African Railway Center of Excellence

MSc in Railway Engineering (Rolling Stock)

A DECISION SUPPORT SYSTEM FOR MAINTENANCE STRATEGY SELECTION

Case Study: Addis Ababa Light Rail Transit Services

Author: Musoba Aaron

ID No: GSR/7942/10

Advisor: Dr. Eshetie Berhan

APPROVAL

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Submitted by

Musoba Aaron …………………… ………………….

Student Sign Date

Approved by

Dr. Eshetie Berhan …………………… …………………..

Advisor Sign Date

…………………………… ………………………. …………………..

Internal Examiner Sign Date

…………………………… ………………………. ….………………..

External Examiner Sign Date

…………………………. …..…………………….. …………………..

Chairman Sign Date

EXECUTIVE SUMMARY

Railway systems are increasingly being used in various parts of the world to increase on the mobility of both passengers and goods in bulk and at lower costs. The high costs for the management of the modern and complex control systems make it necessary to enhance the current maintenance processes in these systems using the available smart *computer-based* maintenance systems. Applying these DSS in the long run, are basically aimed at decreasing the maintenance cost and increase maintenance quality, which are the basic objectives of modern rail transportation (MRT) corporations. The use of inappropriate maintenance strategy may as well increase the maintenance cost which will increase the operation costs. Selection of a maintenance strategy to a particular machine or group of machines is a problem of decision making and it is always a challenging task for maintenance Manager/Engineer. Therefore, the objective of this research is to develop a structured Decision Support system (DSS) based on the fuzzy logic, to aid maintenance management to decide on the appropriate maintenance policy of the various rolling stock systems for the Railway Company. The developed DSS is based on two criteria, frequency and downtime, whose rules are determined from the Decision-Making Grid (DMG). By using the decision-making tools like DMG, maintenance decisions based on the system's maintenance history will be easily analyzed for each system. Present research work shows that the problem of selecting an optimum maintenance strategy to a machine can be overcome by using decision making tool.

Keywords—Maintenance Management, Maintenance Strategies, Decision Support System, Decision Making Grid

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ABBREVIATIONS:

1.	DMG	Decision Making Grid
2.	CBM	Condition Based Maintenance
3.	SLU	Skill Level Upgrade
4.	CM	Corrective Maintenance
5.	CMMS	Computerized Maintenance Management System
6.	CM	Corrective Maintenance
7.	DOM	Design-out of Maintenance
8.	LCC	Life-cycle costing
9.	RTF	Run To Failure.
10.	FTM	Fixed Time Maintenance
11.	PdM	Predictive Maintenance
12.	PM	Preventive Maintenance
13.	RCM	Reliability-Centered Maintenance
14.	TBM	Time-based maintenance
15.	TPM	Total Productive Maintenance
16.	TOCs	Train Operating Companies
17.	DSS	Decision Support System
18.	FL	Fuzzy Logic
19.	ERC	Ethiopian Railway Corporation
20.	AALRT	Addis Ababa Light Rail Transit
21.	MTTR	Mean Time To Repair
22.	MTBF	Mena Time Between Failures

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CHAPTER ONE

1. INTRODUCTION

1.1.BACKGROUND

Many complex systems, in different engineering application fields (e.g. aerospace, aeronautic, naval, railway), work in specific environmental conditions for which it is required to be compliant with specific requirements of usability, reliability, safety, and maintainability. In particular, regarding these requirements, the target of the maintainability is to maximize the lifetime of the systems produced with the minimum global cost (*Life Cost Cycle*). Based on this consideration, the maintenance of a system becomes a strategic element for the economic competitiveness of the infrastructure operators. According to Dekker and Scarf (1998), maintenance management could have benefited from the advent of a large area in operations research, called maintenance optimization.

Railway systems in specific, consist of both mechanical and electrical components combined into several systems containing a large number of moving parts. To achieve an acceptable railway service level, each system needs to kept operational and regular maintenance is the essential factor to achieving this. A railway system can be sub-divided into two sub-systems namely: rolling stock and Infrastructure. Rolling stock refers to all the vehicles that move on a railway. These vehicles can either be powered or unpowered vehicles or a combination of both.

Examples of rolling stock include locomotives, railroad cars, coaches and wagons. Rolling stock is the most maintenance intensive part of the railway system and therefore, the most vulnerable if maintenance is neglected. According to Wyman (2009) “maintenance accounts for approx. 30% of the lifecycle costs of a high-speed train, making it the largest rolling stock operating cost factor besides energy”. When a train breaks down during operation, it immediately blocks the railway track. This delay causes a disruption to the timetable schedule for that track until the train either becomes operational or removed from the track. The importance of the maintenance functions and management have greatly grown in all sectors of manufacturing and service organizations.

Therefore, the need arises to clearly define the goals of the maintenance department, in order to evolve and continuously enhance the management methods, to efficiently integrate the maintenance activities with the ones related to service provisioning, and operation, and to use smart *computer-based* artificial intelligence systems to aid in maintenance strategy selection.

Addis Ababa Light Rail Transit (AALRT), having a maintenance department, taking care of 41 rolling stock equipment, has not yet implemented this kind of system, which makes appropriate decision making a challenge while handling huge amounts of maintenance data. More so, coming up with an acceptable cost-effective maintenance strategy is also a challenge. Therefore, the purpose of this research is to improve on the efficiency and effectiveness of maintenance of rolling stock to reduce costs associated with maintenance, increase on availability of the rolling stock, and to enhance scheduling and planning using a Decision Support System based on Fuzzy Logic and rules adopted from the Decision-Making Grid

1.2.PROBLEM STATEMENT

In light rail transit system (LRT) there is an ongoing demand for performance increase, which is driven by the need to keep a competitive edge against other means of transportation such road transport. This calls for high technical and economical requirements such as higher train velocities, larger passenger transport capacity, lower energy consumption, greater traveler comfort, low emission better safety levels and lower life cycle costs, Asekun (2014).

Addis Ababa light rail transit services is working aggressively on fixed infrastructure building but there is no comparable progress seen on implementing better fleet and maintenance management system. Implementing a complete and sustainable maintenance strategy will have immense influence on railway system operation. It will also decrease the systems life cycle cost and improve on the quality of rail transport operation.

Through an earlier problem identification process, it was found that the AALRT as a company has not yet developed its own maintenance strategy. AALRT is on the way to adapt a well-recognized international operator’s experience by outsourcing the maintenance system to a foreign consultancy firm. The main problem observed on adopting other operators experience prior to setting the company’s own maintenance strategic goal, is that, there’s a mix up of maintenance strategies which is difficult to understand for both managers and technical staff.

With 41 rolling stocks at AALRT, and each having various systems that need to be maintained, culminates into huge maintenance data captured and stored, making it difficult to process and analyze the data for decision making. This is the basic reason as to why the manufacturer's manuals are used to select the maintenance strategies, since it is less hectic and the costs are minimal.

Whereas it is important to follow the maintenance manuals, it is important to also note that, according to Labib, 2003, machine designers often lack experience on machine failures, and means of prevention, as those who operate and maintain them, and the vendors may have a hidden agenda of maximizing spare parts replacements through frequent PM activities.

Therefore, companies need to analyze the maintenance data to evaluate which maintenance strategy suits and is in line with the company goals and objectives, which consumes a lot of time.

More so, the proposed DSS should be able to carry out data analysis to help the maintenance engineers, carryout maintenance decisions, related to maintenance policy selection, easily and fast.

Having successfully completed a course in Railway Maintenance practices, and fully comprehended the challenges facing AALRT maintenance department, it is therefore an opportunity to put these skills and knowledge to use to see that the department's challenges are mitigated.

The developed system is a Decision Support System for AALRT Maintenance department. The motivation is based on the literature review from books, articles, internet resources, international journals, and paper publications and also from study visit, survey, interview, data collection from AALRT. These show the fact that a DSS is needed as an intelligent module for maintenance management at AALRT. The decision-making model used is a DMG, which was originally proposed by Labib (2004).

1.2.1. BASIC RESEARCH QUESTIONS.

The following research questions are drawn from the above research problem statement and will guide in this research;

Q1. What are the possible maintenance strategies for light rail transit operations?

Q2. Why is it necessary to a specific maintenance strategy for each rolling stock system than adopting a single strategy?

Q3. What are the basic input parameters for the DSS?

1.3.OBJECTIVES

1.3.1. MAIN OBJECTIVE

The purpose of this research is to come up with an alternative method for the selection of Rolling Stock maintenance strategies at AALRT basing on the maintenance data collected, with the help of a well-structured decision support system.

1.3.2. SPECIFIC OBJECTIVES

- To determine the effect of various maintenance strategies on achieving reliable and dependable rolling stock operation using the key performance measurements.
- To review different maintenance strategies and recommend a specific maintenance strategy for each rolling stock system.
- To develop a structured DSS based on Fuzzy Logic and rules from the DMG.

1.4. RESEARCH LIMITATIONS

The thesis focuses on the analysing the maintenance activities and the maintenance strategies in the rolling stock maintenance department at AALRT. 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.

The study also analyzes the strategies selected based on the identified criteria. The model to be applied in the study is the DMG and applying the Fuzzy Logic technique to smoothen the boundaries.

The DSS developed is a tool capable of utilizing the available data in the database, to help the maintenance personnel in making informed decisions in less time, based on a predetermined criterion.xxxz

1.5.THESIS OUTLINE

This thesis is organized as follows:

- Chapter 1. Presents a comprehensive review concerning the problem statement, the research questions of the research carried out and gives an introduction to the research, outlines the objectives and method of the research that is carried out.

- Chapter 2. Literature survey on maintenance; maintenance strategies; maintenance planning and scheduling, rolling stock maintenance, Artificial intelligence techniques and highlights examples where DSS have been used in various industries.
- Chapter 3 presents the details of maintenance at AALRT and the Rolling stock systems that are maintained by the department.
- Chapter 4 presents the methodology of the research. This is the Decision Making Grid and Fuzzy Logic. The proposed model is applied to the case study till the final results are obtained
- In chapter 5. Presents the research data analysis and presentation. The data obtained from AALRT is applied to the methodology to obtain results which are linked to the maintenance strategies.
- Chapter 6 presents the research conclusion and recommendations, depending on the results obtained from the methodology and data analysis.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. INTRODUCTION

With the increasing demand on Maintainability, operations, and safety, rolling stock equipment have become more complex and capital intensive. Developing and implementing a maintenance program is a difficult process that suffers from many problems. It often suffers from lack of a systematic and a consistent methodology. In addition, since the process of developing the program relates to different parties with interests in maintenance, it becomes difficult to achieve all round satisfaction of these parties, and at the same time achieve the objectives of the company. Developing a DSS is an iterative process that involves different decision makers, who may have conflicting objectives. In deriving these objectives maintenance managers usually try to achieve multiple, and sometimes, conflicting objectives such as maximizing throughput, availability, and quality subject to constraints on maintenance plan, available spares, manpower, and skills. However, even though all parties are harmonized, coming up with a decision concerning an appropriate maintenance strategy for each rolling stock system, basing on the maintenance data obtained, can be time consuming and errors are easily made. Therefore, a structured DSS is required, which can help determine the appropriate strategy within a lesser time.

DSS are used extensively in business and industry to assist in decision-making across a wide spectrum of problem areas. There are a number of approaches and techniques employed, from simple information reporting tools, to sophisticated Artificial Intelligence systems using Bayesian statistics or genetic algorithms (Rippen, 2005). They all share three common components of decision support systems:

1. An information store house of knowledge, which relates to asset management. Asset management is a process of identification, design, construction, operation, and maintenance of physical assets. Over the years a number of different definitions and approaches to asset management have been presented. A popular definition is that “asset management is concerned with obtaining and using the knowledge needed to optimize trade-offs among financial performance, and operational performance” (Ness & Lambie,

2004). Further, the science of asset management aims to equip engineers to become businessmen and introduces structured methods for handling reliability, performance, and maintenance (Woodhouse, 2001). An individual who is responsible in managing organizational assets, for example, an asset manager, is considered a pivot that bridges the gap between business objectives and the considerable complexities of technical and human issues. An Asset Manager acts as a professional translator by converting options, such as asset design or maintenance strategies or asset replacement decisions, into business language.

2. A process by which this knowledge may be systematically interrogated to provide answers to questions. This is the component that predominantly distinguishes between different Decision Support Systems.
3. A user interface providing users with a perceptive, accessible tool for gaining the information they require.

2.2.MAINTENANCE PERFORMANCE MEASUREMENT

Tsang *et al*. (1999) expresses, since maintenance spending constitutes a large part of the operating budget in organizations with heavy investments in machinery and equipment, tracking the performance of maintenance operations in such organizations should be a key management issue. Another reason for linking the measurements to the organization’s strategy, according to Tsang, is the influence of the used performance measurements on employee behaviors (Tsang, 1998).

In a study performed by Tsang (Tsang *et al*. 1999), the following characteristics of the maintenance performance measurement system were shared by the studied companies:

- It is an exception rather than the norm that the maintenance organization uses a structured process to identify measures of its performance. Management is typically not aware of the part the measurement system can play in achieving the vertical alignment of goals and horizontal integration of activities across organizational units.
- The commonly used measures are financial indicators such as operational and maintenance (O&M) costs, and equipment-based or process-oriented measures such as equipment availability, labor productivity, and the number of incidents caused by in-service failures.

- Benchmarking is gaining acceptance as a methodology for evaluating performance and establishing targets by making reference to the achievements of best-in-class organizations.

2.3.MAINTENANCE, MAINTENANCE PLANNING AND SCHEDULING

A literature study on the different maintenance strategies as well as the importance of planning and scheduling maintenance is discussed to provide a background to the research problem.

2.3.1. MAINTENANCE

The role of maintenance has become very important in all kinds of industries. As such, the need for maintenance has increased over the years and companies have come to adopt maintenance as an activity that adds value rather than view it as a necessary evil for expenses which contributes to the business profit (Sharma, Yadava & Deshmukh 2011). Maintenance actions involve implementing every decision made at all levels of an organisation in order to achieve and sustain a high level of reliability and availability of its asset. It deals with specific methods, resources and personnel utilized in order to keep a piece of equipment or system running efficiently during its designed life (Anderson & Neri 1990).

Any piece of equipment is designed to function for a period of time after which its performance is expected to degrade. When this happens, maintenance is needed to rectify the equipment after failure or when a failure is foreseen. In a (normal case) maintenance is performed to keep a piece of equipment functional during its designed life considering that the practical operation of the components of a piece of equipment is a time-based function.

A brief understanding of the fundamental principles of failure is required to fully grasp the concept of maintenance. A piece of equipment is said to have failed when it no longer operates within its stipulated design specifications. Smith (1993) explains that failure can also occur within a complex system which consists of other subsystems that have failed even when these may not be visible and the equipment still stays in operation. This is called a “hidden failure”. It is necessary to check for such failures, as they could result to operational failures and/or accidents.

A component’s statistical lifespan can be illustrated with the use of a graphical representation called the bathtub curve (see Figure 1). The curve shows that a component has a high probability of failure during its first few weeks of operation, which could be as a result of errors during its installation or manufacturer. This period is referred to as the infant mortality period. Following the infant mortality period is the normal life period. In this period, the equipment exhibits a relatively low probability of failure for a long period although the component may experience random failures. After the normal life period, the probability of failure becomes relatively high as a result of the equipment reaching its wear-out period (Klutke, Kiessler & Wortman 2003).

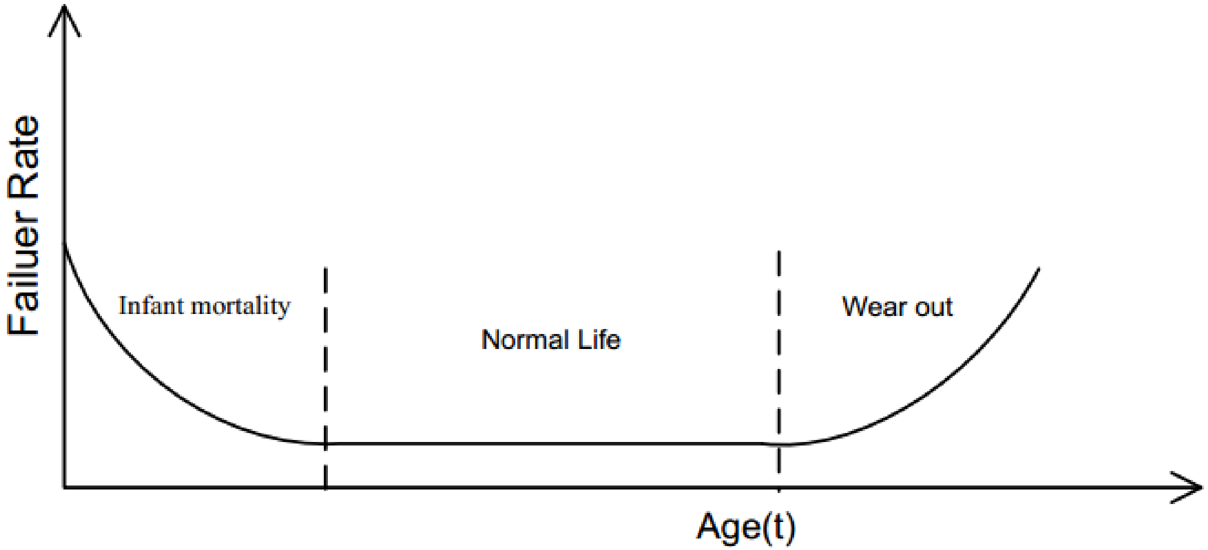
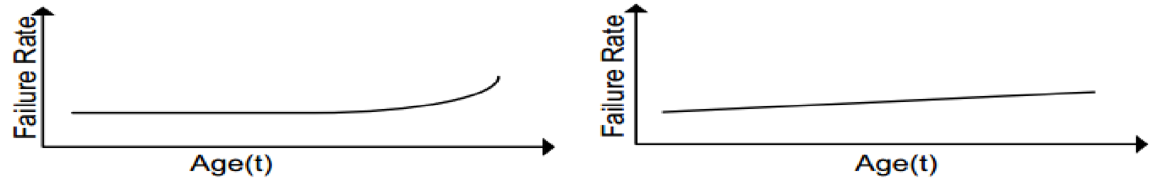


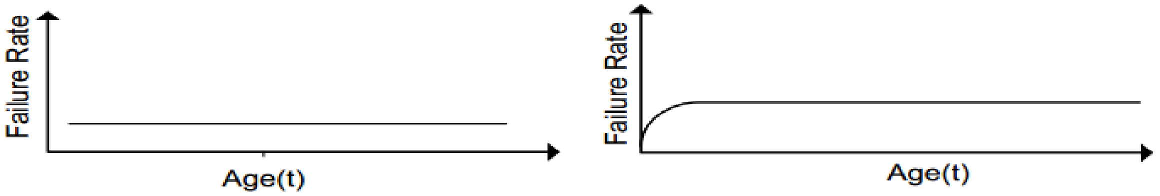
FIGURE 1: COMPONENTS FAILURE RATE OVER TIME (BATHTUB CURVE) (KLUTKE, KIESSLER & WORTMAN

It has however, been shown by the commercial aviation industry, that this is not the case for every component. An investigation conducted by Smith (1993) found that a component can experience five other failure forms besides the bathtub curve. These forms are based on the age-reliability relationship of the components and are illustrated in Figure 2.



