0.010704
No Icon	N20. System compatibility	0.00102	0.000177
No Icon	N13. Passenger Safety	0.14859	0.019745
No Icon	N14. Worker safety	0.22529	0.029937
No Icon	N15. System safety	0.62611	0.083198
No Icon	N1. Mental attitude of maintenance staff	0.36769	0.074018
No Icon	N2. Training Requirement for personnel	0.14543	0.029276
No Icon	N3. Employment Issues	0.11121	0.022387
No Icon	N4. Employment wages	0.37568	0.075627

Figure 9: The priorities of all the nodes in the model

The values are extracted from the figure above and have been properly elaborated in the table (table 8) below as shown from the excel sheet. The values under the *Limiting* column heading are simply the

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

values from any column of the Limit Matrix. The ***Normalized by Cluster*** values are obtained by normalizing the priorities in each component so they sum to 1.0.

Name	Normalized By Cluster	Limiting
Condition Based Maintenance	0.34427	0.047759
Corrective Maintenance	0.12201	0.016926
Preventive Maintenance	0.20151	0.027954
Total Productive Maintenance	0.33222	0.046087
N5. Personnel Training Cost	0.43987	0.072299
N6. Loss of Ridership	0.32857	0.054006
N7. Severity of failure of machine	0.05923	0.009735
N8. Cost of Maintenance Equipment	0.17233	0.028325
N16. Fianancial Feasibility	0.19384	0.03376
N17. Human and Managerial willingnes	0.71249	0.12409
N18. Availability of Technology	0.03119	0.005432
N19. Personnel Capability	0.06146	0.010704
N20. System compatibilty	0.00102	0.000177
N13. Passenger Safety	0.14859	0.019745
N14. Worker safety	0.22529	0.029937
N15. System safety	0.62611	0.083198
N1. Mental attitude of maintenance staf	0.36769	0.074018
N2. Training Requirement for personne	0.14543	0.029276
N3. Employment Issues	0.11121	0.022387
N4. Employment wages	0.37568	0.075627
N9. Reliability of the rollingstock	0.31249	0.058923
N10. Fault Identification	0.2185	0.0412
N11. Improved Company Brand	0.29416	0.055466
N12. Customer satisfaction	0.17484	0.032968
Optimum Maintenance strategy	0	0

Table 11: The priorities of the nodes in the model.

The proposed decision model of maintenance selection is implemented for 20 criteria (factors) and five main criteria. The priorities as determined after the model evaluation is seen from the table of priorities obtained after the pairwise evaluations. The most important criterion ***Human and Managerial willingness to support the strategy*** with a normalized factor of 0.712. Also, the least essential criteria

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

that affects maintenance selection are *the system compatibility* and *Availability of Technology*. This implies that the Human and Managerial willingness to support the strategy is the most influential determinant in choosing the most optimum maintenance strategy. Then the Availability of Technology and the system compatibility are the least influential factors in trying to select an appropriate maintenance strategy.

It can be said that results of this study are consistent since inconsistency ratio of all pair wise comparisons is less than 0.1. The *Super-Decisions* computations command was used to perform necessary matrix algebra in relation to the creation of the three super-matrices associated with this model which include; the unweighted super-matrix, the weighted super-matrix and the limit matrix. From the obtained limit matrix, one can simply read the global priorities of the criteria and the alternatives from any column.

5.1.3 Formation of the Unweighted Super-matrix

In the Un weighted Super-matrix, the priorities of the elements are arranged both vertically and horizontally according to the clusters. The paired comparison provided vector will become part of the column in Super-matrix. This represents the impact, with respect to the control criterion of the elements of that cluster on a single element of the same or another cluster, listed at the top. A section of the Super-matrix for our model is provided in the Table (Table 12) below; A full demonstration of the unweighted super-matrix is shown in the Appendix section of this report.

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

Cluster Node Labels	DECISION ALTERNATIVES	ECONOMIC FACTORS			
		N5, Personnel Training Cost	N6, Loss of Ridership	N7, Severity of failure of machine	N8, Cost of Maintenance Equipment
DECISION ALTERNATIVES	Condition Based Maintenance	0.000000	0.000000	0.000000	0.000000
	Corrective Maintenance	0.000000	0.000000	0.000000	0.000000
	Preventive Maintenance	0.000000	0.000000	0.000000	0.000000
	Total Productive Maintenance	0.000000	0.000000	0.000000	0.000000
ECONOMIC FACTORS	N5, Personnel Training Cost	0.354004	0.000000	0.000000	0.000000
	N6, Loss of Ridership	0.131322	0.000000	0.000000	0.000000
	N7, Severity of failure of machine	0.160671	0.000000	1.000000	0.000000
	N8, Cost of Maintenance Equipment	0.354004	0.000000	0.000000	1.000000

Table 12: The unweighted super-matrix

5.1.4 Formation of the weighted Super-matrix

The weighted priorities at the cluster's priority matrix are used to weight all the elements in the block of column priorities of the Super-matrix corresponding to the impact of the elements of that cluster on another cluster. The weighted super-matrix is formed by the combination of the unweighted super-matrix and the *control hierarchy* matrix or a *cluster* matrix. A control hierarchy matrix is an $n \times n$ matrix where n is the number of clusters in the network. The cluster, C_i scores priorities over all the clusters to which it is connected i.e. all the clusters that C_i is connected to, are pairwise compared their influence on C_i . These weights are listed in the control hierarchy matrix which is combined by multiplication to the unweighted super-matrix. This process is repeated for all the clusters resulting in the weighted Super-matrix. The weighted Super-matrix for this model is provided in the Table (Table 13) below; A full demonstration of the weighted super-matrix is shown in the Appendix section of this report.

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

Cluster Node Labels	DECISION ALTERNATIVES				ECONOMIC FACTORS			
	Condition Based Maintenance	Corrective Maintenance	Preventive Maintenance	Total Productive Maintenance	N5, Personnel Training Cost	N6, Loss of Ridership	N7, Severity of failure of machine	N8, Cost of Maintenance Equipment
Condition Based Maintenance	0.000000	0.000000	0.000000	0.000000	0.070801	0.000000	0.000000	0.000000
Corrective Maintenance	0.000000	0.000000	0.000000	0.000000	0.026264	0.000000	0.000000	0.000000
Preventive Maintenance	0.000000	0.000000	0.000000	0.000000	0.032134	0.000000	0.000000	0.000000
Total Productive Maintenance	0.000000	0.000000	0.000000	0.000000	0.070801	0.000000	0.000000	0.000000
N5, Personnel Training Cost	0.084973	0.071288	0.098677	0.084232	0.000000	0.000000	0.000000	0.000000
N6, Loss of Ridership	0.028757	0.024851	0.000000	0.018394	0.000000	0.000000	0.250000	0.000000
N7, Severity of failure of machine	0.032257	0.038715	0.039160	0.044601	0.000000	0.000000	0.000000	0.000000
N8, Cost of Maintenance Equipment	0.054013	0.065145	0.062163	0.052772	0.000000	0.000000	0.000000	0.250000
DECISION ALTERNATI VES								
ECONOMIC FACTORS								

Table 13: Weighted super-matrix

5.1.5 Formation of limiting matrix

Now, we want to obtain final influence of an element on the highest goal. The limiting matrix and the system's solution is derived from multiplying the weighted Super-matrix by itself, which accounts for variable interaction, until the system's raw values converge to the same value for each column of the matrix. This power method process yields the limiting matrix, which provides the relative importance weights for every element in the model. The limiting matrix is provided in the Table (Table 14) below; A full demonstration of the Limit super-matrix is shown in the Appendix section of this report.

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

Cluster Node Labels	DECISION ALTERNATIVES				ECONOMIC FACTORS			
	Condition Based Maintenance	Corrective Maintenance	Preventive Maintenance	Total Productive Maintenance	N5. Personnel Training Cost	N6. Loss of Ridership	N7. Severity of failure of machine	N8. Cost of Maintenance Equipment
DECISION ALTERNATIVES	Condition Based Maintenance	0.047759	0.047759	0.047759	0.047759	0.047759	0.047759	0.047759
	Corrective Maintenance	0.016926	0.016926	0.016926	0.016926	0.016926	0.016926	0.016926
	Preventive Maintenance	0.027954	0.027954	0.027954	0.027954	0.027954	0.027954	0.027954
	Total Productive Maintenance	0.046087	0.046087	0.046087	0.046087	0.046087	0.046087	0.046087
ECONOMIC FACTORS	N5. Personnel Training Cost	0.072299	0.072299	0.072299	0.072299	0.072299	0.072299	0.072299
	N6. Loss of Ridership	0.054006	0.054006	0.054006	0.054006	0.054006	0.054006	0.054006
	N7. Severity of failure of machine	0.009735	0.009735	0.009735	0.009735	0.009735	0.009735	0.009735
	N8. Cost of Maintenance Equipment	0.028325	0.028325	0.028325	0.028325	0.028325	0.028325	0.028325

Table 14: The Limit matrix

5.2 Discussion of Results

5.2.1 Discussion of the Unweighted Super-Matrix

The unweighted super-matrix contains the local priorities derived from the pairwise comparisons throughout the network as shown in Table 9 above. The unweighted super-matrix is composed of column vectors that are the priorities obtained by comparing nodes in a cluster with respect to a parent node. The column for a given node contains all the priority vectors in the system with that node as a parent of the comparison. A parent node may have children in many different clusters, so the priority vectors are stacked on top of each other in the parent node's column. This is demonstrated clearly in (Figure 10) below. Each priority vector sums to 1.0, so the numbers in the column of a given node may sum to more than 1, though the sum will always be an integer (or zero if that node is not connected to any other nodes in the entire system).

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

FEASIBILITY FACTORS		
N16. Fianancial Feasibility	N17. Human and Managerial willingness to support the startegy	N18. Availability of Technology
0.481627	0.329998	0.240380
1.000000	0.428571	0.800000
0.000000	0.142857	0.000000
0.000000	0.000000	0.200000
0.000000	0.000000	0.000000
0.000000	0.000000	0.310814
1.000000	0.000000	0.493386
0.000000	0.000000	0.000000

Figure 10: Priority vectors stacked on top of each other in the Financial feasibility (N16) node column for children nodes from other clusters and the columns (N17,N18) with their own children nodes.

The priorities of the children elements (nodes) along the rows; *Personnel training cost* and *Loss of Ridership*, with respect to Condition Based Maintenance can be extracted as 0.424863 and 0.143784. Therefore, these values may be interpreted with the statement, "The *Personnel training cost* characteristic of CBM is between weakly and strongly preferred, or 2 times, more preferred characteristic than the *Loss of Ridership* aspect." All the local priority information can be read directly from the unweighted Super-matrix. Below is a figure showing the Economic cluster priorities for the CBM column extracted from the unweighted super-matrix.

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

ECONOMIC FACTORS	N5. Personnel Training Cost	0.424863
	N6. Loss of Ridership	0.143784
	N7. Severity of failure of machine	0.161286
	N8. Cost of Maintenance Equipment	0.270066

Figure 11: The local priorities of the economic cluster elements in the CBM column(brown)

The local priorities of *Severity of failure of machine* and the *cost of maintenance* are evaluated to be 0.161286 and 0.270066 respectively.

A **component** in a super-matrix is the block defined by a cluster name at the left and a cluster name at the top. For example, the (Decision Alternatives, Decision Alternatives) component in Figure 12 is composed of the block of four zeros in the upper left-hand corner shown in the screen clip in the figure below;

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

Cluster Node Labels		DECISION ALTERNATIVES			
		Condition Based Maintenance	Corrective Maintenance	Preventive Maintenance	Total Productive Maintenance
DECISION ALTERNATIVES	Condition Based Maintenance	0.000000	0.000000	0.000000	0.000000
	Corrective Maintenance	0.000000	0.000000	0.000000	0.000000
	Preventive Maintenance	0.000000	0.000000	0.000000	0.000000
	Total Productive Maintenance	0.000000	0.000000	0.000000	0.000000

Figure 12: Screen clip of component (block) for the decision Alternatives

Another example is the (Decision alternatives, Economic factors) component as shown in the figure below (Figure 13). It is a component containing the alternatives cluster at the top and the Economic factors cluster at the left.

ECONOMIC FACTORS	N5. Personnel Training Cost	0.424863	0.356440	0.493386	0.421162
	N6. Loss of Ridership	0.143784	0.124257	0.000000	0.091970
	N7. Severity of failure of machine	0.161286	0.193576	0.195800	0.223007
	N8. Cost of Maintenance Equipment	0.270066	0.325727	0.310814	0.263861

Figure 13: The (Decision Alternative, Economic factor) component extracted from the unweighted super-matrix

5.2.2 Discussion of the weighted Super-matrix

The weighted super-matrix is obtained by multiplying all the elements in a component of the unweighted super-matrix by the corresponding cluster weight. This is known as weighting the components in-order to make all the columns to sum to ‘one’ in the weighted super-matrix. Using the same example from above, the local priorities for the (Decision alternative, Economic factor) component changed in order for the column to add up to ‘one’ in (Figure 14) below;

ECONOMIC FACTORS	N5. Personnel Training Cost	0.084973	0.071288	0.098677	0.084232
	N6. Loss of Ridership	0.028757	0.024851	0.000000	0.018394
	N7. Severity of failure of machine	0.032257	0.038715	0.039160	0.044601
	N8. Cost of Maintenance Equipment	0.054013	0.065145	0.062163	0.052772

Figure 14: The (Decision alternative, Economic factor) component extracted from the Weighted Super-matrix

5.2.3 Discussion of the Limit Super-matrix

The Limit super-matrix is obtained by raising the weighted super-matrix to powers by multiplying it times itself until the matrix converges. When the column of numbers is the same for every column for each row, the limit matrix has been reached and the matrix multiplication process is halted. The limit super-matrix for this particular model is shown in the figure above in the results section (Table 14). The previous example of the (decision alternative, Economic factor) component is used to demonstrate the difference with Limit matrix values. shown in (Figure 16) below;

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

ECONOMIC FACTORS	N5. Personnel Training Cost	0.072299	0.072299	0.072299	0.072299
	N6. Loss of Ridership	0.054006	0.054006	0.054006	0.054006
	N7. Severity of failure of machine	0.009735	0.009735	0.009735	0.009735
	N8. Cost of Maintenance Equipment	0.028325	0.028325	0.028325	0.028325

Figure 15: The (Decision alternative, Economic factor) component extracted from the Limit Super-matrix

The final synthesized results are extracted from the Limit matrix in the goal node column (purple). The figure below shows the values of the decision alternatives stacked under the goal node (purple). These values are the same values used as 'RAW' values in the synthesized priorities.





Name	Graphic	Ideals	Normals	Raw
Condition Based Maintenance		1.000000	0.344271	0.047759
Corrective Maintenance		0.354400	0.122010	0.016926
Preventive Maintenance		0.585307	0.201504	0.027954
Total Productive Maintenance		0.964982	0.332215	0.046087

Figure 17: The final synthesized result

It can be seen from the figures above (Figure 16 & Figure 17) that the values in the goal(purple) column are the same exact values in the raw column of the synthesized result.

5.2.4 Discussion of the Synthesized values

The synthesized values from the simple network model of this study are shown in the figure above (Figure 17). The ‘**Raw**’ values are directly extracted from the Limit matrix. The **Normalized** values are obtained from them (raw values) by normalizing (i.e. Summing the whole **Row** column and dividing each row by the total sum obtained). The **Normalized** column values always have to add up to ‘1’. The **Ideals** are obtained by dividing all **Row** values by the largest of them. The normalized column shows the overall priority of the decision alternatives.

From the results obtained, it can be seen that the best ranked alternative is **Condition Based Maintenance** followed closely by **Total Productive Maintenance** in second place and then **Preventive maintenance** and **Corrective maintenance** ranked in the third and fourth place respectively.

5.3 Sensitivity Analysis of Model

5.3.1 Sensitivity analysis on the final outcome

Sensitivity analysis can be done to determine whether the final answer is stable with respect to changes in the inputs either judgments or priorities. It is interesting to find out if there is any change in the alternatives because of input changes.

The *ANP Row sensitivity and Influence Analysis* are used for this particular model (simple network model). The model utilized in this study does not have sub-networks therefore no **real sensitivity** or **influence analysis** calculations are possible with this model and does not make sense, and “**with respect to**” sensitivity actually shows *no* sensitivity. This explains why the *ANP Row sensitivity* is utilized in this study. ANP Row Sensitivity and influence analysis opens up a vista of analysis unavailable before. We can now see quickly which nodes are most influential (either through rank changes, raw changes, or infinitesimal changes).

The figure below (Fig 20) is a graph showing the node sensitivity for Condition Based Maintenance node. This graph is obtained in Super-decisions under the ‘computations’ menu and then ‘Node sensitivity’ is selected. The ‘Condition based Maintenance’ node is then selected.

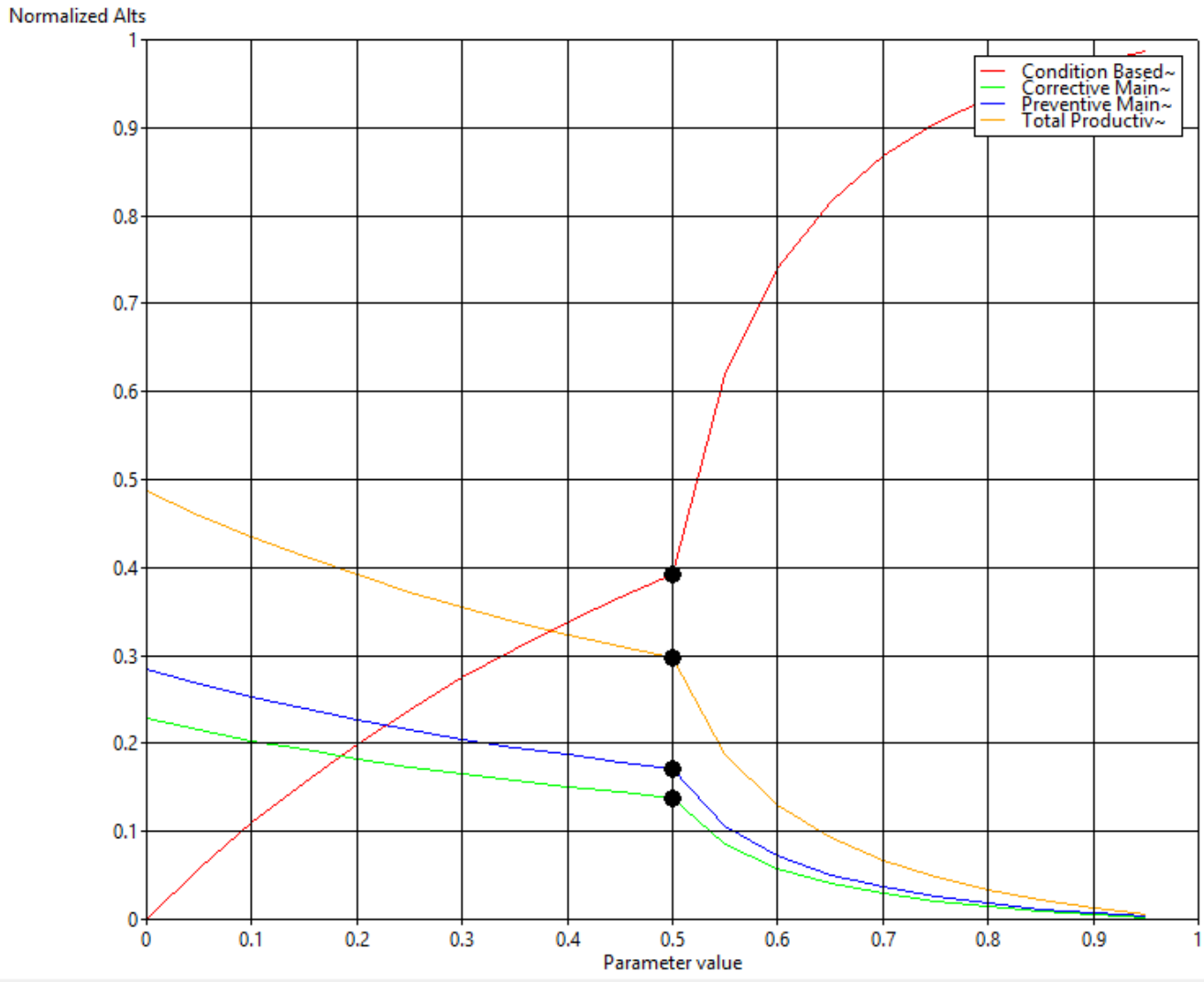


Figure 18: Node Sensitivity graph with original parameter value, p at 0.5

In the graph above (Figure 18) It can be noticed that the non-smooth point, parameter value p is at $p=0.5$. This occurs because, by default $p=0.5$ is the original value. The rank for the alternatives at this point is seen to be that Condition Based Maintenance (CBM) is ranked as the best and TPM ranked as second best. The importance of the node goes up and below, it goes down. The rest value for ' p ' is changed to a point that makes the graph smooth. This is done by choosing '*Computations-*