A: Constant or gradually increasing failure probability followed by a distinct wear out period

B:Gradually increasing failure probability with no identifiable wear out period



C: Constant failure probability through all periods

D: Low initial failure probability followed by a constant failure probability

E:Infant mortality followed by a slow increasing constant failure probability

FIGURE 2: FAILURE TRENDS OF A COMPONENT OF A PIECE OF EQUIPMENT (SMITH 1993)

Although these failure forms represent the combinations of failure probabilities in the aviation industry, it can also be assumed that the probability of failures of components in other industries can take these forms. However, one must consider that the ratio of these probabilities could differ slightly with respect to the type of component. Smith’s study established that the most common age-reliability failure form (in Figure 2 above) shows a high initial probability of failure rate and decreases to a lower and constant probability of random failure with time. According to Smith (1993), an understanding of these different failure forms has an effect on choosing an appropriate maintenance strategy.

2.3.2. MAINTENANCE OBJECTIVES

Maintenance has been practised as far back as the 1930s before the Second World War, when the engineers believed maintenance was not needed as it increased cost of production and had no impact on the value of the production. Emphasis was to minimize the system cost rate but the importance of reliability performance was not taken into consideration (Sharma, Yadava &

Deshmukh 2011). As a result, maintenance was only carried out after a system breaks down. However, during the World War II in the 1940s, there were advances in engineering and scientific technology which brought about new kinds of maintenance that were cost effective and maintenance was categorized as a function of the production system.

In recent times, organizations have been made aware of the importance of environmental safety, quality of products and services thereby making maintenance an important aspect of their asset to contribute to the growth and success of the company. These have led to the need for defining the purpose of maintenance and creating maintenance objectives in order to measure performance in meeting these objectives. According to Dekker (1996), the purpose and objectives of maintenance are defined as follows:

- Reducing breakdowns and emergency shutdowns.
- Maximizing production at lower cost, highest quality and within optimum safety standards.
- Optimizing the use of maintenance resources.
- Optimizing the utilization of resources to reduce downtime.
- Increasing reliability of the operating systems.
- Improving spares parts stock control.
- Optimizing capital equipment life.
- Improving equipment efficiency which reduces scrap rate.
- Identifying and implementing cost reductions.
- Optimizing the useful life period of the equipment.
- Minimising energy usage.

Maintenance contributes towards organizational profit, hence the need to include it in corporate objective (Sharma, Yadava & Deshmukh 2011). It is therefore important that maintenance objectives are consistent with the goals of production and that they are comprehensive enough to include specific responsibilities (Kelly 2006). Dekker (1996) summarized maintenance objectives into four distinctive heading namely;

- Ensuring system function

- Ensuring system life

- Ensuring safety

- Ensuring human well-being

Dekker suggests that providing the correct reliability, availability, capability and efficiency should be the main maintenance objectives for a system to be maintained.

2.3.3. MAINTENANCE STRATEGIES

Mobley (2011) identifies run to failure and preventive maintenance as the two most common maintenance management strategies used by organizations to achieve their maintenance objectives. These strategies can be managed using the different types of maintenance, that is, corrective, reactive, preventive, and proactive.

These are explained in the sections that follow and summarized in Figure 3 below. It is important to note that each of these strategies has different age reduction impacts on system.

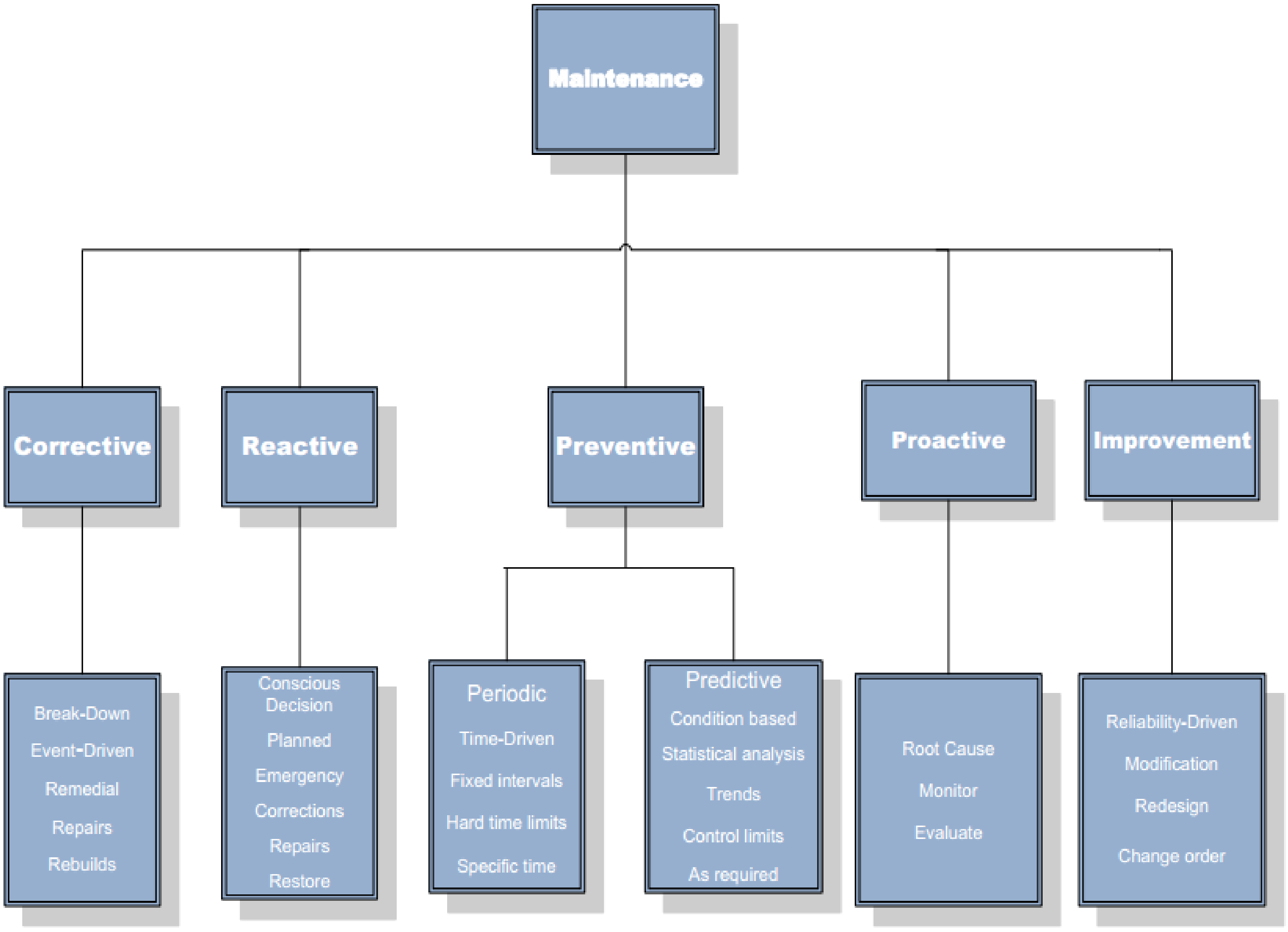


FIGURE 3: TYPES OF MAINTENANCE ADAPTED FROM (MOBLEY 2011)

2.3.3.1. CORRECTIVE MAINTENANCE

Corrective Maintenance (CM) aims to maximise the effectiveness of all critical systems, minimise breakdowns, minimise unnecessary repairs, and reduce the deviations from optimum operating conditions. CM is event-driven and involves tasks performed to identify, isolate, and amend faults of a failed piece of equipment so that its operational conditions can be restored within the tolerances or limits established for in-service. CM is associated with break downs, emergencies, remedial and repairs and often times require rebuilding the equipment. Depending on the impact of the fault, CM can either be performed instantly or delayed if the system requires to be shut down in order to make repairs. It is by far the simplest type of maintenance strategy. Equipment service levels are generally below acceptable levels and the quality of product is usually affected (Wireman 2005).

2.3.3.2.REACTIVE MAINTENANCE

Reactive maintenance (RM) is similar to corrective maintenance (CM) but defers in that RM involves a conscious decision to allow a piece of equipment operate until it breaks down before CM actions are carried out. It is used for run-to-failure maintenance management approach therefore sometimes referred to as Run-To-Failure maintenance (RTF). RM is carried out in order to repair, replace and restore actions performed on a system after a failure has occurred for the purpose of restoring the system to an acceptable working condition (Mobley 2011). This is the oldest and most expensive type of maintenance practiced. This type of maintenance is known to be associated with high expenses in spare parts inventory, machine down time, overtime labour costs and low production availability. RM can be subdivided into two different categories, namely:

Emergency maintenance (EM): refers to maintenance which is done immediately or at the earliest possible time in order to reinstate a failed equipment to achieve maximum productivity with minimum wasted effort or expense.

Breakdown maintenance (BM): refers to maintenance performed after a failure which is considered to be advanced, has occurred. In this case, provision would have been made in the form of repair method, spares, materials, labour and equipment to tackle the breakdown.

2.3.3.3.PREVENTIVE MAINTENANCE

Preventive maintenance (PM) aims to minimize the probability of failure occurring during the operation of a piece of equipment. PM involves maintenance tasks carried out to avoid premature equipment damage as well as reducing unscheduled interruption that could lead to corrective activities. The maintenance tasks are based on completed time or hours of operation and scheduled on the basis of the mean time to failure (MTTF) statistic (Mobley 2011). According to Vasili, Hong & Ismail (2011), PM involves a set of management, administrative and technical actions which are aimed at reducing the age of the equipment for the purpose of improving the availability and reliability of the system.

PM can become very expensive if not done effectively and efficiently. It is generally understood that it involves regular inspection of equipment to check for failures or faults. This is not always the case as PM activities can be used to satisfy most of the maintenance objectives set out by an organisation. PM can either be performed as Periodic (Time-based) maintenance or as Predictive (Condition-based) maintenance.

PM tolerates planned downtime's addition into the production schedule and decreases the occurrence of breakdowns. It also reduces maintenance cost because cost is used for part replacement only while also reducing the risks of injury and environmental degradation.

2.3.3.4.PERIODIC MAINTENANCE (TIME DIRECTED MAINTENANCE TDM)

Time directed maintenance are activities that take place based on a measure of interval. This could be in the form clock time, calendar days, number of cycles or number of kilometres travelled. The activities consist of occasionally inspecting, overhauling and cleaning a piece of equipment, replacing affected parts to prevent unexpected failure and process complications (Levitt 2003).

TDM is broken down into two tasks: Time-Based (TB) which is an Inspection task and Time-Based Instructive task (TBI) which refers to tasks that involve opening up a piece of equipment. TB has been the major application of PM, but lately, there has been an increase in computer simulations and automation which necessitating a shift from TB maintenance to Predictive maintenance.

2.3.3.5.PREDICTIVE MAINTENANCE

Predictive maintenance (PdM) is done by forecasting possible failures based on regular monitoring of a piece of equipment for the purpose of preserving its components from failure and sustain it against hazards. PdM a data-oriented type of maintenance and doesn't necessarily require the purchase of new equipment (Levitt 2003). PdM is sometimes also referred to as Condition based maintenance (CBM) or Condition Monitoring.

PdM/CBM is a systematic or scheduled maintenance where specific components are replaced at regular intervals as they become worn. It is a process in which the decision to replace or not is based on the outcome of a diagnosis study (Lyonnet 1991). PdM is made popular by the use of control systems in a piece of equipment for the purpose of gathering data and feeding the data to a condition-based maintenance decision system. PdM is a tool used to generate corrective activities. CM activities generated from PdM can be planned and scheduled because of the time interval between the diagnosis and the required corrective action. It is a very accurate PM strategy when used to manage serious equipment wear. PdM can be expensive to implement at first, but this effect is cushioned by its ability to bring maintenance closer to production and supporting quality programs (Levitt 2003).

PdM improves system reliability while reducing maintenance costs in that, the reduced number of maintenance activities causes a decrease of human fault impacts. As mentioned earlier, PdM implementation has high installation cost, the costs involved are divided unequally as a result of unpredictable maintenance periods. The value of minor part of a piece of equipment is usually higher than the actual equipment; hence, PdM is used rarely for less important parts of a piece of equipment (Liu, Wang & Golnaraghi 2010).

2.3.3.6.PROACTIVE MAINTENANCE

Proactive Maintenance is the opposite of RM; its focus is on determining the root causes of machine wear and failure and resolving those causes before they manifest. Proactive maintenance is seen as money saving maintenance practice because of its ability to reduce machine wear and failure thereby reducing the need for maintenance. It uses a technique of monitoring and correcting failure root causes in a piece of equipment for example contamination (Swanson 2001).

Proactive maintenance differs from PM and PdM in that it makes use of corrective activities to eradicate the sources of failure. This strategy extends equipment life as opposed to relying on conventional conditions for impending machine breakdown. It also uses systematic scheduled maintenance to prevent the breakdowns. Proactive maintenance does not accept failure as a routine or anticipate crisis failure maintenance, all of which are characteristics of PM and PdM. When used correctly, proactive maintenance prevents loss of productivity due to broken or inoperable piece of equipment and this saves costs (Swanson 2001).

2.3.3.7.RELIABILITY-CENTERED MAINTENANCE (RCM)

This type of maintenance is reliability-driven. It is aimed at reducing the need for maintenance of equipment by improving the reliability of the machine. This is achieved by focusing on ways to preserve the function of a piece of equipment in its totality and not part specific. It involves modification of the equipment by adding accessories that could support a part thereby reducing its need for regular maintenance. It also involves redesigning or changing the order of operation if applicable (Mobley 2011). Reliability-centred maintenance (RCM) is based on the principle that analysing the costs of failure and the definite preventive maintenance with the use of a well-disciplined decision logic analysis process can give room for more efficient life time maintenance and logistic support programs (Duarte *et al.*, 2010).

RCM has been identified as a very efficient and well used strategy for the preservation of operational efficiency of a piece of equipment. RCM functions by finding an equilibrium point between high maintenance costs and cost of preventive maintenance policies while, taking into consideration the potential shortening of useful life of the piece of equipment (Afefy 2010). RCM is defined by four characteristic features which include preserving system functionality, identifying specific failure modes that result to functional failures, prioritizing the failure mode by order of importance, and selecting an applicable and effective PM activities to eliminate the failure modes (Rommelspacher 2012).

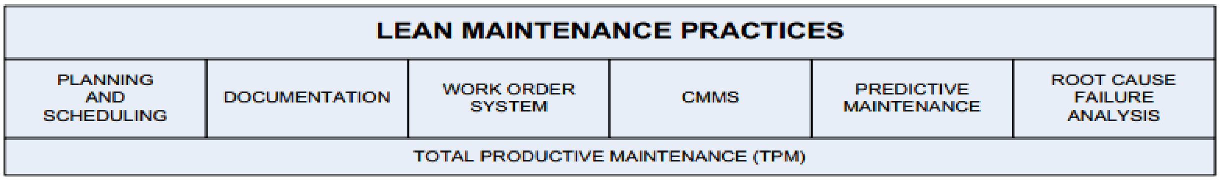
2.3.3.8.TOTAL PRODUCTIVE MAINTENANCE

Total Productive Maintenance (TPM) is a newly defined concept of maintenance program. TPM is a strategy that gives emphases on operator’s involvement in the basic aspects of maintenance. In TPM, operators are expected to take possession of any piece of equipment they operate by performing routine maintenance activities during the normal operation of the piece of equipment (Rommelspacher 2012). The goal of the TPM program is to increase production significantly while simultaneously increasing employee self-esteem and job satisfaction. It is directed primarily to the commercial manufacturing environment (Kalbande, Sawlekar & Thampi 2010).

TPM shows the importance of accepting maintenance as a vital part of a business and not to be viewed as a non-profit activity. Activities of maintenance such as replacements, repairs, are to be scheduled as part of the production process. The reason for doing this is to reduce unscheduled maintenance, breakdown and emergency during system operation. This aligns with the objective of TPM which is to eliminate equipment breakdowns, speed losses and inconsequential stoppages. According to Kalbande, Sawlekar & Thampi (2010), TPM promotes defect-free production, just-in-time (JIT) production, and automation.

2.3.3.9.LEAN MAINTENANCE

Lean maintenance was introduced as a prerequisite for successfully implementing lean in maintenance. It is a planned and scheduled maintenance approach which is achieved by the combination of TPM practices and RCM strategies. Lean maintenance has a foundation of TPM; this means in order to successfully implement lean in maintenance, TPM should have been established and operating efficiently (Smith & Hawkins 2004). The objective of lean maintenance is eliminating every type of waste in the maintenance process without taking serious reliability problems into account. However, Ghayebloo and Shahanaghi (2010) state that this is not necessarily the case and developed a multi-objective decision-making model to apply lean maintenance to decrease waste and increase system reliability. Lean maintenance is shown in Figure 4.