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

Influence/Sensitivity-Options-Smart p0'. Doing this creates the following graph (Note that the dots have moved). This is demonstrated in the graph below;

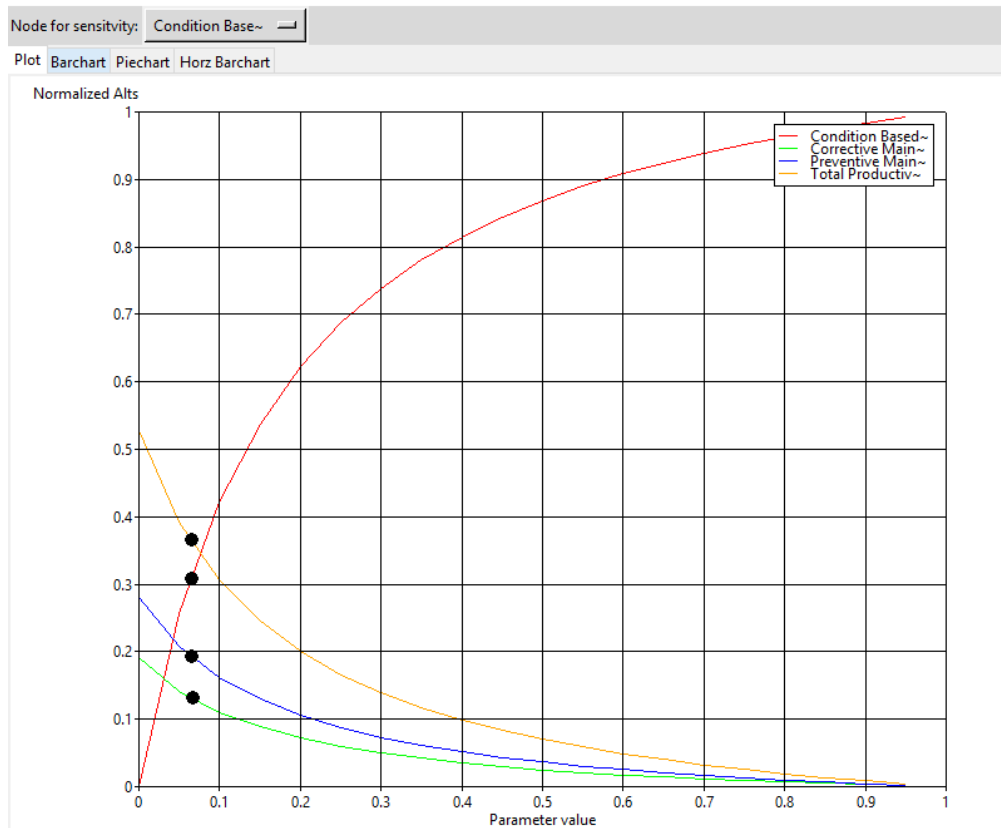


Figure 19: Node sensitivity graph with parameter value, p moved to 0.08

It can be seen that in both graphs (Fig 19&20), the node is important enough it causes Condition Based Maintenance to beat all the rest of the other alternatives i.e. CM, PM, and TPM after the parameter value. In the figure 20, there is a new resting parameter value at $p=0.08$. In this case, the best ranked value is Total Productive Maintenance while Condition Based Maintenance is ranked second best.

This is best elaborated in the table below;

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

<i>Decision Alternatives</i>	<i>Rank with (p= 0.5)</i>	<i>Rank with (p= 0.08)</i>
Preventive Maintenance	3	3
Corrective Maintenance	4	4
Condition Based Maintenance	1	2
Total Productive Maintenance	2	1

Table 15: The ranks for the different alternatives based on two different parameter values

5.3.2 Influence Analysis

Influence analysis is further executed on this model. First of all, the value of $p=0.5$ is selected again and then the path selected is '*Computations-Influence/sensitivity-Influence matrix*' which stores the result in a CSV file. The resulting data can be found in Table 1 in the appendix. The results show that the most influential nodes are the following (after removing the alternatives from that list).

- N11.Improved Company Brand: It brings up Total Productive Maintenance and brings down the rest.
- N16. Financial Feasibility: It brings up Total Productive Maintenance and brings down the rest of the alternatives.
- N5. Personnel Training Cost: It brings up Total Productive Maintenance and Condition Based Maintenance but brings down the rest of the alternatives.
- N9. Reliability of the rollingstock: upper: It brings up Total Productive Maintenance and Condition Based Maintenance and brings down the rest of the alternatives.

5.3.3 Rank Influence

Rank influence demonstrates how much the significance of a given node must vary to cause a change in the rankings of the alternatives (i.e. the change in the parameter p that is needed to change the ranking of some alternatives). The more miniscule the change needed, the more rank influence that node has. To perform this calculation in Super Decisions, the tab '*Computations-Influence/sensitivity-Rank Influence matrix*' is chosen. The resulting data is shown in the appendix section (table 13). The top influencers are in the following order;

1. N11.Improved Company Brand
2. N6. Loss of Ridership

These influencers improved Total Productive Maintenance (TPM).

5.3.4 Marginal Influence

Marginal influence calculates what the infinitesimal rate of change of the alternative scores are with respect to a given node (that is, the derivative of alternative score with respect to the parameter p for a fixed node). This measures which nodes are most sensitive to small changes in priority (i.e. which nodes one must be very careful to have the best data possible about the priority of those nodes as they have the most immediate impact on alternative scores). To obtain this analysis in Super Decisions, select the path, '*Computations-Influence/sensitivity-Marginal Influence*'. The resulting data is in the appendix (Table 14). The most marginally influential nodes are obtained to be the following;

N11. Improved Company Brand

N16. Financial Feasibility

N5. Personnel Training Cost

N15. System safety

5.3.5 Perspective Analysis

Perspective analysis means, “what would the resulting alternative scores be if the given node was the most important” (this is achieved by taking the limit as p takes to 1.0 for the given node and then modifying the alternative scores). The results are shown in the Table 15 in the appendix section. We see that the top three changers are the same as the regular influence analysis, i.e.

- N11. Improved Company Brand
- N16. Financial Feasibility
- N5. Personnel Training Cost
- N1. Mental Attitude of maintenance staff

Therefore, it can be seen from the table shown in the appendix section that in the perspective of ‘***Improved company brand***’, the scores of the alternatives can be seen to be as shown below;

- Preventive Maintenance: 0.221893
- Condition Based Maintenance: 0.19334
- Total Productive Maintenance: 0.460777
- Corrective Maintenance: 0.12399

In the perspective of improved company brand, the alternative, Total Productive Maintenance wins all the rest hands down and Corrective Maintenance is ranked the least preferred alternative.

Chapter Six: Conclusions, Recommendations and Future Work

This chapter basically comprises of an overview of this study and the main findings of the research. It highlights the conclusions of the study, limitations of adopting an ANP-based framework to assess an appropriate maintenance strategy. Finally, this chapter gives some directions and suggestions for future research and recommendations.

6.1 Conclusions of the study

This study proposes an ANP-based framework for assessing an appropriate maintenance strategy for the AALRTS. The ANP Algorithm is applied to this study in trying to determine a suitable maintenance strategy for this case study. The maintenance strategies have been evaluated based on five main categories of criteria: Social factors, Feasibility factors, Safety factors, Value-addition factors and Economic factors.

The data for the influence of the factors on each other and on the maintenance strategies, was derived from questionnaires filled in by the expert group. The experts were selected from the AALRTS Headquarters in Kality, Ayat and at ERC. Some were selected from the Railway engineering departments. Using the framework to assess the maintenance strategies made it possible to represent the interdependences between elements of the evaluation problem to be accounted for. It also provided the possibility of evaluating effective relationships of each criterion on each other both in the same cluster and in different clusters and the influence of the final goal on each of the criteria through the form of a network.

Furthermore, this research argued about the structure of choosing an appropriate maintenance strategy by using the ANP method. The structure contained five steps. First step was started by specifying the

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

variables, and criteria which could affect the maintenance strategies. Second step was Model assembly and problem construction, third step was forming Pairwise Comparison Matrices and Eigen vector Calculation, fourth step was forming super matrices and calculating weights and the final step was selection of the best Alternative decision.

Therefore, a software SUPERDECISION is utilized to carry out this whole analysis by simply feeding in the combined (synthesized) opinion of the expert group and formulating the ANP network model. The output from the software is an appropriate maintenance strategy which is selected as ***Condition Based Maintenance (CBM)*** which is closely followed by the ***Total Production Maintenance (TPM)*** strategy and the least recommended strategy as ***Corrective Maintenance (CM)***. The strategy, ***TPM*** already has ***CBM*** strategy embedded inside of it therefore it is only right to conclude that ***TPM*** is selected as the best strategy among all the alternatives to be applied to this study. The currently applied strategies at AALRT are preventive maintenance and corrective maintenance therefore application of the Total Production Maintenance can help to improve company operations, improve systems safety, and improve company profits.