LEAN MAINTENANCE PRACTICES					
PLANNING AND SCHEDULING	DOCUMENTATION	WORK ORDER SYSTEM	CMMS	PREDICTIVE MAINTENANCE	ROOT CAUSE FAILURE ANALYSIS
TOTAL PRODUCTIVE MAINTENANCE (TPM)					

FIGURE 4: LEAN MAINTENANCE PRACTICES (SMITH, HAWKINS 2004)

2.3.4. WHY EACH SYSTEM REQUIRES A UNIQUE MAINTENANCE STRATEGY

Improvement projects in the area of maintenance strategies are always necessary because of the return on investment they can achieve (Willson, 1999). Making a cost-effective maintenance decision is not an easy task, especially when the system consists of several different components with different maintenance characteristics and the maintenance program must combine technical requirements with the firm’s managerial and business strategies (Alsyouf, 2004, p.43). Practice shows that if a decision maker relies on experience only, he takes erroneous decisions which lead to fatal consequences, such as economic stagnation, environmental degradation. To have an opportunity for taking rational decisions, both organizational and personal, we need to use a wider range of scientific knowledge. Actually, decision-making is now an international problem of interest to mathematicians, economists, sociologists, psychologists, and engineers (Ayzerman et al., 1983).

The decision maker needs to select from all the applicable maintenance approaches the right policy for each component, module or equipment. The identification and implementation of the appropriate maintenance policy will enable the managers to avoid premature replacement costs, maintains table production capabilities, and prevent the deterioration of the system and its components (See among others Williams et al., 1994; Mann et al., 1995; Dekker, 1996; Vineyardetal., 2000; Sherwin, 2000; Waeyen berghand Pintelon, 2002).

Effective maintenance ultimately aims to determine suitable action's that can keep machine performance at acceptable level and extend the life cycle of the machine. Different types of maintenance alternatives have been proposed to achieve the ultimate goal. However, a maintenance policy implemented in a similar machine but in different environments may not produce similar results because of various operating factors such as humidity, temperature and work load.

In addition, decision-making in maintenance selection is often accompanied by diverse constraints and economic perspectives. Examples of these constraints include; operator safety issues, government regulation, resource limitation and budget, consequently the selection of a suitable maintenance policy becomes a crucial decision-making process to obtain high levels of success for the firm beneficiaries in any industry.

2.3.5. IMPORTANCE OF MAINTENANCE PLANNING AND SCHEDULING

Organizations are making efforts to increase profitability by increasing labour productivity, while at the same time maintaining a high level of quality, service and timelines. For this to be achieved, the importance of maintenance management has grown in all organizations. Maintenance is an important aspect in the life cycle of assets and needs to be planned and scheduled efficiently to minimize the costs involved. As maintenance operations increase in complexity, so does the complexity of the maintenance functions. These operations involve complex mechanical faults which require a level of skilled human resources to tackle.

Assigning the right repair skills to carry out the maintenance operations would reduce the downtime of production. It is therefore important to ensure that maintenance activities meet the organizational objectives whereby total operating and maintenance costs are reduced (Paz & Leigh 1994).

Manpower, equipment and material are the three major resources required for executing maintenance. These resources differ in their impacts on production and are managed differently. Manpower has been shown to be the most vulnerable of the resources, which makes it very difficult to control. Maintenance management is not involved with manpower's direct labour cost, rather it can be used to schedule i.e. how, when and where maintenance work is to be carried out which eventually has an effect on the total maintenance cost. An effective distribution of manpower through scheduling would increase the productivity of the workforce (Paz & Leigh 1994). Duffuaa *et al.*, (2001) also state the importance of planning and scheduling by regarding it as the most critical aspect of the maintenance process.

The objective of maintenance planning and scheduling is to reduce the idle time of equipment and maintenance personnel, minimize total scheduling time, reduce delay time of certain job, increase work time efficiency, maximize equipment availability and minimize shut-down cost and time (Duffuaa & Al-Sultan 1997). When this objective is carried out successfully, maintenance cost is reduced considerably, maintenance workforce is utilized efficiently thereby reducing disruptions in the system. The quality of maintenance work is improved with efficient planning and scheduling as it undertakes the best methods and actions and assigns the most experienced workers for the job (Al-Turki 2009).

2.3.6. MAINTENANCE PLANNING

An understanding of the process of successfully carrying out maintenance is required for all the different strategies of maintenance discussed above. Irrespective of the kind of maintenance, some kind of preparation or plan is needed to carry out the necessary maintenance activities. This preparation is known as maintenance planning, which helps to increase overall efficiency and effectiveness in maintenance (Al-Turki 2009).

Planning involves the process of determining future decisions and actions required to achieve a set of objectives. It involves the identification of parts and tools required and suitable to carry out a job. Planning helps to achieve set out objectives efficiently by minimizing costs, reducing risks and missing possibilities (Umar M & Al-Turki 2009). A maintenance plan is important in that it helps to determine the most cost-effective way to maintain the value of an asset. The three basic levels of planning processes are:

1. Long Range planning (covers a period of 2 years and above)
2. Medium range planning (between a month and a year)
3. Short range planning (includes daily and weekly plans)

Maintenance planning relates to the job capacity and workforce planning. It gives a detailed process of how a maintenance force should operate and a comprehensive outline for major overhauling, construction jobs, preventive maintenance plans, plant shutdowns and vacation planning. Duffuaa *et al.*, (1999) summarises the process of a proper planning after a job request has been made as follows:

- Define job content.
- Plan job work order by specifying job scope.
- Specify craft and establish skill level for the job.
- Estimate required time to execute the job.
- Specify anticipated parts and tools.
- Order parts and tools.
- Specify special tools required and obtain them.
- Review safety process.
- Create a priority work sheet for the job.
- Estimate cost required to complete the job
- Complete the work order.
- Review and control backlog.
- Use an effective forecasting system to predict maintenance load.

2.3.7. MAINTENANCE SCHEDULING

After a strategic maintenance plan has been developed, the next requirement for implementation is to allocate resources and workforce to the planned activities. This process is referred to as scheduling. Scheduling deals with assigning jobs with the necessary required resources (material and work force) which are arranged in the order of execution. The tasks are allocated durations, predecessors, successors and resource availability. Maintenance scheduling is therefore, the scheduling of planned maintenance activities (Al-Turki 2009). It is a process of executing the six elements of a successful maintenance job namely, the mechanic(s), tools, materials and spare parts, availability of scheduled machine, required information for job execution and approved permissions in an outlined efficient manner. Scheduling can be categorized into three main levels

1. Master Schedule (Medium range schedule: 3 months to 1 year)

2. Weekly Schedule

3. Daily Schedule

The master schedule relies on existing maintenance work orders. It is used to create a balance between medium range planning activities and available resources. This level of scheduling gives an overview of resource requirements and necessary plans are put in place to have them available when needed. The master schedule is revised often and updated to reflect changes to plan and completed maintenance work. The weekly schedule is created from the master schedule; it gives the description of the current operations schedules and economic considerations. The daily schedule is prepared from the weekly schedule, it gives description of the activities to be executed for the day. In some cases, the weekly schedule is interrupted for emergency maintenance activities.

Al-Turki (2009) presents the following as necessary requirements to carry out scheduling effectively:

1. Written work orders that are derived from a well-conceived planning process. This includes work to be done, methods to be followed, crafts needed, spare parts needed, and priority.
2. Time standards.
3. Information about craft availability for each shift.
4. Stocks of spare parts and information on restocking.
5. Information on the availability of special equipment and tools necessary for maintenance work.
6. Access to the plant production schedule and knowledge about when the facilities will be available for service without interrupting the production schedule.
7. Well-define priorities for maintenance work.
8. Information about jobs already scheduled that are behind the schedule (backlog).

Al-Turki (2009) further outline the scheduling procedure as follows:

1. Sort backlog work orders by skills needed.
2. Arrange orders by their priority.
3. Compile a list of completed and carry over jobs.
4. Consider job duration, location, travel distance, and the possibility of combining jobs in the same area.
5. Schedule multi-skill jobs to start at the beginning of every shift.
6. Issue a daily schedule.
7. Authorize a manager to compose work assignments.

The importance of maintenance as a value adding activity was highlighted in this chapter. The major objective of maintenance is to contribute to an organization's profit either by minimizing, identifying, or improving an element of the organization's objective. The reliability and availability of components increase when a proper maintenance strategy is adopted. These strategies have been described briefly and it can be summarised into two major categories which are corrective and preventive maintenance for rolling stock. To properly execute maintenance, it needs to be planned and scheduled efficiently to reduce the production loss time and cost. Off all the resources required for maintenance, manpower is the most challenging resource to control in maintenance management and should therefore be scheduled in the most efficient way possible.

2.4.EMAINTENANCE

eMaintenance refers to the use of ICT solutions in the maintenance area (Levrat, Iung, & Marquez, 2008). The management of maintenance consists of all activities that determine maintenance objectives, strategies and responsibilities, their implementation through maintenance planning and maintenance control, and their improvement. This is shown in Figure 5, extracted from International Electrotechnical Commission (IEC), 2004. The elements of maintenance support planning are: maintenance support definition, maintenance task identification, maintenance task analysis and maintenance support resources.

Maintenance preparation comprises the planning of maintenance tasks, scheduling activities, and assigning and obtaining resources. The maintenance execution phase includes the actual performance of maintenance, recording results and special safety and environmental procedures.

Maintenance assessment refers to the measurement of maintenance performance, analysis of results and determination of actions to be taken.

Finally, maintenance improvement is achieved by improving the maintenance concept, improving the resources, improving the procedures and modifying the equipment that is maintained (IEC, 2004).

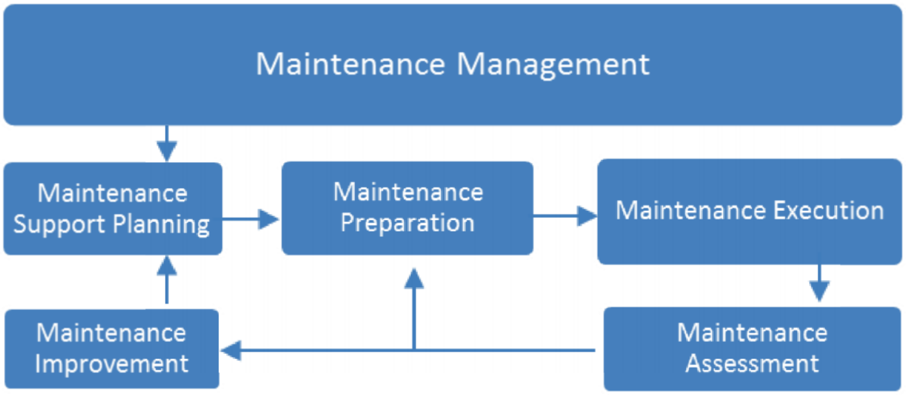


***FIGURE 5: PHASES OF AN OVERALL MAINTENANCE PROCESS* (IEC, 2004)**

Maintenance processes are supported by heterogeneous resources, such as documentation, personnel, support equipment, materials, spare parts, facilities, information and information systems (ISO/IEC, 2008). The provision of the right information to the right user with the right quality and at the right time is essential (Parida & Kumar, 2006) (J. Lee, Ni, Djurdjanovic, Qiu, & Liao, 2006). This situation can be achieved through appropriate information logistics, providing just-in-time information to targeted users and optimising the information supply process. While the provision of just-in-time information to the right users is essential to maintenance, we propose adding the need for correct information at the correct time, i.e. information based upon high quality data.

eMaintenance is a multidisciplinary domain based on maintenance and ICT. Its services are aligned with the needs and business objectives of customers and suppliers during the whole product lifecycle (Kajko-Mattsson et al. 2011). eMaintenance is a process managed and performed via computing. This includes activities in all phases of the maintenance process, with a variety of ICT solutions ranging from computerized maintenance systems to sensor technologies. In eMaintenance, assets are monitored and proactive maintenance decisions arrived at using Internet and other ICT tools (Verma, Srividya, & Ramesh, 2010).

eMaintenance also provides companies with predictive intelligence tools to monitor their assets (equipment, products, process, etc.) through Internet and wireless communication systems to prevent them from unexpected breakdowns. These tools can show a product's performance through globally networked monitoring systems, allowing companies to focus on degradation monitoring and prognostics rather than fault detection and diagnostics (J. Lee, 2001).

Briefly stated, eMaintenance technologies increase the possibility of:

1. Utilizing data from multiple origins;
2. Processing large volumes of data and making more advanced reasoning and decision making;
3. Implementing collaborative activities (Iung, Levrat, Marquez, & Erbe, 2009).

2.5.ARTIFICIAL INTELLIGENCE IN MAINTENANCE

AI techniques have been used successfully in the past two decades to model and optimize maintenance problems. Since the resurgence of AI in the mid-1980s researchers have considered the applications of AI in this field.

Examples covering the area of application of AI techniques in maintenance including fault diagnosis include the following;

- Case Based Reasoning (CBR)
- Genetic Algorithms (GAS)
- Neural Networks (NN)
- Fuzzy Logic (FL)
- Knowledge Based Systems (KBSs)

2.5.1. FUZZY LOGIC (FL)

FL has been used in various applications in the maintenance area to deal with uncertainty. Oke and Charles-Owaba (2006) apply an FL control model to Gant charting preventive maintenance scheduling. Al-Najjar and Alsyouf (2003) use a fuzzy multiple criteria decision making to select in advance the most informative (efficient) maintenance approach, i.e. strategies, policies or philosophies. Braglia et al. (2003) adopt FL to help an approach to allow analysts formulating efficiently assessment of possible causes of failure in mode, effects and criticality analysis.

Sudiarso and Labib (2002) investigated FL approach to an integrated maintenance/ production scheduling algorithm. Jeffries et al. (2001) develop an efficient hybrid method for capturing machine information in a packaging plant using FL, fuzzy condition monitoring, in order to reduce wastage and maintenance overheads.

Examples of FL hybrid applications include the use of a KBS for bridge damage diagnosis which aims at providing information about the impact of design factors on bridge deterioration with FL used to handle uncertainties (Zhao and Chen 2001). Sinha and Fieguth (2006) propose a neuro-fuzzy classifier that combines FL and NNs for the classification of defects by extracting features in segmented buried pipe images.

Applications for FL in fault diagnosis include fault diagnosis of railway wheels (Skarlatos et al. 2004), thrusters for an open- frame underwater vehicle (Omerdic and Roberts 2004), chemical processes (Dash et al. 2003) and rolling element bearings in machinery (Mechefske 1998).

2.6.DECISION MAKING

Decision making (ability to argue) is the central element of administrative activities. By saying decision making we mean *"a specific type of human activities aimed at choosing the best among available alternatives"* (Kolbin, 2003, p.346). This definition indicates three necessary elements in the decision-making process:

- The problem to be solved;
- A person or collective body which takes a decision;
- Several alternatives among which a choice will be made.

In the absence of one element, the process of selection ceases to exist. Conscious activities of man are inseparably linked with planning, which anticipates and determines all of his purposeful actions. Any planning process can be represented as a sequence or set of decision-making processes. Each decision captures the result of a specific planning problem, which allows the logical design for elaboration of a plan to be represented as a graph of such problems. (Kolbin, 2003, p.346)

Decision making can be classified in to two broad categories; it can be either a manual or an automated decision. Manual Decisions can be made with the help of Graphical Tools or Diagrammatic tools like graphs, flow charts, and Entity-relationship diagrams; which consume a lot of time and easily prone to error. This clearly reflects the importance of automation, or, in other words, intelligent software is vital especially for repeated processing.

2.7. APPLICATION OF A DSS AT FAST CAPITAL CONNECT IN UNITED KINGDOM

Fast Capital Connect is a railway company that developed a DSS using the DMG model and yielded positive outcomes. The Fast Capital Connect (FCC) maintenance regime for its Class 319 fleet comprises mileage-based maintenance (i.e. “exams”); there are four light maintenance exams (A, B, C and D exams) that vary in terms of frequency and maintenance tasks. In addition to this, mileage based heavy overhaul of the underframe equipment (C4 exams) and time-based overhaul of the vehicle interiors (C6 exams) are carried out.

The most important criteria at FCC in terms of system failures on rolling stock are the frequency of failures (i.e. impact on train performance) and the unit downtime due to failures (i.e. the number of delay minutes incurred due to each failure – which is a measure of the cost of each failure to the TOC)

Initially, FCC engineers used data stored in XV to determine which systems cause the greatest impact to the business in terms of train performance and delay minutes on a periodic basis and to identify trends in failures of systems on a long-term basis – this is a considerably time and manpower consuming process. Use of the DMG in FCC would assist engineers in analyzing defect information, prioritizing systems for maintenance, identifying the optimal type of maintenance that should be carried out and prioritizing which sub-systems should be focused on far more quickly – this in turn would allow FCC to allocate maintenance resources more effectively to the systems most critical to train performance and downtime.

Application of the DMG at FCC would also assist engineers in clearly and quickly being able to identify the different approaches that should be taken for systems that perform at the extremes for the two criteria considered (i.e. high frequency, low downtime failures and low frequency, high downtime failures) – this too would ensure that resources are deployed more effectively and focused on improving system performance such that the failure modes with the greatest impact are eradicated.

Furthermore, using the DMG would reduce the risk of low frequency failures with a high impact on the business from going undetected as both frequency of failure and impact of failure (in terms of delay minutes) are simultaneously used in the application of the DMG.

It was true that the DMG is suitable for use at FCC because the data required for the application of the DMG, listed in the following, is already available in the CMMS used at FCC.

- An Asset Register.
- A record of all the faults that have occurred on each of the systems (stored in XV).
- Delay minutes caused by each of the systems.

It was observed that this DSS assisted FCC engineers in making decisions about what types of maintenance should be done and would also allow maintenance to be adapted to suit the changing real-world performance of the fleets.

The advantages of ensuring maintenance work is prioritized yielded the following advantages to FCC as a business:

- Lower downtime of the units.
- Reduced maintenance costs because of focus on the most effective work that can be done.
- Reduced impact on passenger services and therefore an improved corporate image in the eyes of the customer.
- Increased profits through the increased availability of units for revenue earning service.
- Increased reliability of the units because the worst performing systems are prioritized and the work carried out is adapted to deal with the root causes of the failures of these worst performing systems.
- Reduced operating costs due to the reduction of failures in service.
- Enables continuous improvement within FCC because after the first set of worst performing systems are improved, work on the next set of worst performing systems can be started.

It should therefore be concluded that the application of the DMG would be worth considering in these TOCs in order to enable the realization of the previously described benefits.

2.8.ROLLING STOCK MAINTENANCE

Railway industries have been considered as an environmentally friendly transportation mode and its demand has been increasing over the years. There is a need to maintain a high level of reliability, safety, availability and maintainability within a rail system. This however, is a challenging task to accomplish considering the two main sub-systems that make up the railway system, namely the Rolling stock and Infrastructure. Infrastructure includes signal, power supply and rail tracks while Rolling stock refers to all vehicles that move on a rail track which could be coaches, wagons and locomotives. Of these two, rolling stock can be classified as the most important and most vulnerable (Park *et al.,* 2011).