Although the ANP technique appears complicated, it can capture the complexity of real-world situations for maintenance strategy selections. The results from the ANP method allows for ranking the maintenance strategies as well as identifying which factors are contributing more or less to the maintenance strategies. The major contribution of this study is with regards to the advancement of the application areas of the ANP method. The study developed an ANP-based framework for evaluating maintenance strategies for the Addis Ababa Light Rail Transit Service. The implementation of the spatial ANP technique to maintenance strategy selection gives an originality value to the present

research because it represents the first attempt to apply the ANP algorithm for maintenance strategy selection for AALRTS.

6.2 Recommendations

The results from this study provide a definitive description of an appropriate maintenance strategy for the AALRTS. The appropriate maintenance strategy is recommended to be ***Total Productive Maintenance (TPM)*** even though ***Condition Based Maintenance (CBM)*** is ranked as best alternative and it is recommended for specifically the mechanical parts of the rollingstock. However, ***Total Productive Maintenance (TPM)*** follows closely with almost the same priority weights as ***CBM***. In addition to that, TPM already consist of CBM by definition and application of TPM processes. The maintenance practices that are currently being used are preventive and corrective maintenance. These maintenance practices provide the necessary operational continuity and relative reliability but the reliability, operations and profitability of the organization is not competitive enough. Therefore, this study recommends the use of ***TPM*** strategies in conjunction with each other to further minimize losses such as downtime losses, set-up and adjustments losses, speed losses, reduced speed, defect losses and reduced yield which can eventually improve company profitability, optimize operations and improve the system safety.

It is strongly recommended that the best ranked strategy be considered to be ***TPM*** i.e. ***TPM*** strategy can embed the ***CBM*** strategy. This implies that CBM can be incorporated under TPM. Therefore, it would best be recommended to consider only ***TPM*** since it is already considered to have ***CBM*** as part of it. This is done also to ensure even more efficient operations and improved safety for passengers, workers

and the whole system since the element of fault identification will be expounded on critically due to the introduction of *Condition Based Maintenance (CBM)*.

6.2.1 Limitations of the ANP-based Framework for Maintenance Strategy Evaluation

There are some limitations of the ANP method. The main drawback, especially in the practical application of ANP, is the large number of comparisons that need to be done. The greater number of comparisons is aggravated by the large number of (complex factors) evaluation criteria. This leads to complexity in the weighting procedure, which makes it difficult for the decision maker to understand the decision outcomes if they are not familiar with the method.

Further, in cases where there are several alternatives in the decision model as in this study, the pairwise comparisons become quite demanding. The computational software (super-decision) for the ANP method enabled the performance of the pairwise comparisons and hence made the procedure less chaotic, but it was found that the software can only solve problems involving 30 or less decision alternatives.

There is the potential presence of uncertainties in any multicriteria decision/evaluation problem. These uncertainties arise in two ways: (1) incomplete or incorrect information about the decision problem, and (2) uncertainties might result from the inherent assumptions of the method. In this present application, given to a certain extent the deterministic nature of the decision problem; i.e., the number of alternatives is known and fixed, and the criteria are objective indicators measured on a quantitative scale, the amount of uncertainty in this study is limited to the specification of weights and measurement errors present in the data. Sensitivity analysis, which is a method for dealing with uncertainties was employed to test the robustness of the evaluation. This process was used to test whether changes in cluster weights modify

the rankings of the alternatives. Although there were changes in the rankings for some items, the position of the different alternatives in the rankings did not change much.

6.3 Future work

There are quite a number of ways to improve the ANP algorithm for the maintenance selection process.

- ✓ The ANP method can be incorporated with the rough-set theory to make the results even more accurate since the decisions are based on the opinions of human beings..
- ✓ The maintenance selection process can be carried out using the ANP algorithm incorporated together with the goal programming method to get more intricate results.
- ✓ The algorithm of ANP and AHP can be compared or combined in future studies to see how the maintenance strategies would be impacted.
- ✓ Furthermore, there could be research done on how spare parts variation with the various maintenance strategies.
- ✓ Determining the ratio of most effective strategy of Preventive maintenance to corrective maintenance would be interesting to research.
- ✓ Finally, implementation of the selected maintenance strategy with detailed implementation guide and a properly budgeted plan will be highly recommended.
- ✓ Other MCDMs can be employed as models for selecting the most effective maintenance strategy such as PROMETHEE model, ELECTRE method, TOPSIS method, or Goal Programming method.

Thus, it is concluded that by using “ANP Method” and suitable software (Super-decision), maintenance managers can make a trust worthy decision in the way of selecting an appropriate maintenance strategy.

Bibliography

Aghaee, M. and Fazli, S. (2012) ‘An improved MCDM method for maintenance approach selection: A case study of auto industry’, *Management Science Letters*, 2, pp. 137–146. doi: 10.5267/j.msl.2011.09.012.

Ahuja, S. (2007) ‘Handbook of Maintenance Management and Engineering’, in Daya, M., Duffuaa, S., and Raouf, A. (eds) *Handbook of Maintenance Management and Engineering*, pp. 417–419. doi: 10.1007/978-1-84882-472-0.

AMCP 706-132 (1975) ‘Engineering Design Handbook: Maintenance Engineering Techniques, Department of Defense, Washington D.C.’, (June).

Baby, S. (2013) ‘AHP Modeling for Multicriteria Decision-Making and to Optimise Strategies for Protecting Coastal Landscape Resources’, 4(2). doi: 10.7763/IJIMT.2013.V4.395.

Bevilacqua, M. and Braglia, M. (2000) ‘Analytic hierarchy process applied to maintenance strategy selection’, *Reliability Engineering and System Safety*, 70(1), pp. 71–83. doi: 10.1016/S0951-8320(00)00047-8.

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

Boorse, J. W. (2000) 'A Dallas light rail transit train approaching the zoo station.', (November).

Borjalilu, N. and Ghambari, M. (2018) 'Optimal maintenance strategy selection based on a fuzzy analytical network process: A case study on a 5-MW powerhouse', 10, pp. 1–10. doi: 10.1177/1847979018776172.

Carnero, M. C. and Gómez, A. (2017) 'Maintenance strategy selection in electric power distribution systems', *Energy*, 129, pp. 255–272. doi: 10.1016/j.energy.2017.04.100.

Cheng, E. W. L. and Li, H. (2005) 'Analytic Network Process Applied to Project Selection', (April), pp. 459–466.

Cheng, Y. H. and Tsao, H. L. (2010) 'Rolling stock maintenance strategy selection, spares parts' estimation, and replacements' interval calculation', *International Journal of Production Economics*. Elsevier, 128(1), pp. 404–412. doi: 10.1016/j.ijpe.2010.07.038.

Chung, S. H., Lee, A. H. I. and Pearn, W. L. (2005) 'Analytic network process (ANP) approach for product mix planning in semiconductor fabricator', *International Journal of Production Economics*, 96(1), pp. 15–36. doi: 10.1016/j.ijpe.2004.02.006.

Coulter, K. and Sarkis, J. (2006) 'An Application of the Analytic Network Process to the Advertising Media Budget Allocation Decision', *The International Journal on Media ...*, 1277(April 2014), pp. 37–41. doi: 10.1207/s14241250ijmm0804.

Dachyar, M., Nurcahyo, R. and Tohir, Y. (2018) 'Maintenance strategy selection for steam power plant in range of capacity 300 - 625 MW in Indonesia', *ARPN Journal of Engineering and Applied Sciences*, 13(7), pp. 2571–2580. doi: 10.1016/j.bbmt.2015.10.018.

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

Dağdevİren, M. (2007) ‘Personnel Selection Using Analytic Network’, *Network*, pp. 99–118. doi: 10.1016/S2092-5212(10)80015-X.

Dhillon, B. S. (2002) *ENGINEERING MAINTENANCE*.

Digital McKinsey (2017) ‘The rail sector ’s changing maintenance game’.

Dr.Eng.Nappi, R. (2014) ‘Integrated Maintenance: analysis and perspective of innovation in railway sector’, *arXiv preprint arXiv:1404.7560*, pp. 1–7.

Faherty, V. (2013) ‘Journal of Education for Social Work Continuing Social Work Education : Results of a Delphi Survey Continuing Social Work Education : Results of a Delphi Survey’, (May 2015), pp. 37–41. doi: 10.1080/00220612.1979.10671539.

Fattahi, V. and Askarizadeh, M. (2013) ‘ERP evaluation and selection using Fuzzy MCDM in Iranian manufactures’, *Advances in Environmental Biology*, 7(8), pp. 1745–1752.

Fazlollahtabar, H. and Yousefpoor, N. (2008) ‘Selection of optimum maintenance strategies in a virtual learning environment based on analytic hierarchy process’, *Proc. of Inter. Conf. Virtual Learning, Constant{c{t}}a, Romania*, pp. 143–152.

Feldman, D. (2002) ‘How to Calculate a Geometric Mean’, 9, pp. 1–11. doi: 10.3969/j.issn.1673-7237.2015.03.005.

Forman, E. and Peniwati, K. (1998) ‘Aggregating individual judgments and priorities with the Analytic Hierarchy Process’.

Gupta, G. and Mishra, R. P. (2018) ‘Identification of Critical Components Using ANP for Implementation of Reliability Centered Maintenance’, *Procedia CIRP*. The Author(s), 69(January), pp.

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

905–909. doi: 10.1016/j.procir.2017.11.122.

Hemmati, N. *et al.* (2018) ‘Maintenance policy selection: a fuzzy-ANP approach’, *Journal of Manufacturing Technology Management*, 29(7), pp. 1253–1268. doi: 10.1108/JMTM-06-2017-0109.

Houria, Z., Besbes, M. and Elaoud, B. (2015) ‘Maintenance strategy selection for medical equipments using fuzzy multiple criteria decision making approach’, *Proceedings - CIE 45: 2015 International Conference on Computers and Industrial Engineering*, (October).

Ilieva, G. (2012) ‘A fuzzy approach for bidding strategy selection’, *Cybernetics and Information Technologies*, 12(1), pp. 61–69. doi: 10.2478/cait-2012-0005.

Ivlev, I., Kneppo, P. and Barták, M. (2015) ‘METHOD FOR SELECTING EXPERT GROUPS AND DETERMINING THE IMPORTANCE OF EXPERTS ’ JUDGMENTS FOR THE PURPOSE OF MANAGERIAL DECISION-MAKING TASKS IN HEALTH SYSTEM’. doi: 10.15240/tul/001/2015-2-005.

Jajimoggala, S., Rao, V. V. S. K. and Satyanarayana, B. (2011) ‘Maintenance Strategy Evaluation Using ANP and Goal Programming’, *International Journal of Strategic Decision Sciences*, 2(2), pp. 56–77. doi: 10.4018/jsds.2011040104.

Kanisuru, A. . (2018) ‘Sustainable Maintenance Practices and skills for Competitive Production system’, in *Intech open*. Ondo state, Nigeria, p. 64. doi: 10.5772/32009.

Liang, X. *et al.* (2013) ‘Using the analytic network process (ANP) to determine method of waste energy recovery from engine’, *Energy Conversion and Management*, 66, pp. 304–311. doi: 10.1016/j.enconman.2012.08.005.

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

Mann, L. J., Saxena, A. and Knapp, G. M. (1995) 'Journal of Quality maintenance Engineering', in *Journal of Quality Maintenance Engineering*, pp. 46–59.

Marten Jr, F. A. (2010) *Reliability Centered Maintenance: A Case Study of Railway Transit Maintenance to Achieve Optimal Performance*. Available at: <http://gradworks.umi.com/33/93/3393488.html%5Cnhttp://trid.trb.org/view.aspx?id=1089633>.

Mckone, E. and Weiss, N. (1998) 'Tpm: planned bridging', 7(4).

Meade, L. M. and Presley, A. (2002) 'R & D Project Selection Using the Analytic Network Process', 49(1), pp. 59–66.

Meade, L. M. and Sarkis, J. (1999) 'Analyzing organizational project alternatives for agile manufacturing processes : An analytical network approach', (September 2013), pp. 37–41.

Mobley, K. . (2008) *MAINTENANCE FUNDAMENTALS*.

Mobley, R. K. and Wikoff, D. J. (2008) *MAINTENANCE ENGINEERING HANDBOOK*.

Moghaddam, K. S. and Usher, J. S. (2011) 'Computers & Industrial Engineering Preventive maintenance and replacement scheduling for repairable and maintainable systems using dynamic programming q', *Computers & Industrial Engineering*. Elsevier Ltd, 60(4), pp. 654–665. doi: 10.1016/j.cie.2010.12.021.

Momoh, J. A. and Zhu, J. Z. (1998) 'Application of AHP/ANP to Unit Commitment in the Deregulated Power Industry', *1998 IEEE International Conference on Systems, Man, and Cybernetics*, pp. 817--822.

Moubray, J. (1997) 'Introduction to Reliability-Centred Maintenance.Pdf'.

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

Muluken, A. T. D. (2017) '*Selection of Maintenance Strategy by AHP Algorithm for Light Rail Transit System*'. Available at: www.esme-ethiopia.org.

Nakajima, S. (1988) *INTRODUCTION TO TPM*. Japan Institute for Plant Maintenance.

Nezami, F. G. and Yildirim, M. B. (2013) 'A sustainability approach for selecting maintenance strategy', *International Journal of Sustainable Engineering*, 6(4), pp. 332–343. doi: 10.1080/19397038.2013.765928.

Padial, N. and Marín, M. (2015) 'Strategic Framework to Maintenance Decision Support Systems', *Procedia Engineering*. Elsevier B.V., 132, pp. 903–910. doi: 10.1016/j.proeng.2015.12.576.

Pariazar, M. *et al.* (2008) 'A combined approach for maintenance strategy selection.pdf', *A combined approach for maintenance strategy selection*.

Pun, K. *et al.* (2017) 'A fuzzy-AHP-based decision support system for maintenance strategy selection in facility management', *PICMET 2017 - Portland International Conference on Management of Engineering and Technology: Technology Management for the Interconnected World, Proceedings*, 2017–Janua(July), pp. 1–7. doi: 10.23919/PICMET.2017.8125300.

Rahimi, M., Sadinejad, S. and Damghani, K. . (2014) 'Selecting the most appropriate maintenance strategies using fuzzy Analytic Network Process: A case study of Saipa vehicle industry', *Decision Science Letters*, 3(2), pp. 237–242. doi: 10.5267/j.dsl.2013.10.003.

Rastegari, A. and Mobin, M. (2016) 'Maintenance decision making, supported by computerized maintenance management system', *Proceedings - Annual Reliability and Maintainability Symposium*, 2016–April. doi: 10.1109/RAMS.2016.7448086.

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

Rezvanizani, S. M. *et al.* (2009) 'Reliability analysis of the rolling stock industry: A case study', *International Journal of Performability Engineering*, 5(2), pp. 167–175.

Saaty, L. . (1991) 'Some Mathematical Concepts of the Analytic Hierarchy Process', (29), p. 7 of 1-9.

Saaty, T. L. (2013) 'The Modern Science of Multicriteria Decision Making and Its Practical Applications : The AHP / ANP Approach The Modern Science of Multicriteria Decision Making and Its Practical Applications : The AHP / ANP Approach', (December 2017).

Sadeghi, A. and Manesh, R. A. (2012) 'The Application of Fuzzy Group Analytic Network Process to Selection of Best Maintenance Strategy- A Case Study in Mobarakeh Steel Company, Iran', *Procedia - Social and Behavioral Sciences*, 62(Mcdm), pp. 1378–1383. doi: 10.1016/j.sbspro.2012.09.236.

Sadeghi, M., Rashidzadeh, M. and Soukhakian, M. (2012) 'Using Analytic Network Process in a Group Decision-Making for Supplier Selection', 23(4), pp. 621–643.

Sankpal, P., Andrew, A. and Kumanan, S. (2015) 'Maintenance Strategies selection using Fuzzy FMEA and Integer Programming', *Proceedings of the International Conference on Advances in Production and Industrial Engineering*, (January 2015), p. 503.

Sarkis, J. (2003) 'Quantitative models for performance measurement systems - Alternate considerations', *International Journal of Production Economics*, 86(1), pp. 81–90. doi: 10.1016/S0925-5273(03)00055-0.

Seiti, H. *et al.* (2017a) 'Maintenance strategy selection with risky evaluations using RAHP', *Journal of Multi-Criteria Decision Analysis*, 24(5–6), pp. 257–274. doi: 10.1002/mcda.1618.

Seiti, H. *et al.* (2017b) 'Maintenance strategy selection with risky evaluations using RAHP', (December

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

2016), pp. 257–274. doi: 10.1002/mcda.1618.

Shou, T. D. and Lin, M. (2018) ‘APPLY ANALYTIC NETWORK PROCESS (ANP) TO ANALYZE THE DECISION FACTORS OF RELIEF RESOURCES ALLOCATION: A CASE STUDY IN TAIPEI STREET TREES RECOVERY IN POST-DISASTER’, 4(1), pp. 1–8.

Velmurugan, R. and Subramanian, S. (2012) ‘The analytic network process for the pharmaceutical sector : Multi criteria decision making to select the suitable method for the preparation of nanoparticles’, (August 2014). doi: 10.1186/2008-2231-20-59.

Vishnu, C. R. and Regikumar, V. (2016) ‘Reliability Based Maintenance Strategy Selection in Process Plants: A Case Study’, *Procedia Technology*. The Author(s), 25(Raerest), pp. 1080–1087. doi: 10.1016/j.protcy.2016.08.211.

Voronova, I. and Skvarciany, V. (2018) ‘PRIORITISING COMPETITIVE STRATEGIES BASED ON THE ANP APPROACH: A CASE OF THE LATVIAN TELECOMMUNICATION COMPANY’, (September). doi: 10.3846/bm.2018.10.

Willmott, P. (1994) ‘Total Quality with Teeth’, 6(4), pp. 48–50.

Wireman, T. (2005) *Developing Performance Indicators for Managing Maintenance, Developing Performance Indicators for Managing Maintenance*.

Zaim, S. *et al.* (2012) ‘Maintenance strategy selection using AHP and ANP algorithms: A case study’, *Journal of Quality in Maintenance Engineering*, 18(1), pp. 16–29. doi: 10.1108/13552511211226166.