Rolling stock is a very important aspect of a railway system. It is established from literature that railway operators have shifted attention to preventive maintenance but the methods of efficiently scheduling these PM activities have been a concern to many countries (Soh, Radzi & Haron 2012).

Rolling stock has a huge effect on the service level of the system because the service level of the rail system is directly proportional to the safety and comfort of the passengers. In order to achieve the required service level, the quality of the rolling stock performance needs to be improved continually and this can be achieved with proper maintenance. A train is also classified as rolling stock and it comprises of several rail vehicles connected in series. The combination of these vehicles are complex, but can be redistributed and reconfigured to include embedded systems, which are combined together to provide a high quality transportation service (Umiliacchi *et al.,* 2011).

Rolling stock maintenance has been categorized generally into corrective maintenance and preventive maintenance (Cheng & Tsao 2010). Nevertheless, these maintenance strategies have been found to be ineffective. Majority of maintenance activities in rolling stock companies are directed towards preventive maintenance, which often leads to incorrect maintenance work, frequent down time, unnecessary maintenance tasks and often reverts to CM/BM (Rezvanizaniani *et al.,* 2008).

Given this scenario, rolling stock industries need to select a maintenance schedule for the adopted strategy that will increase system reliability and reduce the need for regular maintenance. Selecting an effective maintenance strategy is an essential concern for a rolling stock industry. Various studies have been done to try to achieve a more efficient maintenance strategy to maintain high system reliability and reduce maintenance cost. In rolling stock, safety is the most significant factor in achieving reliability and the wheel sets are the most critical part of the subsystem (Rezvanizaniani *et al.*, 2008).

Another problem in rolling stock maintenance is reducing the hold time of rolling stock during maintenance. A robust schedule constructed in a manner that a sequence of the tasks is allocated to each resource for which the make span value can be predicted when the duration of the tasks is increased, can be used to ensure the task is complete at the planned duration. This was achieved by modelling the problem and solving with a robust genetic algorithm (Sevaux & Le Quéré 2003).

Selecting the right maintenance strategy and keeping the right amount of spare parts in rolling stock can be challenging. Cheng and Tsao (2010) attempted to solve this problem by applying Analytic Network Process (ANP) to determining a suitable maintenance strategy for rolling stock. Their results show that preventive maintenance should be used more than corrective maintenance as it requires less spare part quantities and replacement interval of component of rolling stock.

Yun, Han and Park (2012) applied GA and simulated annealing to determine the optimal preventive maintenance interval and optimal number of spare parts of rolling stock in order to satisfy the system availability requirements at minimum cost. The authors concluded that as the availability increases, the number of optimal spare parts reduces.

CHAPTER THREE

3. MAINTENANCE AT AALRT

3.1.INTRODUCTION

Rolling stock divisions is one of the 7 divisions under maintenance center. It was launched operation at September 19, 2015 on the NS line and November 15, 2015 on the EW line. It is one of the core parts of maintenance center. Its basic objective is to ensure safe and efficient light rail transit service with strong coordination with other related AALRT department divisions.

Light rail train adopts preventive maintenance and corrective maintenance together. There are 41 rolling stocks, 20 of them for NS line and 21 rolling stocks in EW line. Rolling stock divisions is classified in two sub divisions which are rolling stock maintenance and rolling stock equipment maintenance sub divisions.

Rolling stock maintenance sub division is responsible for maintenance failures of rolling stock whereas rolling stock equipment maintenance sub- division is responsible for maintenance work and supervision of Auxiliary equipment's. Currently there are 68 staffs in our division including the division manager and the management structure is shown in Figure 6 below.

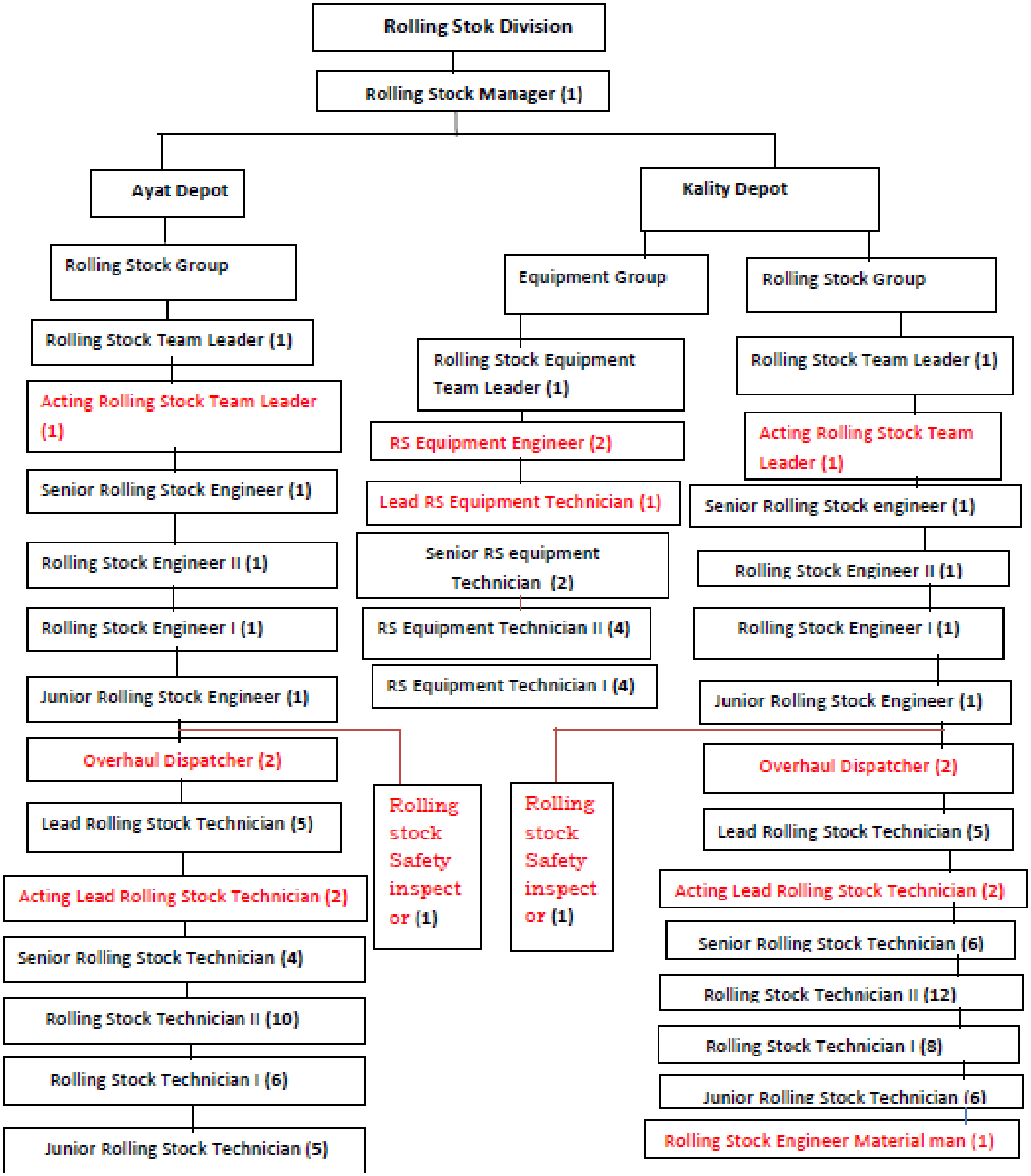


FIGURE 6: ROLLING STOCK STAFF STRUCTURE AT AALRT

From the figure above, shown in red, are the positions that need to be filled whereas the posts indicated in black are the ones which are occupied. The numbers in brackets are the number of people for that given post.

More so, a lot of information circulates among different departments. The division in question is the Rolling stock division. Shown below in figure 7; is a summary of some of the flow of important information handled by the maintenance department.

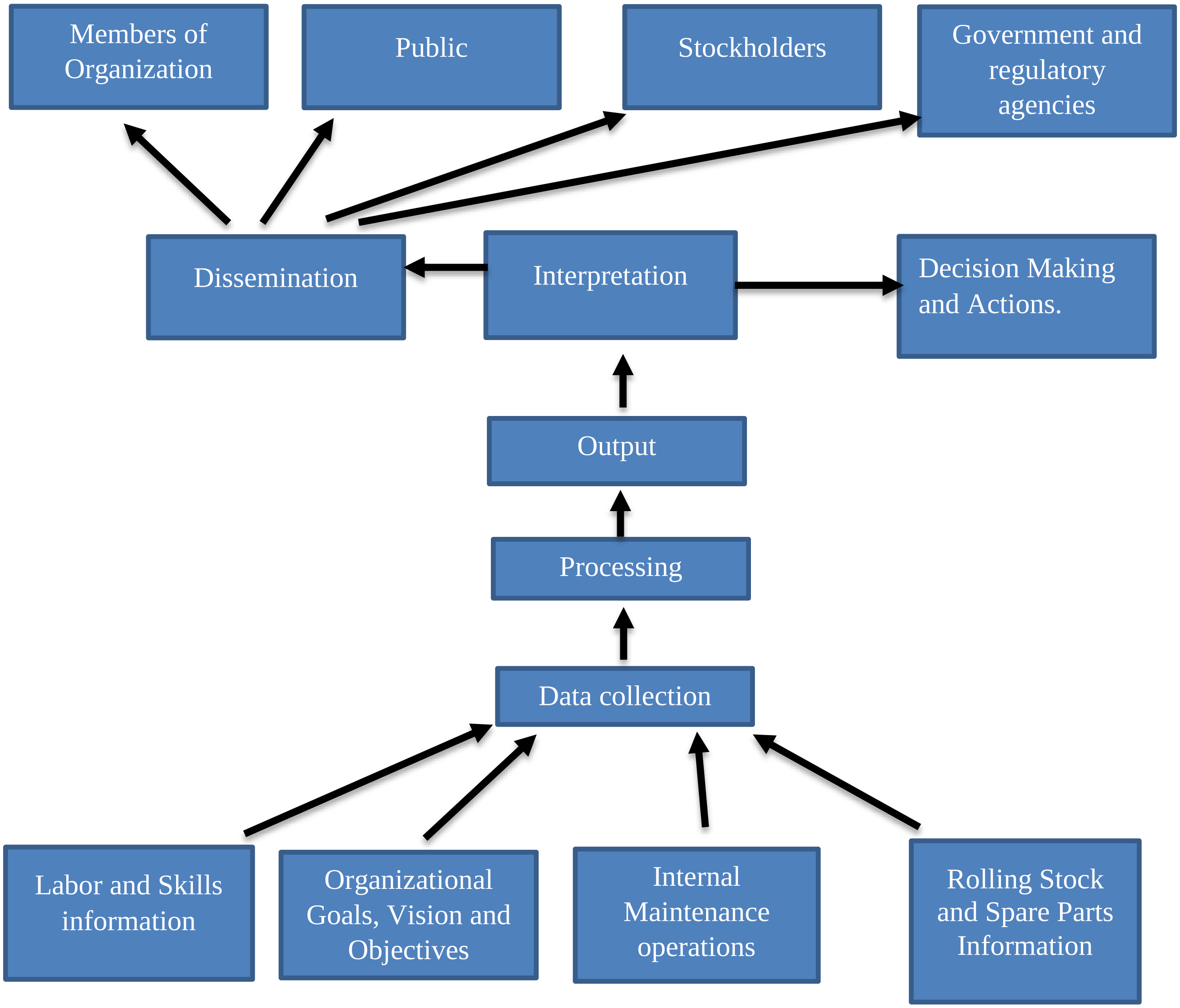


FIGURE 7: AALRT ROLLING STOCK DIVISION AS AN INFORMATION PROCESSING ENTITY

Maintenance at AALRT is categorised into;

- Daily:

  The shift group is responsible for daily inspections and main line failure handling. After the train comes back to the depot every day, the shift group will finish the function check at the daily inspection workshop
- Monthly, **(8,000KM or every month):**

The inspection items of the monthly inspection basically include; air conditioning and the replacement of the air conditioning filters; the inspection of pantographs, including clean insulators and arrestor.

- Quarterly, **(20,000KM or every three months):**

  Mainly focus on checking the important components (such as doors, bogies, brakes, pantograph, air conditioning.) of rolling stocks which will affect the safety operation, including measuring the pantograph pressure and up-down time, measuring the height of gangway and the size of Free hinge and flexible hinge, measuring wheel flange size.
- Annually; which is carried out every after a year.

Most of the maintenance information is written on paper and the data kept on computers is in Excel. There is no CMMS yet implemented. More so, there hasn’t been any form of condition base monitoring yet. The maintenance strategies adopted are basically Preventive and Corrective Maintenances. As discussed above these are basically reactive means of managing maintenance. The maintenance department takes care of 41 rolling stocks at Kality and Ayat depots, hence handles a lot of maintenance information of each rolling stock together with their respective components and subsystems, (though most of the information is store on paper). This tends to be tiresome and time consuming; especially when it comes to making daily, monthly, quarterly, or annual reports, since a lot of paper work has to be done.

3.2.ROLLING STOCK SYSTEMS AT AALRT THAT WERE CONSIDERED

1. Train Control Management Systems (TCMS)

Train Control & Management System (TCMS) is a train-borne distributed control system. It comprises computer devices and software, human-machine interfaces, digital and analogue input/ output (I/O) capability and the data networks to connect all these together in a secure and fault-resistant manner. TCMS is the standard control, communication and train management system for all vehicle platforms and applications ranging light rail trains as shown in Figure 9.

FIGURE 8: SHOWS THE TCMS WITH THE HUMAN MACHINE INTERFACE

2. Passenger Information System

A passenger information [display] system (PIS or PIDS) is an automated system for supplying users of public transport with information about the nature and state of a public transport service, through visual, voice or other media. See figure 10

FIGURE 9: SHOWS THE PASSENGER INFORMATION SYSTEM

3. Main circuit systems

The main circuit systems are the circuits those transmits power from catenary to auxiliary power supply system and traction systems and from these two systems to traction motors, air-conditioning systems, lightning, passenger information systems all controlling systems. See figure 11 below.

FIGURE 10: THE MAIN CIRCUIT SYSTEM

4. Auxiliary power Supply systems

Auxiliary power is electric power that is provided by an alternate source and that serves as backup for the primary power source at the station main bus or prescribed sub-bus. See figure 12. This system provides three phase power for Air conditioning systems and Heater and provides 24DC to all equipment except traction motor. It also used for charging the battery which used for emergency case and for initial activation of rolling stocks.

FIGURE 11: SHOWS THE AUXILIARY POWER SUPPLY SYSTEM AT AALRT

5. Air condition systems

The air conditioning unit has been supplied and used for Addis Ababa, Ethiopia LRV project. The air conditioning system can perform air treatment in saloon, to achieve dehumidification and refrigerating function, and to create a comfortable environment for passengers. See figure 13.

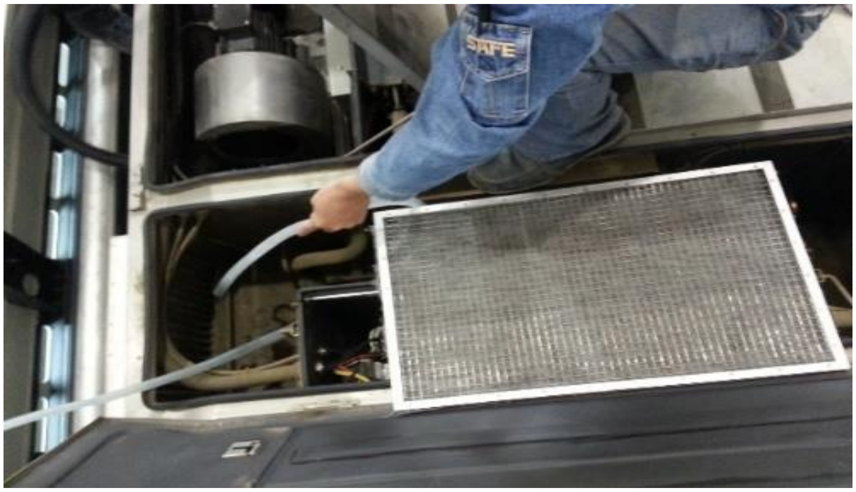


FIGURE 12: SHOWS THE AIR CONDITIONING SYSTEM DESCRIBED ABOVE

6. Traction systems

The traction system is the systems that convert the DC voltage into three-phase AC and give traction power to the motor which finally create motion of rolling stocks. Traction systems mainly consists of line contactor, IGBT inverter, chopper power unit, logical control unit and filter capacitor as shown in figure 14.

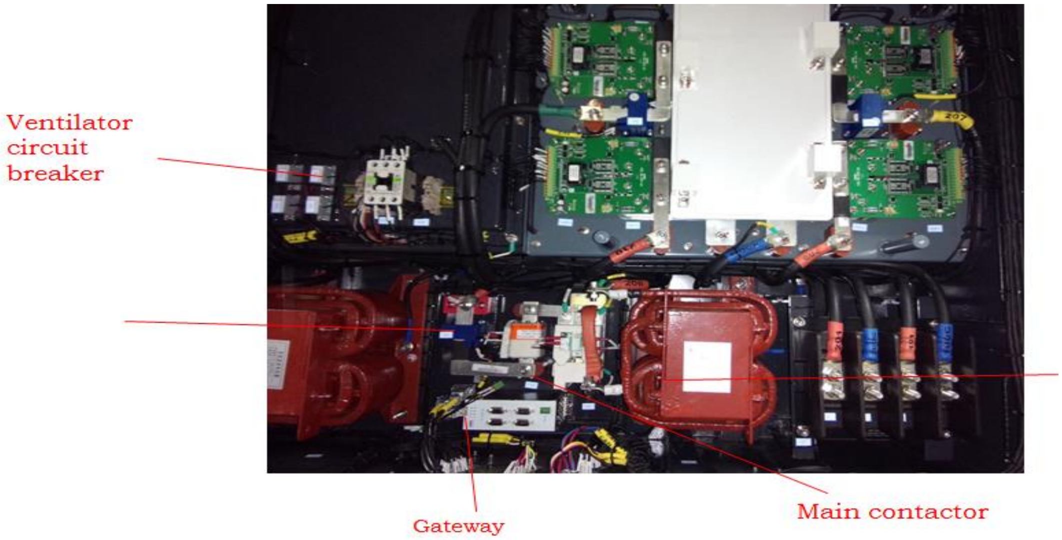


Figure 13: the Traction System that Converts DC to Three Phase Ac

7. Bogie systems

This is the part that support the overall body and guide the train on the rail, absorbing vibration generated by track irregularities and minimize centrifugal forces when trains run on curves at high speed. The bogie systems are mainly composed of bogie frame, wheel set axle box, primary suspension assembly, secondary suspension assembly, central traction assembly, traction motors, driving device, foundation brake device, bogie pipes and auxiliary device assembly. See figure 15.