Appendix A

I. QUESTIONNAIRE FORMATS USED FOR PAIRWISE COMPARISONS

	Graphical	Verbal	Matrix	Questionnaire	Direct																
Comparisons wrt "OPTIMUM MAINTENANCE STRATEGY" node in "ECONOMIC FACTORS" cluster																					
N5. Personnel Training Cost is ?????? more important than																					
N6. Loss of Ridership																					
1. N5. Personnel Tr~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	N6. Loss of Rid~
2. N5. Personnel Tr~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	N7. Severity of ~
3. N5. Personnel Tr~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	N8. Cost of Mai~
4. N6. Loss of Rid~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	N7. Severity of ~
5. N6. Loss of Rid~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	N8. Cost of Mai~
6. N7. Severity of ~	>=9.5	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	>=9.5	No comp.	N8. Cost of Mai~

II. APPENDIX SECTION FOR THE VALIDATION GRAPHS

Net: Toplevel network.	Parameter Value	Distance	CBM	Corrective	Preventive	TPM
Original Values	0.5	0	0.3166	0.130452	0.191406	0.361538
N5. Personnel Training Cost:upper	0.9	0.110482	0.34483	0.131406	0.170259	0.353507
N6. Loss of Ridership:upper	0.9	0.042458	0.32851	0.132241	0.193057	0.346188
N7. Severity of failure of machine:upper	0.9	0.009971	0.31345	0.130361	0.192452	0.36374
N8. Cost of Maintenance Equipment:upper	0.9	0.082731	0.32742	0.119659	0.178072	0.37485
N16. Fianancial Feasibility:upper	0.9	0.204436	0.32499	0.106798	0.152276	0.415934
N17. Human and Managerial willingness to sup	0.9	0.06989	0.32667	0.138701	0.198357	0.33627
N18. Availability of Technology:upper	0.9	0.014369	0.31984	0.131834	0.191979	0.356343
N19. Personnel Capability:upper	0.9	0.013983	0.31813	0.132199	0.193189	0.356483
N20. System compatibilty:upper	0.9	0.000846	0.31634	0.130441	0.191431	0.361791
Optimum Maintenance strategy:upper	0.9	0	0.3166	0.130452	0.191406	0.361538
N13. Passenger Safety:upper	0.9	0.035972	0.31465	0.133962	0.198291	0.353098
N14. Worker safety:upper	0.9	0.017201	0.31545	0.132411	0.194698	0.357446
N15. System safety:upper	0.9	0.073763	0.29325	0.132426	0.191277	0.383047
N1. Mental attitude of maintenance staff:uppe	0.9	0.075806	0.336	0.120563	0.184297	0.359143
N2. Training Requirement for personnel:upper	0.9	0.044721	0.32045	0.124618	0.184584	0.370345
N3. Employment Issues:upper	0.9	0.019459	0.31925	0.127913	0.193219	0.35962
N4. Employment wages:upper	0.9	0.052394	0.32799	0.135731	0.193684	0.342596
N9. Reliability of the rollingstock:upper	0.9	0.097198	0.33362	0.117772	0.18859	0.360022
N10. Fault Identification:upper	0.9	0.039632	0.32186	0.133602	0.197324	0.34721
N11. Improved Company Brand:upper	0.9	0.352931	0.20487	0.124747	0.219079	0.45131
N12. Customer satisfaction:upper	0.9	0.036909	0.31828	0.128471	0.198471	0.354774
N5. Personnel Training Cost:lower	0.1	0.011642	0.31292	0.129408	0.193139	0.364535
N6. Loss of Ridership:lower	0.1	0.007469	0.31424	0.130043	0.191739	0.363978
N7. Severity of failure of machine:lower	0.1	0.000415	0.31674	0.130462	0.191366	0.361436
N8. Cost of Maintenance Equipment:lower	0.1	0.004213	0.31585	0.131001	0.192078	0.361073
N16. Fianancial Feasibility:lower	0.1	0.018298	0.31575	0.132358	0.194908	0.356988
N17. Human and Managerial willingness to sup	0.1	0.018061	0.31328	0.128474	0.190183	0.368068
N18. Availability of Technology:lower	0.1	0.000586	0.31647	0.130395	0.191383	0.36175
N19. Personnel Capability:lower	0.1	0.00093	0.31653	0.13033	0.191325	0.361814
N20. System compatibilty:lower	0.1	0.000029	0.31661	0.130452	0.191405	0.36153
Optimum Maintenance strategy:lower	0.1	0	0.3166	0.130452	0.191406	0.361538
N13. Passenger Safety:lower	0.1	0.006854	0.31692	0.129713	0.190094	0.363271
N14. Worker safety:lower	0.1	0.003019	0.31641	0.130058	0.191197	0.362338
N15. System safety:lower	0.1	0.016842	0.32194	0.129974	0.191334	0.356756
N1. Mental attitude of maintenance staff:lowe	0.1	0.00821	0.31401	0.130881	0.191565	0.363549
N2. Training Requirement for personnel:lower	0.1	0.002277	0.31619	0.130749	0.191825	0.361239
N3. Employment Issues:lower	0.1	0.002059	0.31619	0.13072	0.191199	0.361886
N4. Employment wages:lower	0.1	0.008903	0.31702	0.12929	0.190292	0.363399
N9. Reliability of the rollingstock:lower	0.1	0.013791	0.3142	0.132251	0.191716	0.361836
N10. Fault Identification:lower	0.1	0.003798	0.31614	0.13017	0.190779	0.362911
N11. Improved Company Brand:lower	0.1	0.035762	0.32793	0.130875	0.188696	0.352503
N12. Customer satisfaction:lower	0.1	0.004191	0.31694	0.130407	0.190604	0.362048

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

Table 16: The Influence analysis

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

Net: Toplevel network.	Parameter Value	Score	Raw Score	CBM	CM	PM	TPM
Original Values	0.5	0	0	0.316604	0.130452	0.191406	0.361538
N5. Personnel Training Cost:upper	0.99	0	0	0.35047	0.130802	0.164697	0.35403
N6. Loss of Ridership:upper	0.982344	0.015625	0.015625	0.337866	0.1324	0.191928	0.337807
N7. Severity of failure of machine:upper	0.99	0	0	0.312819	0.130371	0.192693	0.364116
N8. Cost of Maintenance Equipment:upper	0.99	0	0	0.329304	0.116699	0.174379	0.379617
N16. Fianancial Feasibility:upper	0.99	0	0	0.326345	0.102669	0.146081	0.424904
N17. Human and Managerial willingness to support the startegy:upper	0.99	0	0	0.329646	0.140257	0.199469	0.330628
N18. Availability of Technology:upper	0.99	0	0	0.320574	0.132145	0.192107	0.355174
N19. Personnel Capability:upper	0.99	0	0	0.318514	0.132528	0.193573	0.355386
N20. System compatibilty:upper	0.99	0	0	0.316276	0.130439	0.191437	0.361848
Optimum Maintenance strategy:upper	0.99	0	0	0.316604	0.130452	0.191406	0.361538
N13. Passenger Safety:upper	0.99	0	0	0.314176	0.134733	0.199859	0.351232
N14. Worker safety:upper	0.99	0	0	0.314911	0.132843	0.195662	0.356584
N15. System safety:upper	0.99	0	0	0.28756	0.132813	0.191189	0.388439
N1. Mental attitude of maintenance staff:upper	0.99	0	0	0.346958	0.110705	0.174778	0.367558
N2. Training Requirement for personnel:upper	0.99	0	0	0.319393	0.124457	0.18585	0.370299
N3. Employment Issues:upper	0.99	0	0	0.319717	0.127544	0.193539	0.3592
N4. Employment wages:upper	0.99	0	0	0.330058	0.136862	0.194459	0.338622
N9. Reliability of the rollingstock:upper	0.99	0	0	0.336973	0.115102	0.187857	0.360068
N10. Fault Identification:upper	0.99	0	0	0.323249	0.134293	0.198822	0.343636
N11. Improved Company Brand:upper	0.835296	0.315723	0.315723	0.216269	0.125421	0.216313	0.441997
N12. Customer satisfaction:upper	0.99	0	0	0.319661	0.127858	0.199197	0.353284
N5. Personnel Training Cost:lower	0	0	0	0.311987	0.129104	0.193533	0.365376
N6. Loss of Ridership:lower	0	0	0	0.313703	0.129949	0.191808	0.364539
N7. Severity of failure of machine:lower	0	0	0	0.316769	0.130465	0.191356	0.36141
N8. Cost of Maintenance Equipment:lower	0	0	0	0.315657	0.131138	0.192244	0.360961
N16. Fianancial Feasibility:lower	0	0	0	0.31553	0.132841	0.195803	0.355825
N17. Human and Managerial willingness to support the startegy:lower	0	0	0	0.312411	0.127966	0.189902	0.369721
N18. Availability of Technology:lower	0	0	0	0.316439	0.130381	0.191377	0.361803
N19. Personnel Capability:lower	0	0	0	0.316513	0.1303	0.191305	0.361883
N20. System compatibilty:lower	0	0	0	0.316615	0.130452	0.191405	0.361528
Optimum Maintenance strategy:lower	0	0	0	0.316604	0.130452	0.191406	0.361538
N13. Passenger Safety:lower	0	0	0	0.317002	0.129527	0.189763	0.363709
N14. Worker safety:lower	0	0	0	0.316347	0.129956	0.191152	0.362545
N15. System safety:lower	0	0	0	0.323247	0.129851	0.191313	0.35559
N1. Mental attitude of maintenance staff:lower	0	0	0	0.313414	0.130982	0.191575	0.364029
N2. Training Requirement for personnel:lower	0	0	0	0.316073	0.130841	0.191962	0.361123
N3. Employment Issues:lower	0	0	0	0.31609	0.130789	0.191147	0.361973
N4. Employment wages:lower	0	0	0	0.317119	0.129004	0.190025	0.363851
N9. Reliability of the rollingstock:lower	0	0	0	0.313578	0.132711	0.191789	0.361923
N10. Fault Identification:lower	0	0	0	0.31603	0.1301	0.190628	0.363242
N11. Improved Company Brand:lower	0	0	0	0.330722	0.130978	0.188022	0.350278
N12. Customer satisfaction:lower	0	0	0	0.317038	0.130392	0.190396	0.362174