Figure 14: the Bogie System As Described Above

8. Brake systems

Brake are used on the cars of railway trains to enable deceleration, control acceleration (downhill) or to keep them standing when parked. There are different equipment's used for braking systems. See figure 16. These are magnetic track brake, electro hydraulic braking equipment and electro dynamic braking equipment.

FIGURE 15: THE BRAKING SYSTEM OF THE ROLLING STOCK

9. Lighting systems

There are different kinds of lighting systems. These systems include normal interior lighting for night times, cab lights, emergency light which is always available and for emergency times, head light which used for night time for rolling stocks motion to ensure safety, tail light used for safety, and light controlling capacitor. See figure 17 below.

FIGURE 16: THE HEAD LIGHTS AND THE INTERIOR LIGHTS

10. Cab systems

As core of train controlling system, the cab is composed of traction system, signal system, PA system, CCTV system, radio station, train control system, control unit of brake system, horn for creating awareness, wiper, wind shield, diver chair as shown in figure 18.

FIGURE 17: THE INTERIOR OF THE CAB

11. Coupler Systems

A coupling (or a coupler) is a mechanism for connecting rolling stock in a train. A semi-automatic coupler is set on both ends of each train of AALRT. As shown in Figure 19, this coupler transmits electrical signal from one train to the other and ensure the safety of both rolling stock when they are coupled together.

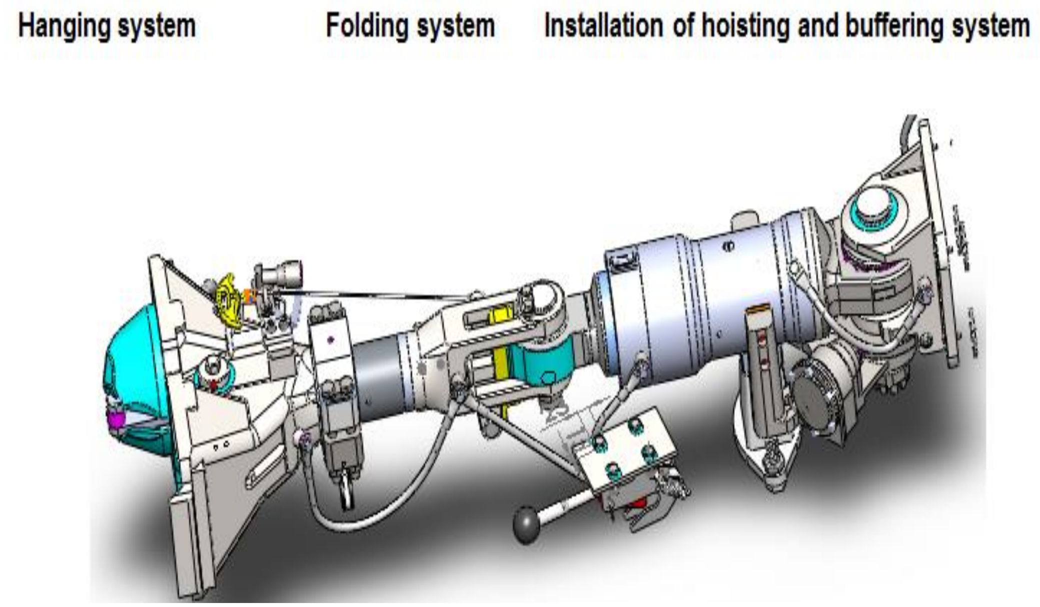


FIGURE 18: THE COUPLER WHICH IS USED ON AALRT ROLLING STOCKS

As mentioned, the strategies applied at ERC are Corrective and Preventive types of maintenance. These are carried out using the manufacturer’s manuals. ERC as a company has not yet adopted its own maintenance management system and hence, its own maintenance strategies.

From the Literature review presented, it can be note that, though some Railway companies have implemented CMMSs and registered numerous advantages, AALRT has not yet. More to that, many Railway Companies, have no decision support systems capable of utilizing the maintenance information in the database to enhance decision making. This therefore, calls for research in these areas, which will be the main focus of the Thesis of developing an intelligent DSS for AALRT to help in maintenance strategy selection.

CHAPTER FOUR

4. METHODOLOGY

4.1.INTRODUCTION

In this Chapter, *Research methodology* is presented as a way to systematically solve the research problem.

The present study uses both quantitative and qualitative analysis. The developed framework includes one model for decision support. The qualitative model, which is based on experts' evaluations is applied on the collected data

Data was collected in the following ways:

1. *Interviews:* a one to one interview was held with the maintenance engineer of AALRT. The purpose was to determine the challenges the maintenance department encounters and time spent while making maintenance decisions. A hypothetical interaction with maintenance and IT managers and the general manager of ERC helped to obtain a set of standard data to complete the research. The interview with the maintenance manager was intended to get information about the vision and objectives of the maintenance department at AALRT. These are presented in chapter 3.
2. The primary data in this research was gathered from the maintenance records kept. The maintenance data captured included the number of failures and the time spent on correcting these failures / Downtime (MTTR + MTTD) from the month of July to December 2018. This was done on the systems that make up the rolling stock at AALRT, as presented later in this chapter. The maintenance data at AALRT is stored using Microsoft Excel application, since they have not yet implemented a CMMS.
3. Secondary data means data that are already available i.e. it refers to the data which have already been collected and analyzed by someone else (Kothari, 2004, p.111). In this research in order to answer the research questions, the secondary data is collected by exploring library, Ebrary, and website of AALRT. Also, some data is collected from previous researches, Magazines, via exploring Google.com, and maintenance activities

in other light rail companies. Chapter 2 deals with the conceptions like as Strategy, Strategy development, maintenance strategies and concepts, maintenance planning, and Computerized maintenance management system. Some maintenance approaches such as *CM*, *PM*, *CBM*, and *PdM* are described (see among (In SS-EN 13306, 2001), (Bengtsson, 2007), (Wireman, 1990)). On the other hand, *TPM*, *RCM*, and *TQMain* are defined as maintenance concepts by exploring previous researches and issues (see among (Pomorski, 2004), (Moubray, 1997), (Al-Najjar, 1996)

The primary data collected was in numbers that can be mathematically manipulated and analyzed with available descriptive and inferential statistics. There were often large amounts of raw data to deal with.

4.2.Research Framework

The objectives are achieved through the following activities: 1) carrying out a literature study; 2) interviewing maintenance engineers from AALRT; 3) participating in conferences and workshops to get more information about the subject of the study; 4) reading about case studies in different Light Rail Companies areas.

The next step is model development, with the goal of developing solutions that can be used as eMaintenance solutions to decision making, with a focus on maintenance strategies. The following activities were conducted to achieve the overall objective, as summarized in the Figure 20 below.

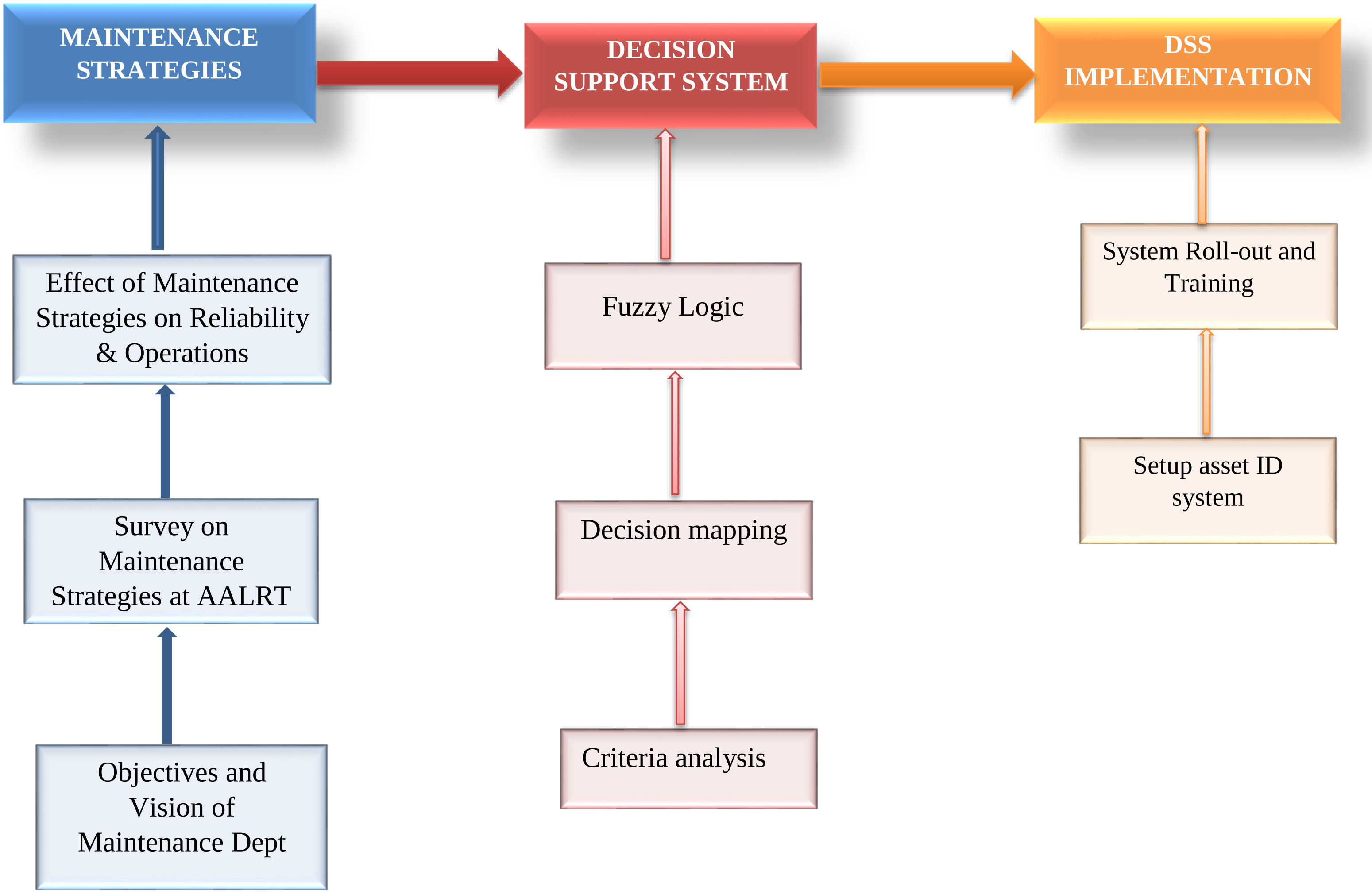


FIGURE 19: THE RESEARCH FRAMEWORK OF THE ACTIVITIES CARRIED OUT

The **Maintenance strategies phase** includes a study and getting a clear knowledge of the maintenance department goals and objectives. This helps to prioritize the solutions that help in decision making which are in line with the company goals and objectives. More so, a study was carried out to analyze the various maintenance strategies and those which are currently applied at AALRT. It was discovered that at the moment, there are two (2) main strategies being employed which are; Corrective and Preventive Maintenance strategies which are broadly explained in chapter 2.

Mobley (2011) identifies run to failure and preventive maintenance as the two most common maintenance management strategies used by organizations to achieve their maintenance objectives. These strategies can be managed using the different types of maintenance, that is, corrective, reactive, preventive, and proactive. It is important to note that each of these strategies has different age reduction impacts on system, as discussed in detail in Chapter 2. Information regarding these strategies is basically obtained from review papers and journals from internet

The implementation of a **Decision-Support System** follows these 3 steps which are as follows:

- Criteria analysis.
- Decision mapping.
- Fuzzy Logic

The model was proposed by Labib (1998) to identify effective maintenance policies at higher levels and can be useful in answering questions such as "how much maintenance should be done on this machine?" How frequently should this part be replaced? How many spares should be kept in stock? How should the shutdown be scheduled? It is generally accepted that the vast majority of maintenance models are aimed at answering efficiency questions, i.e. questions of the form "How can this particular machine be operated more efficiently?" and not at effectiveness questions, like "Which machine should we improve and how?" The latter question is often the one in which practitioners are interested, (Labib, 2003).

The DMG acts as a map on which the performances of the worst machines are located according to multiple criteria. The objective is to implement appropriate actions that will lead to the movement of machines towards an improved state with respect to these criteria, (Labib, 2003).

The model is based on identification of criteria of importance such as downtime and frequency of failures. The DMG then proposes different maintenance policies based on the state in the grid. According to the criteria used in the DMG, that is to say, Frequency and downtime, will be used as the key performance measurements in determining the appropriate maintenance strategy.

The implementation of a **Decision-Making Module** follows these 2 steps which are as follows:

- Criteria analysis.
- Decision mapping.

Step 1: criteria analysis

The objective of this phase is to assess how bad, are the worst performing machines, for a certain period of time, say one quarter using two important criteria, viz. downtime and frequency of calls.

For this study, downtime is only limited to the mean time to repair and the mean time to diagnose, (MTTR + MTTD), whereas frequency is the number of times the system breaks down every after a period of six months. The worst performers as regards each criterion are sorted and placed into high, medium, and low sub-groups. These ranges are selected so that machines are distributed evenly among every criterion.

Step 2: decision mapping

The aim here is twofold; high, medium, and low groups are scaled and hence genuine worst machines in both criteria can be monitored on this grid. This also monitors the performance of different machines and suggests appropriate actions. The next step is to place the machines' performance on the DMG shown in Figure 21, and accordingly, to recommend asset management decisions to management. This grid acts as a map on which the performances of the worst machines are located according to multiple criteria. The objective is to implement appropriate actions that will lead to the movement of the grid location of the machines' performance towards the top-left section of low downtime, and low frequency.

The method to create partitions between Low, Medium and High Frequency and Downtime was, introduced by Fernandez *et al.* (2003). It is done by subtracting the lowest values from the highest values, divide by three and multiply by two. Let h be the highest value in the list and l the lowest value in the list. Then;

Medium/High Boundary = $h - 1/3$

Low/Medium Boundary = $h - 2/3$

Low Boundary = Low Boundary = l

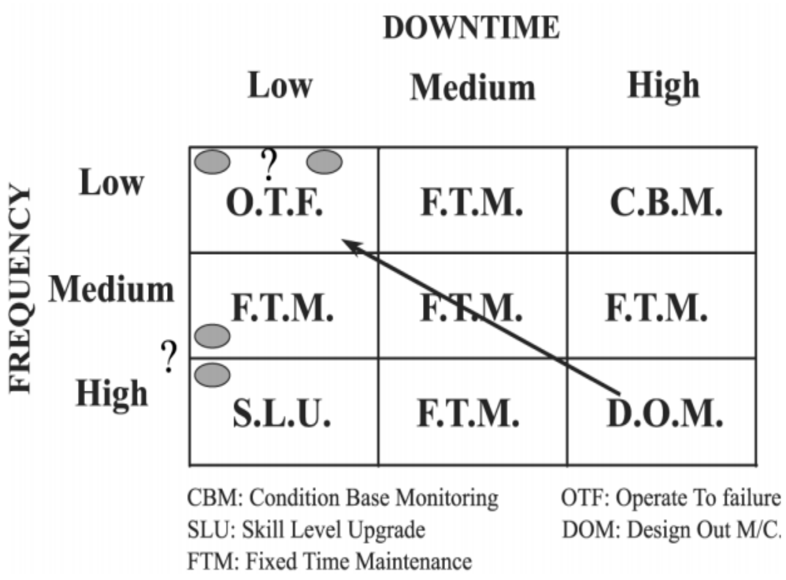


FIGURE 20: THE DECISION-MAKING GRID WITH RESPECTIVE RULES, (LABIB, 2004).

According to Labib (2004), the regions in the DMG is defined as follows;

- In the top-left region the action to implement, or the rule that applies, is operate to failure (OTF)
- In the bottom left region; it is skill level upgrade (SLU), because data collected from breakdowns – attended by maintenance engineers – indicates that the equipment has been visited many times (high frequency) for limited periods (low downtime). In other words, maintaining this machine is relatively easy task that can be passed to operators after upgrading their skill levels.
- Machines for which the performance is located in the top-right region, is a problematic one, in maintenance words a “killer”. It does not breakdown often (low frequency), but when it does it usually presents a big problem that lasts for a long time (high downtime). In this case the appropriate action to take is to analyze the breakdown events and closely monitor its condition, i.e. condition base monitoring (CBM).
- Location in the bottom-right region indicates a worst performing machine on both criteria; a machine that maintenance engineers are used to seeing not working rather than performing normal duty. A machine of this category, will need to be structurally modified and major design out projects need to be considered, and hence the appropriate rule to implement will be design out maintenance (DOM).

- If a medium downtime or a medium frequency is indicated the rule is to carry on with the preventive maintenance schedules. However, not all of the “medium” locations are the same. There are some that are near to the top left corner where the work is “easy” fixed time maintenance (FTM) – because the location is near to the OTF region – issues that need to be addressed include who will perform the work or when it will be carried out. For example, the performances of machines situated in the region between OTF and SLU and the question is about who will do the job – the operator, maintenance engineer, or subcontractor. Also, the position on the grid of a machine which has been shifted from the OTF region due to its relatively higher downtime and hence the timing of tasks needs to be addressed.
- Other preventive maintenance schedules need to be addressed in a different manner. The “difficult” FTM issues are the ones related to the contents of the job itself. It might be the case that the wrong problem is being solved or the right one is not being solved adequately. In this case, such machines need to be investigated in terms of the contents of their preventive instructions and an expert advice is needed. Figure 21 below, represents these circumstances.

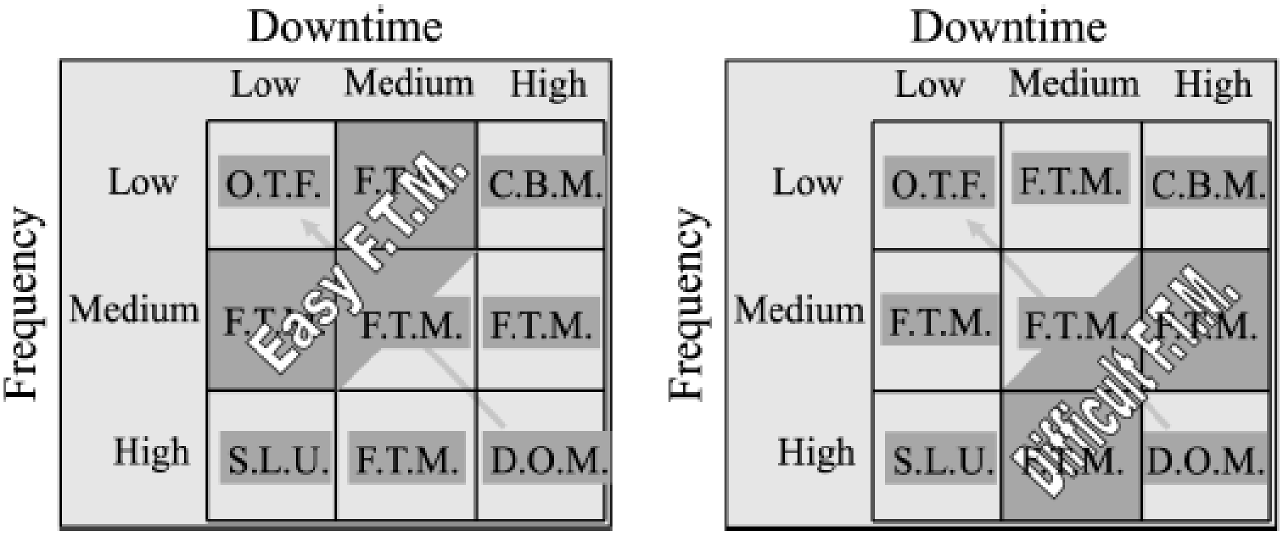


Figure 21: Shows When to apply RCM and TPM in the DMG, (Labib, 2004).

In practice, however, there can exist two cases where one needs to refine the model. The first case is when the performance makers of two machines are located near to each other on the grid but on different sides of a boundary between two policies, (See Fig. 22).

In this case we apply two different policies despite a minor performance difference between the two machines. The second case is when two such machines are on the extreme sides of a quadrant of a certain policy. In this case we apply the same policy despite the fact they are not near each other.

For two such cases, we can apply the concept of FL where boundaries are smoothed and rules are applied simultaneously with varying weights.

4.3.FUZZY LOGIC

Fuzzy logic is gaining more and more popularity due to factors such as conceptually easy to understand, flexibility, tolerant of imprecise data, being based on natural language, etc. Fuzzy logic expresses vague and subjective relationships mathematically. It is a convenient way to map an input space to an output space using a fuzzy set.

4.3.1. FUZZY INFERENCE SYSTEMS

Fuzzy inference is the process of formulating the mapping from given input(s) to an output using fuzzy logic, the mapping then provides a basis from which a decision can be made. The most common approaches to fuzzy reasoning are Mamdani and Sugeno approaches. Setnes et al. (1998) showed that using the Sugeno approach it would be difficult to give a linguistic interpretation of the information that is described in the rule base. While, Mamdani approach is typically used in modelling human expert knowledge, as they cited.

Fuzzy inference systems are also known as fuzzy-rule-based systems, fuzzy models, fuzzy associative memories (FAM), or fuzzy controllers when used as controllers. Basically, a fuzzy inference system is composed of five functional blocks (see Fig. 23):

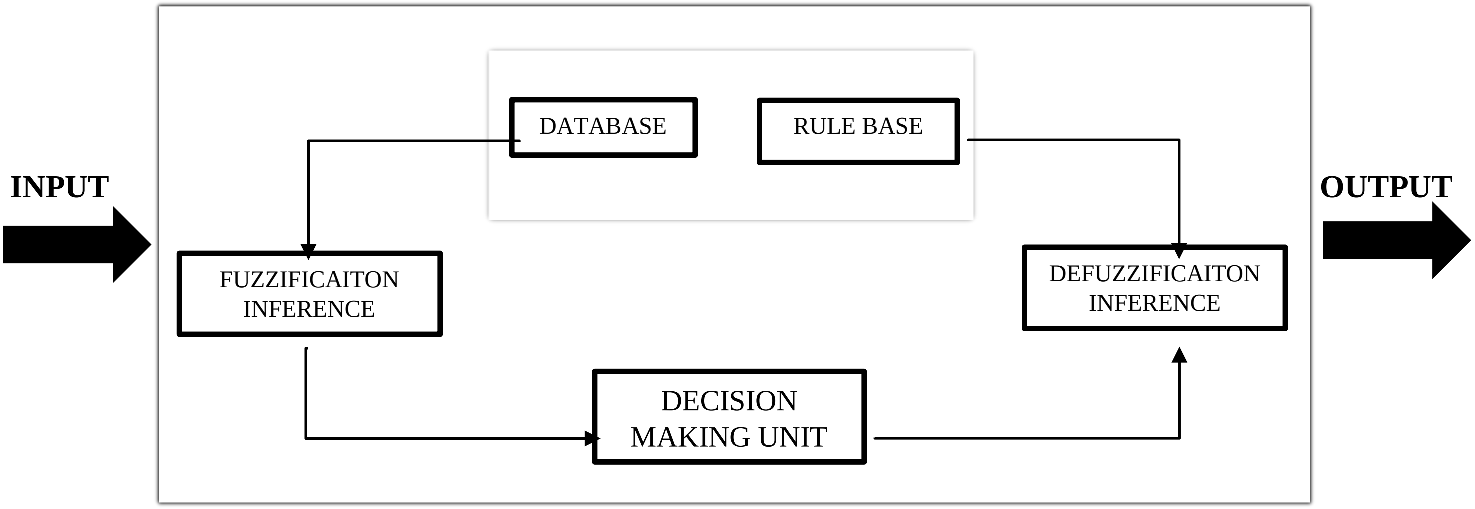


FIGURE 22: FUZZY INFERENCE SYSTEM, (JANG 1993)

1. A rule base containing a number of fuzzy if-then rules. The decision which the fuzzy inference system makes is derived from the rules which are stored in the database. These are stored as a set of rules. Basically, the rules are 'If-Then' statements that are intuitive and easy to understand, since they are nothing but common English statements. 'If" refers to an antecedent that is compared to the inputs and "Then" refers to a consequent, which is the result or output;
2. A database which defines the membership functions of the fuzzy sets used in the fuzzy rules;
3. A decision-making unit which performs the inference operations on the rules;
4. A fuzzification interface which transforms the crisp inputs into degrees of match with linguistic values;
5. A defuzzification interface which transform the fuzzy results of the inference into a crisp output. In this research the defuzzification method considered is the center of gravity or area method in order to produce a result. It is the most commonly used and popular method though has drawbacks. According to Jyh-shing *et.al*, and Negnevitsky, for a fuzzy set A of a universe of discourse Z, the center of area COG is given by:

$$COG = \frac{\int_a^b \mu A(z) z dz}{\int_a^b \mu A(z) dz}$$

Where:

μA(Z) is the aggregated output membership function. Based on this approach, the defuzzification process is illustrated using Mamdani-style fuzzy inference approach to aggregate rule consequents

Usually, the rule base and the database are jointly referred to as the ***knowledge base.*** The steps of ***fuzzy reasoning*** (inference operations upon fuzzy if-then rules) performed by fuzzy inference systems are:

- Compare the input variables with the membership functions on the premise part to obtain the membership values (or compatibility measures) of each linguistic label. (This step is often called fuzzification).
- Combine (through a specific T-norm operator, usually multiplication or min.) the membership values on the premise part to get firing strength (weight) of each rule.
- Generate the qualified consequent (either fuzzy or crisp) of each rule depending on the firing strength.
- Aggregate the qualified consequents to produce a crisp output. (This step is called defuzzification.)

From the fuzzy inference system, Figure 24 shows, the deduced system specifically modeled aid in decision analysis of the maintenance strategies, with frequency and downtime being the inputs.

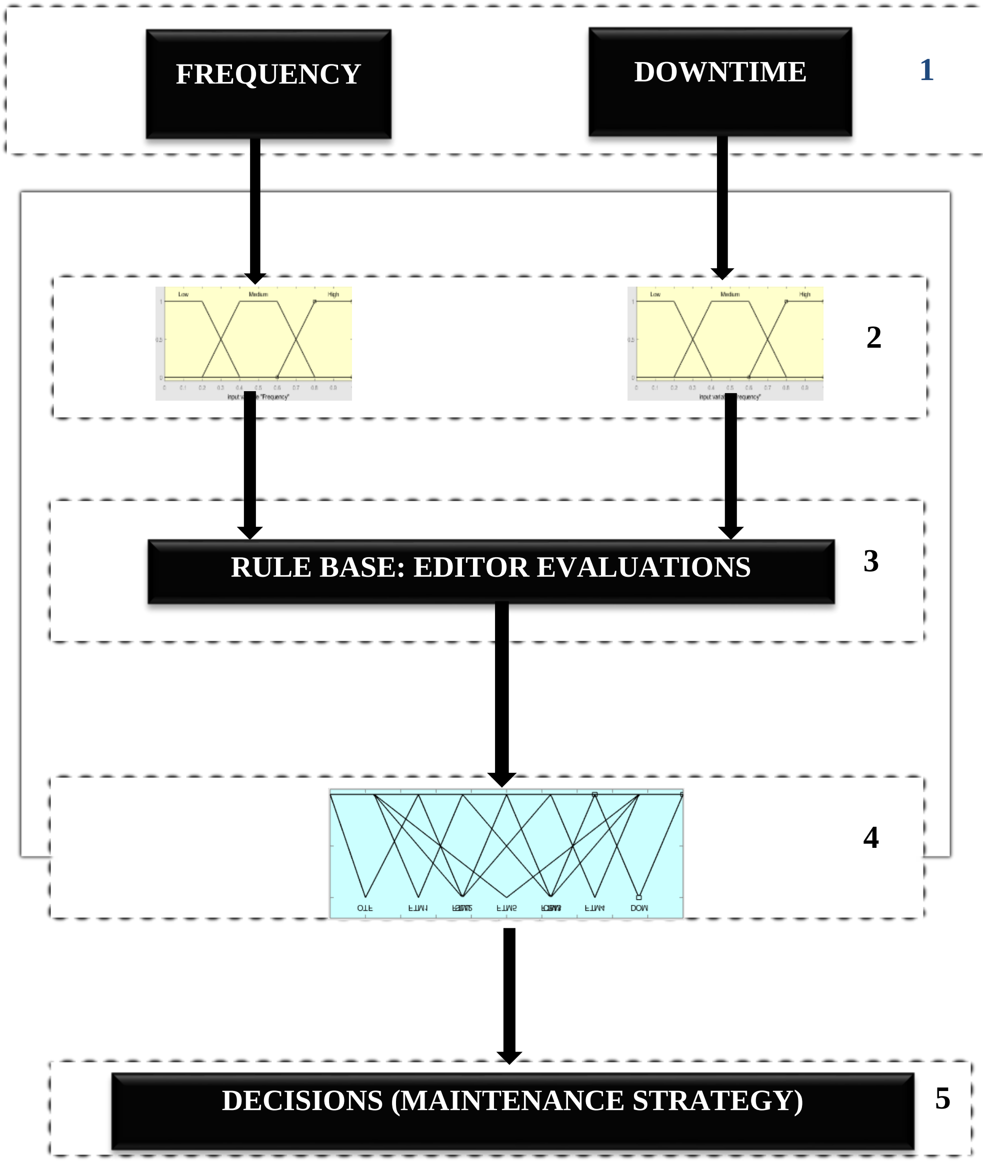


FIGURE 23: THE HIERARCHICAL FUZZY MODEL FOR MAINTENANCE STRATEGY EVALUATION

The stages in Figure 23 are shown below;

1- Inputs
2- Fuzzification
3- Rule Base
4- Decision Making Unit
5- Defuzzification

CHAPTER FIVE

5. DATA ANALYSIS AND PRESENTATION

5.1.INRTODUCTION

After the data are collected, the next task is analysis. This requires a number of closely related operations, including establishing categories, applying these categories to raw data through coding, tabulating data and then drawing statistical inferences. The maintenance raw data that was collected from AALRT was analyzed and grouped in a tabular form. This presented the rolling stock systems considered with their respective number of failures and time taken to address these failures.

From chapter three, which presents the methodology of this research, the following procedures are presented starting from the Decision Support System stage as shown in the frame work.

5.2.CRITERIA ANALYSIS

The objective of this phase is to assess how bad, are the worst performing machines, for a certain period of time, for one quarter using two important criteria, viz. downtime and frequency of calls.

Maintenance strategies are developed based on the most important criteria to AALRT– which are generally, the failure rate of systems, the impact on services, the availability of units to operate peak services and specifically the cost impact of defects in service (i.e. delay hours).

In the following, a Pareto analysis has been carried out for the most important criteria for AALRT; which are the number of failures and the number of delay minutes caused by different systems.

The data for each of these criteria were obtained from the maintenance data collected and handled by the maintenance department at AALRT, as the primary data. The data are arranged from the highest to the lowest. The ten rows of data are then categorized into high, medium and low such that the systems are distributed approximately equally in each range.

5.3.DECISION MAPPING

Table 2 shows data collected for a period of six (6) months from July to December 2018, of the failure frequency and delay minutes of systems according to the criteria that were selected. The next step in the application of the DMG is to allocate each system to the appropriate cell of the DMG shown in the following. Each of these cells indicates what type of maintenance should be carried out on each of the worst performing systems – i.e. reactive, predictive, preventive, and maintenance prevention.

TABLE 1: SYSTEMS WITH THEIR RESPECTIVE FAILURE FREQUENCY AND DELAY MINUTES

Criteria 1 (Frequency)	No. of Failures	Time taken to repair (Hours)	Time taken to Diagnose (Hours)	Criteria 2 (Downtime) Frequency * (MTTR + MTTD)
Train control and management system	0	4	1	0
Doors	44	6	2	352
Traction	63	8	4	756
Passenger information system	19	6	4	190
Brakes	10	8	4	120
Auxiliary power supply	10	8	6	140
cab	11	4	4	88
Couplers	0	4	4	0
Air Conditioning	29	3	2	174
Lighting	0	4	4	0
Bogie	4	24	6	120
Gangway and Car body	13	4	4	104
Main Circuit	2	3	4	14

The total downtime for this research considers the sum of MTTR and MTTD since all the systems considered are repairable; unlike the replaceable ones which only require MTTR

The machines, as regards each criterion are sorted and placed into a top ten list of high, medium, and low boundaries, which are divided into three categories using the tri-quadrant approach as follows (Burhanuddin (2009)) from equations 1 to 6.

$$K = \frac{Xmax - Xmin}{3},$$

Where;

X is the frequency of failures

Xmax = maximum frequency,

Xmin = minimum frequency;

Then the intervals are obtained as:

High frequency = [*X*max, *X*max - *k*] (1)

Medium frequency = [*X*max - *k*, Xmax - 2*k*] (2)

Low frequency = [*X*max - 2*k*, Xmin] (3)

Therefore, from equations 1, 2 and 3;

High frequency = [63, 43]

Medium frequency = [42, 23]

Low frequency = [22, 2]

Similarly, for the downtime of the machines.

$$L = \frac{(Ymax - Ymin)}{3},$$

Where;

Y is the downtime

Ymax = maximum downtime,

Ymin = minimum downtime;

Then the intervals are obtained as:

High downtime = [*Y*max, *Y*max - L] (4)

Medium downtime = [*Y*max - L, *y*max – 2*L*] (5)

Medium downtime = [*Y*max – 2*L*, *Y*min] (6)

Therefore, from equations 4, 5 and 6;

High downtime = [756, 509]

Medium downtime = [508, 262]

Low downtime = [261, 14]

Using the above ranges, the systems are mapped into a two-dimensional matrix based on their respective intervals on frequency of failures and downtime. Next, decision strategies for systems such as OTF, FTM, SLU, CBM, DOM, RCM or TPM can be implemented (Labib (1998)).

TABLE 2: THE FREQUENCY AND DOWNTIME OF THE WORST PERFORMING SYSTEMS

		Criteria 1 (Frequency)	**No. of Failures**			**Criteria 2 (Downtime)**	**Delay Hours (MTTR + MTTD)**
🟥	**A**	Traction	63	🟥	**A**	Traction	756
🟥	**B**	Door	44	🟨	**B**	Door	352
🟨	**C**	Air Conditioning	29	🟩	**D**	Passenger Information System	190
🟩	**D**	Passenger Information System	19	🟩	**C**	Air Conditioning	174
🟩	**E**	Gangway and Car body	13	🟩	**H**	Auxiliary power supply	140
🟩	**F**	Cab	11	🟩	**G**	Brakes	120
🟩	**G**	Brakes	10	🟩	**I**	Bogie	120
🟩	**H**	Auxiliary power supply	10	🟩	**E**	Gangway and Car body	104
🟩	**I**	Bogie	4	🟩	**F**	Cab	88
🟩	**J**	Main Circuit	2	🟩	**J**	Main Circuit	14

In Table 3, it is clear which systems of the AALRT rolling stock are the worst performing in terms of the criteria that has been selected, which are frequency of failures and the number of delay minutes attributed to each system.

Each of those systems are then allocated to a cell in the DMG, as shown in Table 4, based on which category (i.e. high, medium or low) that system is allocated to, in each criterion.