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

Table 17: The Rank Influence analysis

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

Net: Toplevel network.	D(Normal) CBM	D(Normal) CM	D(Normal)PM	D(Normal) TPM	Total	Calc Err
Original	0.316604	0.130452	0.191406	0.361538	0	0
N5. Personnel Training Cost:upper	0.076821	0.010327	-0.046112	-0.041036	0.099088	0.00016
N6. Loss of Ridership:upper	0.009587	0.004837	0.009186	-0.02361	0.027516	0.000084
N7. Severity of failure of machine:upper	-0.008571	-0.000491	0.002568	0.006494	0.011066	0.000007
N8. Cost of Maintenance Equipment:upper	0.030068	-0.022883	-0.028057	0.020872	0.051484	0.000074
N16. Fianancial Feasibility:upper	0.02664	-0.066504	-0.118487	0.158351	0.210348	0.000173
N17. Human and Managerial willingness to support the startegy:upper	0.021405	0.023563	0.020463	-0.065431	0.075587	0.000035
N18. Availability of Technology:upper	0.008098	0.003456	0.001432	-0.012985	0.015754	0
N19. Personnel Capability:upper	0.003412	0.004768	0.004576	-0.012756	0.014766	0.000003
N20. System compatibilty:upper	-0.00067	-0.000026	0.000063	0.000632	0.000924	0
N13. Passenger Safety:upper	-0.004749	0.008967	0.017218	-0.021436	0.029307	0.000003
N14. Worker safety:upper	-0.000081	0.0052	0.006102	-0.01122	0.01379	0.000027
N15. System safety:upper	-0.057245	0.005498	-0.000085	0.051832	0.077419	0.000006
N1. Mental attitude of maintenance staff:upper	0.031739	-0.010343	0.000531	-0.021926	0.039942	0.000089
N2. Training Requirement for personnel:upper	0.018225	-0.019241	-0.02905	0.030066	0.0495	0.000057
N3. Employment Issues:upper	0.007766	-0.008328	0.005457	-0.004894	0.013542	0.000016
N4. Employment wages:upper	0.03345	0.013203	0.002095	-0.048748	0.060613	0.000051
N9. Reliability of the rollingstock:upper	0.04798	-0.034326	-0.006173	-0.007482	0.059786	0.000054
N10. Fault Identification:upper	0.011221	0.008	0.013251	-0.032472	0.037682	0.000027
N11. Improved Company Brand:upper	-0.365538	-0.016752	0.093898	0.288391	0.475273	0.000174
N12. Customer satisfaction:upper	-0.006182	-0.003379	0.026712	-0.017151	0.032516	0.000099
N5. Personnel Training Cost:lower	0.009147	0.002296	-0.004626	-0.006817	0.012523	0.000005
N6. Loss of Ridership:lower	0.006378	0.001096	-0.000957	-0.006517	0.009234	0.000004
N7. Severity of failure of machine:lower	-0.000328	-0.000025	0.000099	0.000254	0.000427	0
N8. Cost of Maintenance Equipment:lower	0.001881	-0.001382	-0.001689	0.00119	0.003117	0
N16. Fianancial Feasibility:lower	0.002154	-0.004729	-0.008633	0.011209	0.015072	0.000001
N17. Human and Managerial willingness to support the startegy:lower	0.00819	0.004849	0.003199	-0.016237	0.019091	0.000001
N18. Availability of Technology:lower	0.00033	0.000141	0.000058	-0.000529	0.000642	0
N19. Personnel Capability:lower	0.000185	0.000301	0.000203	-0.000688	0.0008	0
N20. System compatibilty:lower	-0.000023	-0.000001	0.000002	0.000021	0.000031	0
N13. Passenger Safety:lower	-0.000782	0.00183	0.003251	-0.004299	0.005745	0
N14. Worker safety:lower	0.000406	0.000959	0.000581	-0.001946	0.002283	0.000001
N15. System safety:lower	-0.013546	0.001164	0.000154	0.012228	0.018286	0.000002
N1. Mental attitude of maintenance staff:lower	0.006999	-0.001129	-0.000647	-0.005223	0.00883	0.000004
N2. Training Requirement for personnel:lower	0.000952	-0.000587	-0.000765	0.000401	0.001413	0.000003
N3. Employment Issues:lower	0.001015	-0.000657	0.000513	-0.000871	0.001575	0
N4. Employment wages:lower	-0.001043	0.002929	0.002863	-0.004749	0.006357	0.000001
N9. Reliability of the rollingstock:lower	0.005884	-0.004423	-0.000813	-0.000647	0.007434	0.000001
N10. Fault Identification:lower	0.001222	0.00071	0.001605	-0.003538	0.004135	0.000001
N11. Improved Company Brand:lower	-0.028519	-0.001078	0.006791	0.022806	0.037158	0.000001
N12. Customer satisfaction:lower	-0.000739	0.000084	0.001949	-0.001293	0.002455	0.000001

Rollingstock Maintenance strategy selection by Application of the Analytic Network Process Algorithm

Table 18: The Marginal Influence analysis

Net: Toplevel network.	Parameter Value	Distance	NormalCBM	Normal CM	Normal PM	Normal TPM
Original Values	0.5	0	0.316604	0.130452	0.191406	0.361538
N5. Personnel Training Cost	0.99375	0.044097	0.350699	0.13077	0.164458	0.354072
N6. Loss of Ridership	0.996875	0.035471	0.340607	0.13239	0.191509	0.335494
N7. Severity of failure of machine	0.95	0.004423	0.313094	0.130365	0.192586	0.363955
N8. Cost of Maintenance Equipment	0.99375	0.031399	0.329376	0.116571	0.174219	0.379834
N16. Fianancial Feasibility	0.99375	0.083731	0.326398	0.10251	0.145847	0.425245
N17. Human and Managerial willingness to support the starategy	0.9875	0.035685	0.329558	0.140215	0.199441	0.330786
N18. Availability of Technology	0.95	0.007091	0.32025	0.132006	0.19205	0.355694
N19. Personnel Capability	0.95	0.006547	0.318341	0.132385	0.193403	0.355871
N20. System compatibilty	0.95	0.000416	0.316303	0.13044	0.191434	0.361823
Optimum Maintenance strategy	0.95	0	0.316604	0.130452	0.191406	0.361538
N13. Passenger Safety	0.975	0.013776	0.314256	0.134605	0.199597	0.351542
N14. Worker safety	0.95	0.006512	0.31516	0.132651	0.195224	0.356966
N15. System safety	0.99375	0.039996	0.287316	0.132828	0.191184	0.388671
N1. Mental attitude of maintenance staff	0.998437	0.043216	0.348544	0.109076	0.173187	0.369192
N2. Training Requirement for personnel	0.95	0.012982	0.320025	0.12443	0.185052	0.370493
N3. Employment Issues	0.95	0.004965	0.319514	0.1277	0.1934	0.359386
N4. Employment wages	0.9875	0.027379	0.330003	0.136831	0.194436	0.33873
N9. Reliability of the rollingstock	0.9875	0.025674	0.336881	0.115176	0.187878	0.360065
N10. Fault Identification	0.9875	0.020724	0.323209	0.134274	0.198779	0.343737
N11. Improved Company Brand	0.99375	0.161287	0.19334	0.12399	0.221893	0.460777
N12. Customer satisfaction	0.975	0.011718	0.31941	0.127964	0.199095	0.353531

Table 19: A table showing the perspective analysis in the perspective of improved company brand

III. THE TABLES BELOW INDICATE THE SUPER-MATRICES OBTAINED FROM SUPER-DECISIONS SOFTWARE

Conditio-	Correct~	Prevent~	Total P~	N5.Pers~	N6. Los~	N7.Seve~	N8. Cos~	N16. Fi~	N17. Hu~	N18. Av~	N19. Pe~	N20. Sy~	OPTIMUM~	N13. Pa~	N14. Wo~	N15. Sy~	N1. Men~	N2. Tra~	N3. Emp~	N4. Emp~	N9. Rel~	N10. Fa~	N11. Im~	N12. Cu~
Conditio-	0.00000	0.00000	0.00000	0.00000	0.38349	0.00000	0.00000	0.00000	0.17478	0.35644	0.35644	0.33000	0.00000	0.00000	0.35644	0.33000	0.33000	0.00000	0.00000	0.33000	0.33000	0.33000	0.33000	0.33000
Correct~	0.00000	0.00000	0.00000	0.00000	0.21854	0.00000	0.00000	0.00000	0.20680	0.12426	0.12426	0.14042	0.00000	0.00000	0.12426	0.14042	0.14042	0.00000	0.00000	0.14042	0.14042	0.14042	0.14042	0.14042
Prevent~	0.00000	0.00000	0.00000	0.00000	0.12478	0.00000	0.00000	0.00000	0.28833	0.19358	0.19358	0.19958	0.00000	0.00000	0.19358	0.19958	0.19958	0.00000	0.00000	0.19958	0.19958	0.19958	0.19958	0.19958
Total P~	0.00000	0.00000	0.00000	0.00000	0.27319	0.00000	0.00000	0.00000	0.33009	0.32573	0.32573	0.33000	0.00000	0.00000	0.32573	0.33000	0.33000	0.00000	0.00000	0.33000	0.33000	0.33000	0.33000	0.33000
N5.Pers~	0.43115	0.13820	0.31081	0.40000	0.00000	0.00000	0.00000	0.00000	1.00000	0.66667	0.66667	0.00000	0.00000	0.33333	0.66667	0.66667	0.49339	0.00000	1.00000	0.00000	0.39052	0.66667	0.66667	0.00000
N6. Los~	0.13820	0.17877	0.00000	0.20000	0.00000	0.00000	1.00000	0.00000	0.00000	0.33333	0.00000	0.00000	0.00000	0.16667	0.33333	0.00000	0.19580	1.00000	0.00000	0.00000	0.13807	0.33333	0.00000	1.00000
N7.Seve~	0.22405	0.36322	0.19580	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.33333	0.00000	1.00000	0.16667	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.19526	0.00000	0.33333	0.00000
N8. Cos~	0.20660	0.31981	0.49339	0.20000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.33333	0.00000	0.33333	0.31081	0.00000	0.00000	0.00000	0.00000	0.27614	0.00000	0.00000	0.00000
N16. Fi~	0.31081	0.25000	0.25000	0.25000	0.33333	0.00000	0.00000	1.00000	0.00000	0.00000	0.31081	0.00000	0.00000	0.31081	0.00000	0.00000	0.19580	1.00000	0.00000	0.19580	0.33333	0.00000	0.00000	0.00000
N17. Hu~	0.49339	0.50000	0.50000	0.50000	0.66667	1.00000	1.00000	0.00000	1.00000	0.00000	0.49339	0.00000	0.00000	0.49339	1.00000	1.00000	1.00000	0.49339	0.00000	0.66667	0.49339	0.66667	0.00000	1.00000
N18. Av~	0.19580	0.25000	0.25000	0.25000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.19580	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
N19. Pe~	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.31081	0.00000	0.33333	0.31081	0.00000
N20. Sy~	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.19580	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
OPTIMUM~	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
N13. Pa~	0.00000	0.00000	0.00000	0.00000	0.50000	0.25000	0.00000	0.00000	1.00000	0.00000	0.41260	0.00000	0.00000	0.40000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
N14. Wo~	0.00000	0.00000	0.00000	0.00000	0.50000	0.25000	0.00000	0.00000	0.00000	0.25992	1.00000	0.00000	0.40000	0.00000	0.00000	0.00000	1.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
N15. Sy~	1.00000	1.00000	1.00000	1.00000	0.00000	0.50000	1.00000	0.00000	0.00000	1.00000	0.32748	0.00000	1.00000	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	1.00000	0.00000	1.00000	0.00000
N1. Men~	0.80000	0.66667	0.66667	0.66667	0.00000	0.49339	0.00000	0.00000	0.00000	0.31081	0.00000	1.00000	0.00000	0.49339	0.49339	0.39521	0.49339	0.00000	0.00000	0.49339	0.49339	0.00000	0.00000	0.75000
N2. Tra~	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.75000	0.00000	1.00000	0.49339	0.66667	0.00000	0.00000	0.31081	0.31081	0.27807	0.31081	0.00000	0.00000	0.31081	0.31081	0.00000	0.00000	0.00000
N3. Emp~	0.00000	0.00000	0.00000	0.00000	0.00000	0.19580	0.25000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.16336	0.00000	1.00000	0.00000	0.00000	0.19580	0.00000	0.00000	0.00000	0.00000
N4. Emp~	0.20000	0.33333	0.33333	0.33333	1.00000	0.31081	0.00000	1.00000	0.00000	0.19580	0.33333	0.00000	0.00000	0.19580	0.19580	0.16336	0.19580	0.00000	1.00000	0.19580	0.00000	1.00000	0.00000	0.25000
N9. Rel~	0.18892	0.40000	0.40000	0.33333	0.00000	0.00000	0.00000	0.00000	0.66667	0.00000	0.66667	0.27807	0.66667	0.00000	0.42486	0.00000	0.00000	0.00000	0.66667	0.66667	0.00000	0.27807	0.00000	0.66667
N10. Fa~	0.43063	0.20000	0.20000	0.33333	0.66667	0.00000	0.00000	0.00000	0.00000	0.00000	0.39521	0.00000	0.00000	0.27007	0.50000	0.66667	0.66667	0.00000	0.00000	0.00000	0.39521	0.00000	0.00000	0.00000
N11. Im~	0.24587	0.20000	0.20000	0.16667	0.00000	0.66667	0.00000	0.00000	0.00000	0.33333	0.16336	0.33333	0.00000	0.14378	0.25000	0.33333	0.33333	0.33333	0.33333	1.00000	0.16336	0.50000	0.33333	0.00000
N12. Cu~	0.13458	0.20000	0.20000	0.16667	0.33333	0.33333	0.00000	0.33333	0.00000	0.00000	0.16336	0.00000	0.00000	0.16129	0.25000	0.00000	0.00000	0.00000	0.00000	0.00000	0.16336	0.50000	0.00000	0.00000