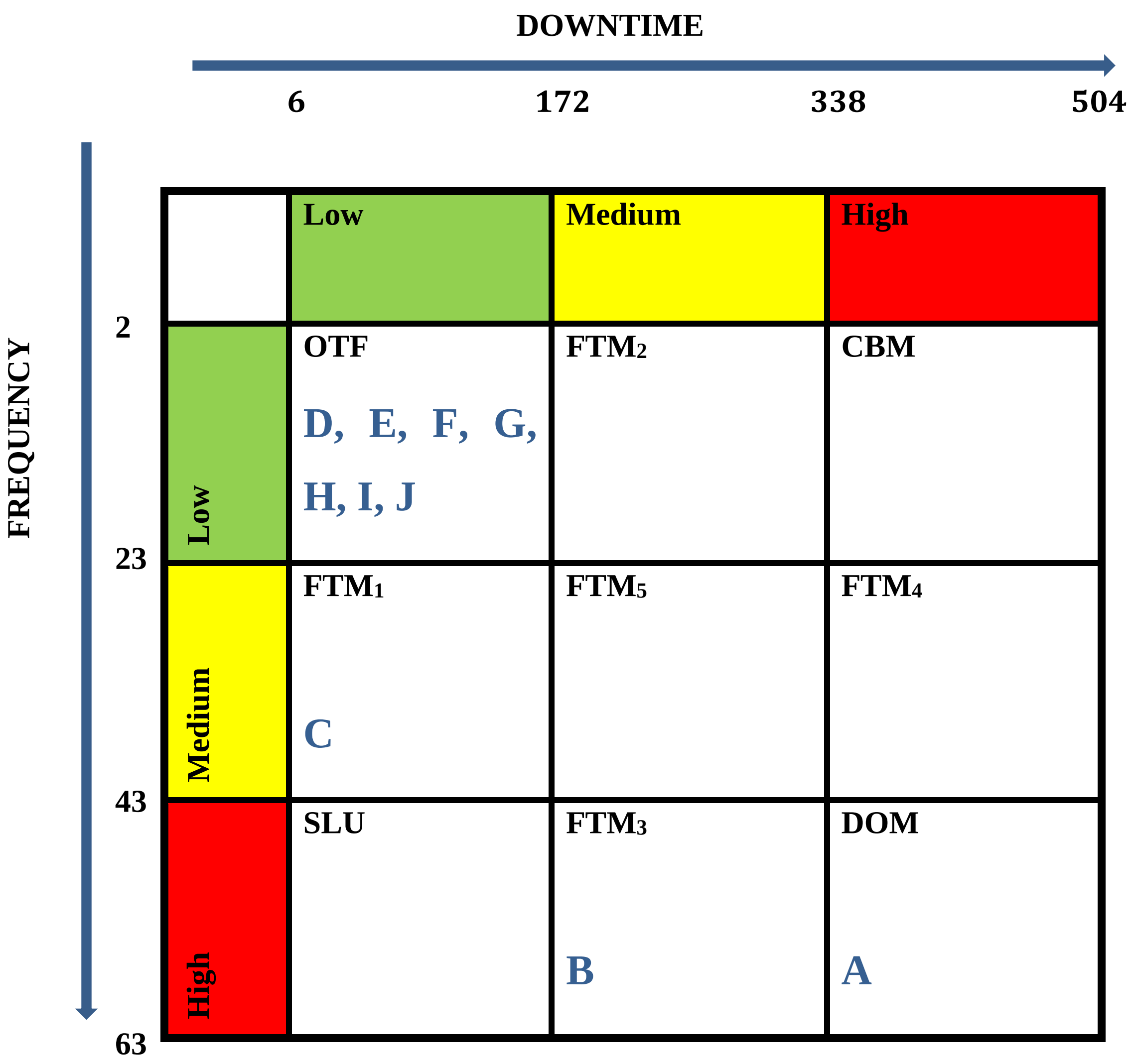
The traction system (A) is classified as (high, high) for the selected criteria, therefore it is allocated to the cell in the bottom right hand corner – which indicates that the approach to be taken is to design out maintenance. This is more applicable to systems and components are still in the design phase, since the costs required to alter the design may be minimal. Therefore, this strategy may not be applicable to AALRT.

The performance of System **C** classified as (low, medium), is situated in the region between OTF and SLU and the question is about; who will do the job – the operator, maintenance engineer, or subcontractor?

Door system (B) is classified as (medium, high) for the criteria and therefore, it needs to be investigated in terms of the contents of the preventive instructions and an expert advice is needed

The rest of the systems, with (Low, Low) for the criteria, fall in the region of OTF. This means that since they have a low failure rate and the mean time to repair is also low, it is economical to operate them until they fail.

TABLE 3: THE SYSTEMS IN THEIR RESPECTIVE POSITIONS IN THE DMG



	🟩 Low	🟨 Medium	🟥 High
🟩 Low	OTF D, E, F, G, H, I, J	FTM$_2$	CBM
🟨 Medium	FTM$_1$ C	FTM$_5$	FTM$_4$
🟥 High	SLU	FTM$_3$ B	DOM A

OTF – Operate to Failure

FTM – Fixed Time Maintenance

CBM – Condition Based Maintenance

SLU – Skill Level Upgrade

DOM – Design Out Maintenance

For the systems that appeared under one criterion but not the other or didn’t appear under both like the lighting, Couplers and the Train Control and Management System, then such systems would not appear in the DMG, as it would be considered to be a one-off event.

Since we now have a scenario where we have got systems near the boundaries of the grid, we need to refine the model using Fuzzy Logic. This will smoothen the boundaries and also enable the researcher and maintenance expert to determine which region in the grid the system exists with more weight. From the grid we have systems B and D with frequencies of failure as 44 and 19. Therefore, these boundaries need to be smoothed.

5.4.FUZZY LOGIC MODEL DEVELOPMENT

Explained below are the steps followed while applying fuzzy logic as explained in the methodology.

5.4.1. DEFINE MEMBERSHIP FUNCTION

Complex relationships between those variables used in fuzzy system are represented by the hierarchical structure shows in Figure 25.

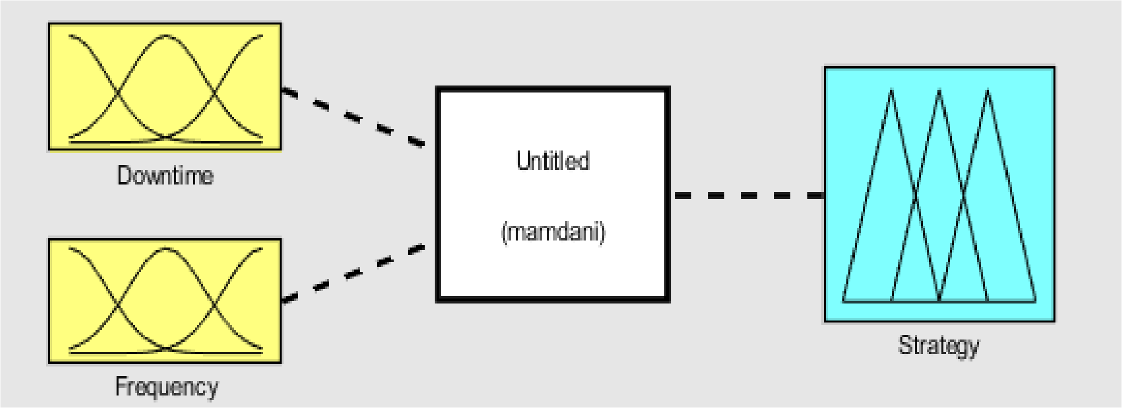


FIGURE 24: THE HIERARCHICAL FUZZY MODEL

The next step, we need to specify the ranges or membership function of our linguistic variables. In practice, all linguistic variables, linguistic values and their ranges membership are chosen by the domain expert. Based on the data collected from AALRT (as shown in Table 2) and refer to research paper by Labib (2004), we have to normalize and define the membership functions as shows in Table 5. This is also referred to as Fuzzification process.

TABLE 4: THE NORMALIZED LINGUISTIC VARIABLES OF INPUTS AND OUTPUTS

Input Linguistic Variable: Frequency	
Linguistic Value	**Numerical Range (Normalized Values)**
Low	[0, 0.4]
Medium	[0.2, 0.6]
High	[0.4, 1]
Input Linguistic Variable: Downtime	
Linguistic Value	**Numerical Range (Normalized Values)**
Low	[0, 0.4]
Medium	[0.2, 0.6]
High	[0.4, 1]
Output: Cost/Benefit (Strategy)	
Linguistic Value	**Numerical Range (Normalized Values)**
OTF	[0, 0.25]
SLU	[0.25, 0.5]
CBM	[0.5, 0.75]
DOM	[0.75, 1]
FTM1	[0.125, 0.375]
FTM2	[0.125, 0.625]
FTM3	[0.375, 0.875]
FTM4	[0.625, 0.875]
FTM5	[0.125, 0.875]

Triangular and trapezoidal membership functions can often provide an adequate representation of the expert knowledge from the maintenance problem, and at the same time significantly simplifies the process of computation. Figure 26 and Figure 27 show the fuzzy sets for frequency and downtime, respectively, that are used in our problem. This is all performed in MATLAB.

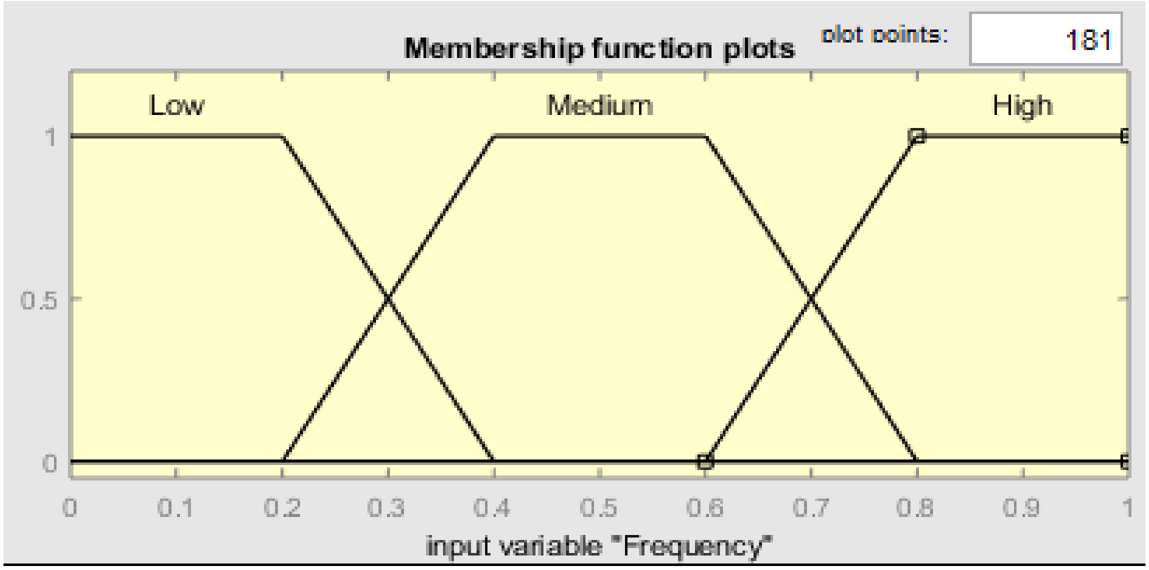


FIGURE 25: FUZZY SET FOR THE LINGUISTIC VARIABLE, FREQUENCY

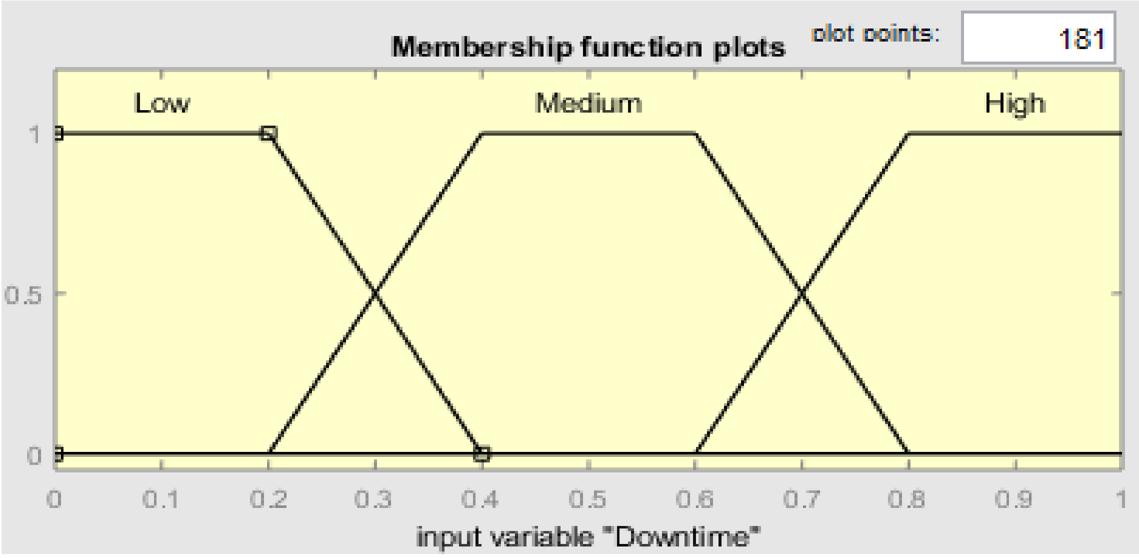


FIGURE 26: FUZZY SET FOR THE LINGUISTIC VARIABLE, DOWNTIME.

Based on Labib (2004), the output strategies shown in Figure 28, have a membership function and have assumed a cost (or benefit) function that is linear and follows the relationship – DOM>CBM>SLU>FTM>OTF.

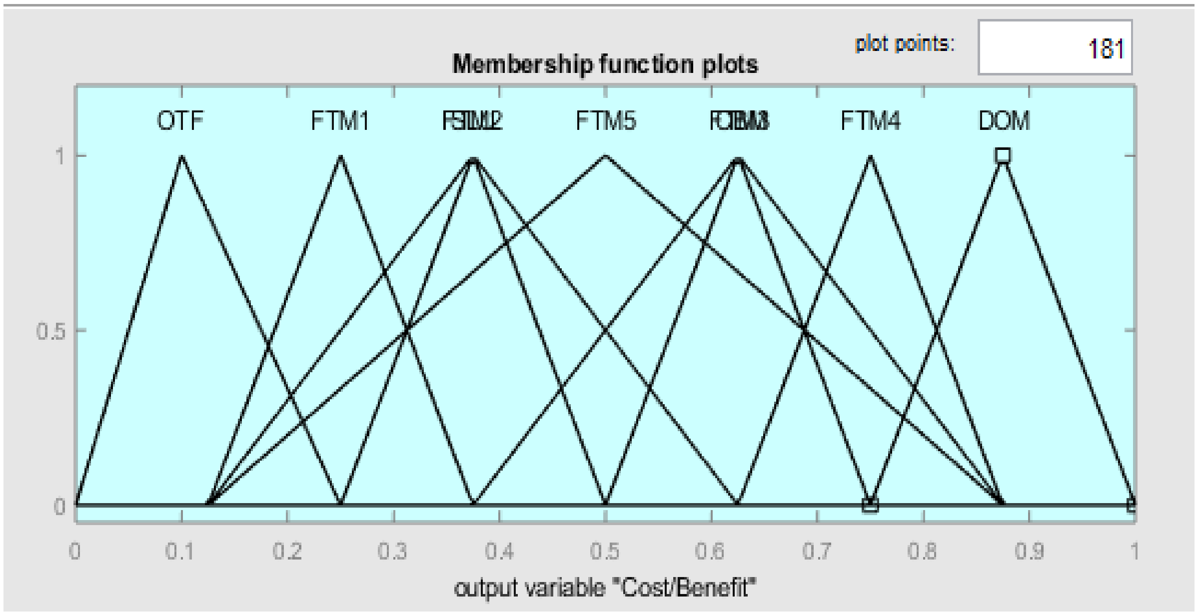


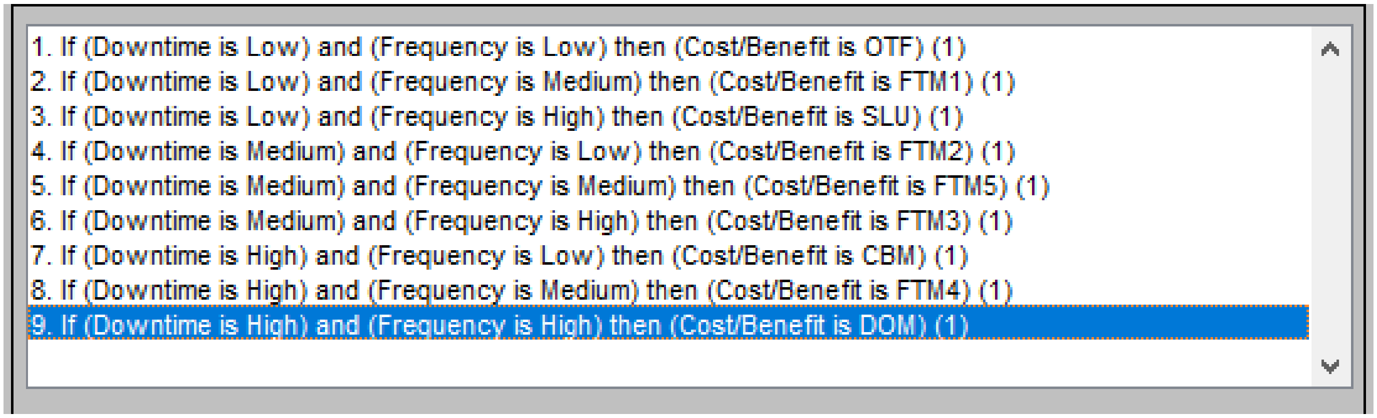
FIGURE 27: FUZZY LINGUISTIC VARIABLE OUTPUT

5.4.2. FUZZY RULES

To accomplish this task, we might ask the expert to describe how the problem can be solved using fuzzy linguistic variable defined previously. The knowledge that required also can be collected from other sources such as books, journals, papers, computer databases, flows diagram and others. In this research, the basic rules used by Labib (2004), were adopted.

There are two inputs and one output variables in the research. It is convenient to represent fuzzy rules in matrix form, in this case, they were obtained based on DMG matrix by Labib (2004). A two by one system (two inputs and one output) is depicted as an M x N matrix of input variables.

Meanwhile, detailed analysis by Labib (2004), has also enabled the derivation of 9 rules that represent complex relationships between all variable used in fuzzy system. These rules are shown in Figure 29, below.