Table 20: The unweighted super-matrix of the ANP model

Condi-	Correct-	Prevent-	Total P-	N5.Pers-	N6. Los-	N7.Seve-	N8. Cos-	N16. Fi-	N17. Hu-	N18. Av-	N19. Pe-	N20. Sy-	OPTIMUM-	N13. Pa-	N14. Wo-	N15. Sy-	N1. Men-	N2. Tra-	N3. Emp-	N4. Emp-	N9. Rel-	N10. Fa-	N11. Im-	N12. Cu-
Condi-	0.0000	0.0000	0.0000	0.0000	0.07670	0.00000	0.00000	0.00000	0.03496	0.07129	0.05941	0.06600	0.00000	0.07129	0.06600	0.06600	0.00000	0.00000	0.08250	0.05500	0.06600	0.08250	0.08250	0.06600
Correct-	0.00000	0.00000	0.00000	0.00000	0.04371	0.00000	0.00000	0.00000	0.04136	0.02485	0.02071	0.02808	0.00000	0.00000	0.02485	0.02808	0.02808	0.00000	0.00000	0.03511	0.02340	0.02808	0.03511	0.02808
Prevent-	0.00000	0.00000	0.00000	0.00000	0.02496	0.00000	0.00000	0.00000	0.05767	0.03871	0.03226	0.03992	0.00000	0.00000	0.03871	0.03992	0.03992	0.00000	0.00000	0.04990	0.03326	0.03992	0.04990	0.03992
Total P-	0.00000	0.00000	0.00000	0.00000	0.05464	0.00000	0.00000	0.00000	0.06602	0.06514	0.05429	0.06600	0.00000	0.00000	0.06514	0.06600	0.06600	0.00000	0.00000	0.08250	0.05500	0.06600	0.08250	0.06600
N5.Pers-	0.08623	0.02764	0.06216	0.08000	0.00000	0.00000	0.00000	0.00000	0.20000	0.13333	0.11111	0.00000	0.00000	0.06667	0.13333	0.13333	0.09868	0.00000	0.25000	0.00000	0.06509	0.13333	0.16667	0.00000
N6. Los-	0.02764	0.03575	0.00000	0.04000	0.00000	0.00000	0.25000	0.00000	0.00000	0.06667	0.00000	0.00000	0.00000	0.03333	0.06667	0.00000	0.03916	0.20000	0.00000	0.00000	0.02301	0.06667	0.00000	0.25000
N7.Seve-	0.04481	0.07265	0.03916	0.04000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.05556	0.00000	0.50000	0.03333	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.03254	0.00000	0.08333	0.00000
N8. Cos-	0.04132	0.06396	0.09868	0.04000	0.00000	0.00000	0.00000	0.25000	0.00000	0.00000	0.00000	0.00000	0.00000	0.06667	0.00000	0.06667	0.06216	0.00000	0.00000	0.00000	0.04602	0.00000	0.00000	0.00000
N16. Fi-	0.06216	0.05000	0.05000	0.05000	0.06667	0.00000	0.00000	0.25000	0.00000	0.00000	0.05180	0.00000	0.00000	0.06216	0.00000	0.00000	0.00000	0.03916	0.25000	0.00000	0.03263	0.06667	0.00000	0.00000
N17. Hu-	0.09868	0.10000	0.10000	0.10000	0.13333	0.25000	0.25000	0.00000	0.20000	0.00000	0.08223	0.00000	0.00000	0.09868	0.20000	0.20000	0.20000	0.09868	0.00000	0.16667	0.08223	0.13333	0.00000	0.25000
N18. Av-	0.03916	0.05000	0.05000	0.05000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.03916	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
N19. Pe-	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000	0.06216	0.00000	0.08333	0.05180	0.00000	0.00000
N20. Sy-	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
OPTIMUM-	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
N13. Pa-	0.00000	0.00000	0.00000	0.00000	0.10000	0.06250	0.00000	0.00000	0.20000	0.00000	0.06877	0.00000	0.00000	0.08000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
N14. Wo-	0.00000	0.00000	0.00000	0.00000	0.10000	0.06250	0.00000	0.00000	0.00000	0.00000	0.04332	0.20000	0.00000	0.08000	0.00000	0.00000	0.00000	0.00000	0.20000	0.00000	0.00000	0.00000	0.00000	0.00000
N15. Sy-	0.20000	0.20000	0.20000	0.20000	0.00000	0.12500	0.25000	0.00000	0.00000	0.20000	0.05458	0.00000	0.50000	0.04000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.16667	0.00000	0.25000
N1. Men-	0.16000	0.13333	0.13333	0.13333	0.00000	0.12335	0.00000	0.00000	0.00000	0.06216	0.00000	0.20000	0.00000	0.09868	0.09868	0.07904	0.09868	0.00000	0.00000	0.12335	0.08223	0.00000	0.00000	0.18750
N2. Tra-	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.18750	0.00000	0.20000	0.09868	0.11111	0.00000	0.00000	0.06216	0.06216	0.05561	0.06216	0.00000	0.00000	0.07770	0.05180	0.00000	0.00000	0.00000
N3. Emp-	0.00000	0.00000	0.00000	0.00000	0.00000	0.04895	0.06250	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000	0.03267	0.00000	0.20000	0.00000	0.00000	0.03263	0.00000	0.00000	0.00000	0.00000
N4. Emp-	0.04000	0.06667	0.06667	0.06667	0.20000	0.07770	0.00000	0.25000	0.00000	0.03916	0.05556	0.00000	0.00000	0.03916	0.03916	0.03267	0.03916	0.00000	0.25000	0.04895	0.00000	0.20000	0.00000	0.06250
N9. Rel-	0.03778	0.08000	0.08000	0.06667	0.00000	0.00000	0.00000	0.16667	0.00000	0.13333	0.04634	0.13333	0.00000	0.08497	0.00000	0.00000	0.00000	0.13333	0.16667	0.00000	0.04634	0.00000	0.16667	0.00000
N10. Fa-	0.08613	0.04000	0.04000	0.06667	0.13333	0.00000	0.00000	0.00000	0.00000	0.00000	0.06587	0.00000	0.00000	0.05401	0.10000	0.13333	0.13333	0.00000	0.00000	0.00000	0.06587	0.00000	0.00000	0.00000
N11. Im-	0.04917	0.04000	0.04000	0.03333	0.00000	0.16667	0.00000	0.00000	0.00000	0.06667	0.02723	0.06667	0.00000	0.02876	0.05000	0.06667	0.06667	0.06667	0.08333	0.25000	0.02723	0.10000	0.08333	0.00000
N12. Cu-	0.02692	0.04000	0.04000	0.03333	0.06667	0.08333	0.00000	0.08333	0.00000	0.00000	0.02723	0.00000	0.00000	0.03226	0.05000	0.00000	0.00000	0.00000	0.00000	0.00000	0.02723	0.10000	0.00000	0.00000

Table 21: The weighted super-matrix of the ANP model