1. If (Downtime is Low) and (Frequency is Low) then (Cost/Benefit is OTF) (1)
2. If (Downtime is Low) and (Frequency is Medium) then (Cost/Benefit is FTM1) (1)
3. If (Downtime is Low) and (Frequency is High) then (Cost/Benefit is SLU) (1)
4. If (Downtime is Medium) and (Frequency is Low) then (Cost/Benefit is FTM2) (1)
5. If (Downtime is Medium) and (Frequency is Medium) then (Cost/Benefit is FTM5) (1)
6. If (Downtime is Medium) and (Frequency is High) then (Cost/Benefit is FTM3) (1)
7. If (Downtime is High) and (Frequency is Low) then (Cost/Benefit is CBM) (1)
8. If (Downtime is High) and (Frequency is Medium) then (Cost/Benefit is FTM4) (1)
9. If (Downtime is High) and (Frequency is High) then (Cost/Benefit is DOM) (1)

FIGURE 28: RULE-BASED MAINTENANCE STRATEGY IMPROVEMENT

After defining the fuzzy sets and fuzzy rules, the next step is to encode them or thus actually build a fuzzy system. The system is built with MATLAB fuzzy logic toolbox from MathWorks. It provides a systematic framework for computing with fuzzy rules and graphical user interfaces.

5.4.3. EVALUATION AND TESTING

The last phase in the development of a DSS, is its evaluation and testing. Several test situations depend on frequency and downtime factor. For example, we take the data analysis from Table 3 for Systems B and D, as explained earlier. System D has a 19 times frequency and a 114-hour downtime, System B has a 44 times frequency and a 264-hour downtime. Logically, System B should be given higher cost for maintenance than system D because it has a higher of failure frequency.

From System B that has a 44 times frequency and a 352-hour downtime, we normalize these inputs by dividing them with the highest number of failure frequency and the highest number of machine downtime to get the weights. After calculation, we get 0.70 weight for input of frequency and 0.47 weight for input of downtime. Having tested the inputs into fuzzy logic system, the output is 0.514 (Figure 30). It then means the suggested strategy for System B is FTM_5 which has a weight of 0.98. Other strategies with lower costs and benefits include, CBM with 0.02, FTM2 with 0.48 and then FTM3 with o.52. On the other hand, considering the strategy FTM_5, since it falls near the FTM_3 boundary and has the second highest weight, the expert can choose FTM_3. This is because FTM_5 as a maintenance strategy is not well defined by Labib on the DMG.

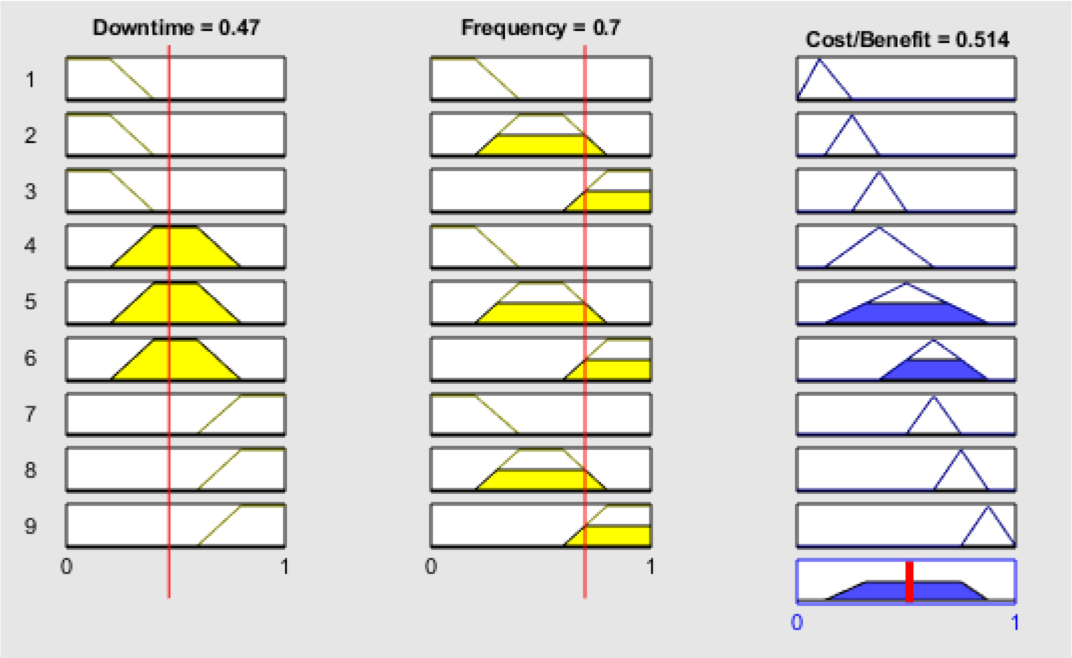


FIGURE 29: SHOWS THE FUZZY LOGIC OUTPUT OF SYSTEM B

At the same calculation method, having tested system D, (0.3; 0.25) as shown in Figure 31. It means the suggested maintenance strategies for System D is FTM_2. From the cost/benefit output variable, it can be noted that, whereas FTM_2 yields the highest benefits, the model offers other options like FTM_5, SLU and FTM_1. Therefore, the maintenance expert could select from those whose cost to implement is a bit lower, though, they are likely to yield low benefits. Other factors like applicability, maintenance goals, safety and environmental factors can be considered while selecting from the options. The rest of the systems are indicated in table 6.

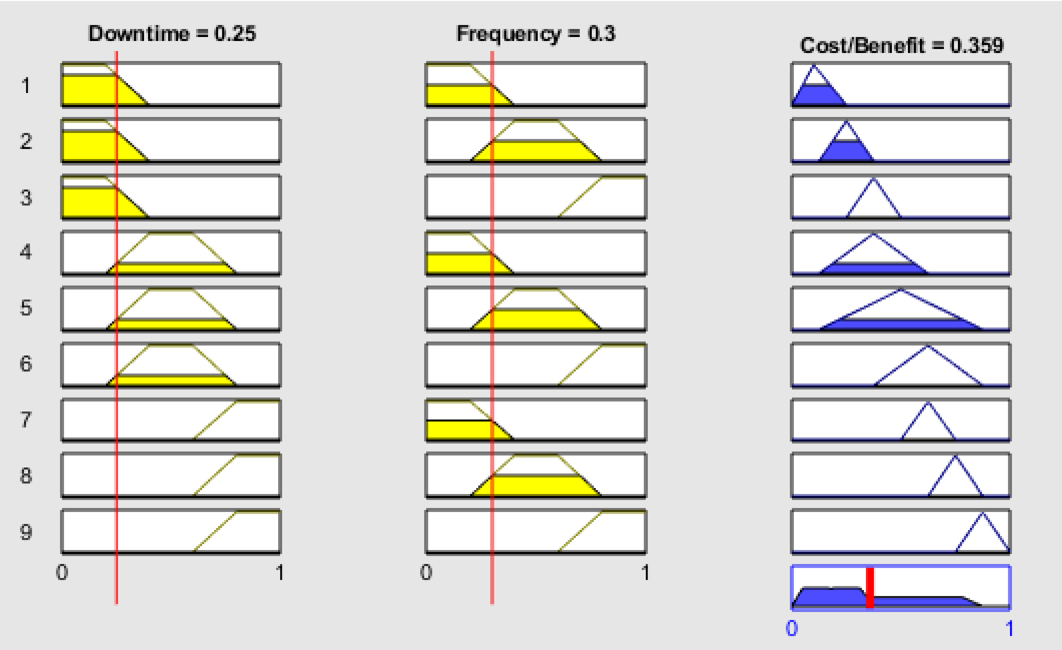
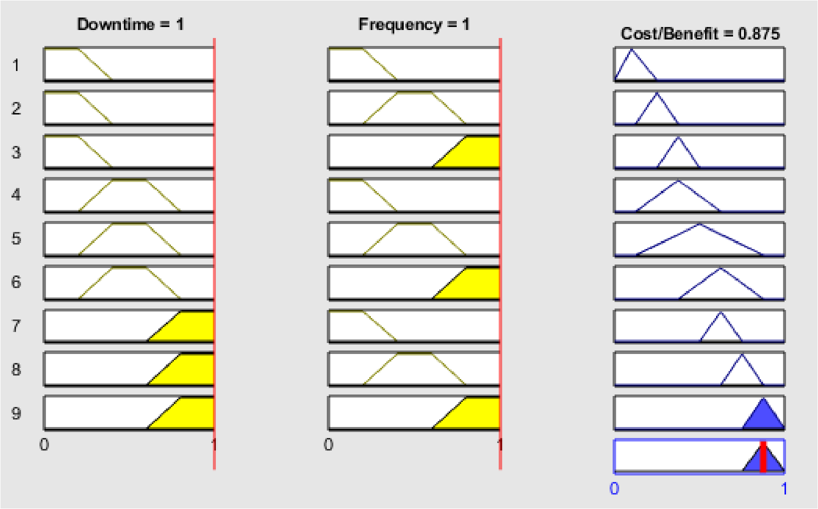
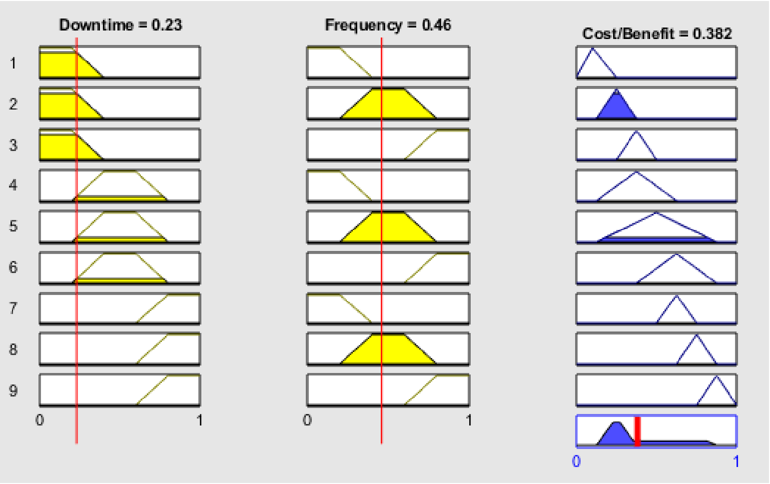
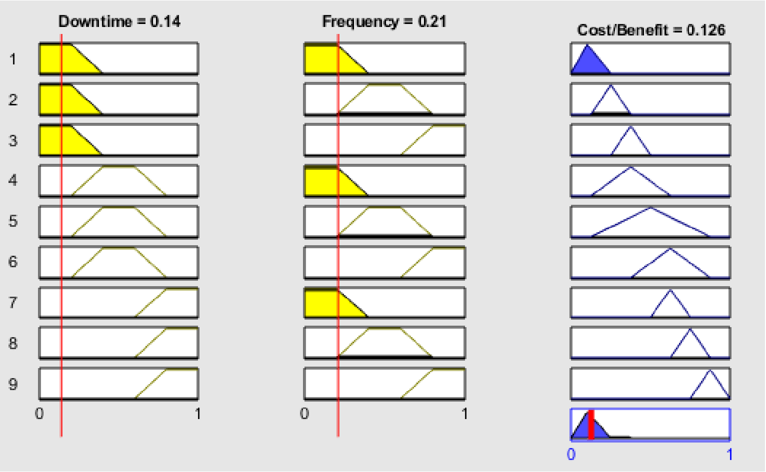
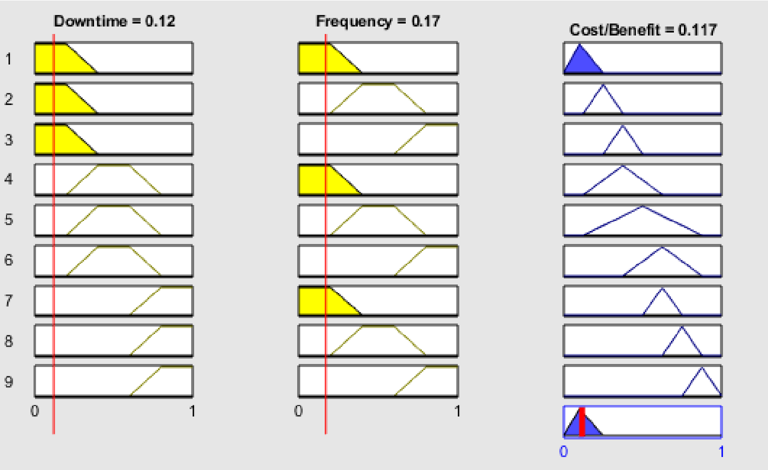


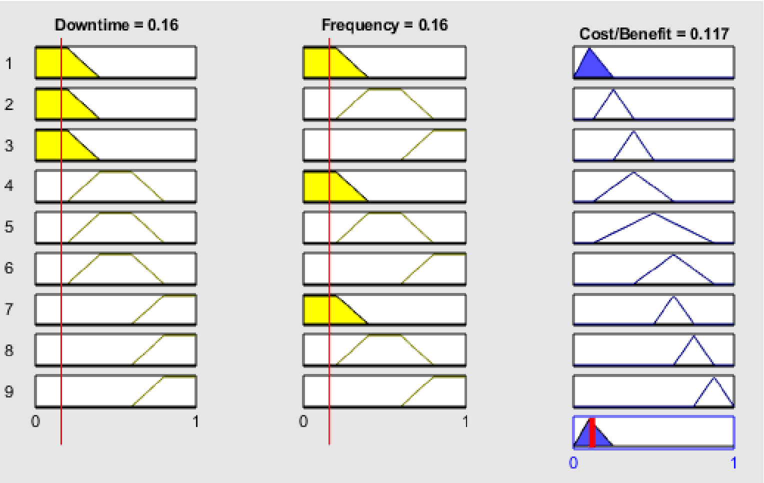
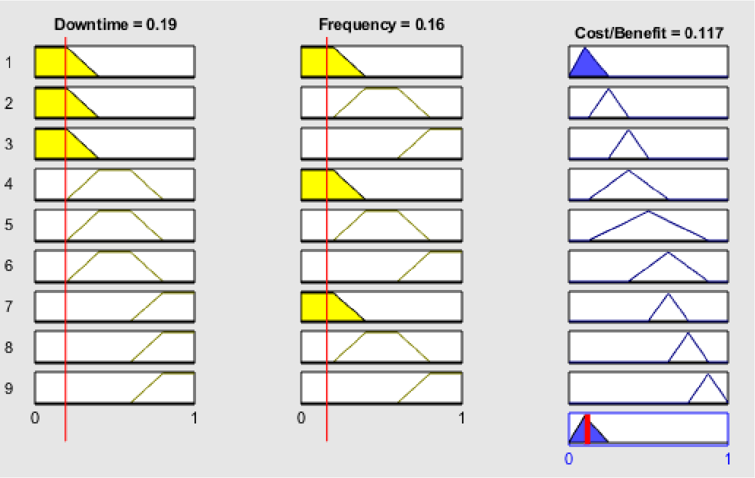
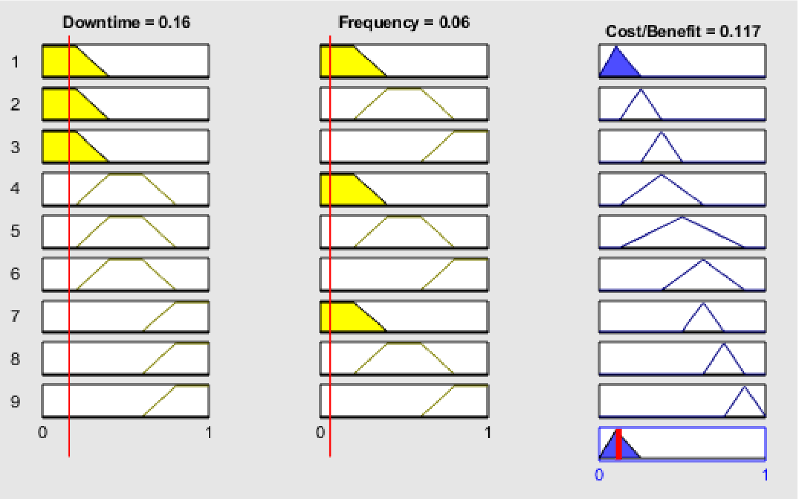
FIGURE 30: SHOWS THE FUZZY LOGIC OUTPUT OF SYSTEM D

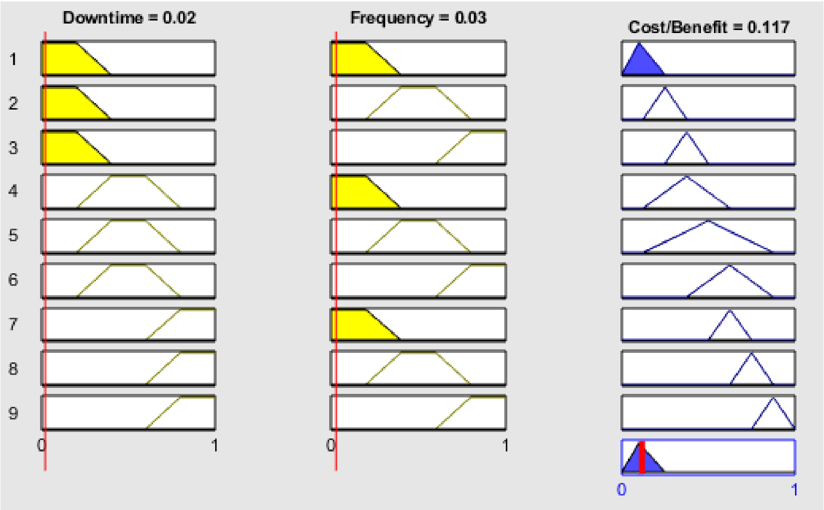
The rest of the rolling stock systems are evaluated and tested similarly and are presented in Table 6 below.

TABLE 5: THE FUZZY LOGIC OUTPUTS OF THE REST OF THE SYSTEMS.

FUZZY LOGIC CONTROL	SYSTEM	STRATEGY	COMMENT
	**A**	**DOM (*0.875*)**	Location in the bottom-right region and engineers are used to seeing such a system in the maintenance depot. System A, will need to be structurally modified and major design out projects need to be considered. This may be on a component(s)

	**C**	**FTM$_1$ (*0.382*)**	This is located in the region between OTF and SLU and the question is about who will do the job – the operator, maintenance engineer, or subcontractor. The final decision is in order to shift the system to OTF region
	**E**	**OTF (*0.126*)**	This is situated in the top-left region and the action to implement, or the rule that applies, is operate to failure (OTF). This is the cheapest strategy to implement.
	**F**	**OTF (*0.117*)**	System F has a low downtime and frequency and the action to implement, or the rule that applies, is operate to failure (OTF).

	**G**	**OTF (*0.117*)**	Similarly, System G should be operated to failure (OTF) based on the output.
	**H**	**OTF (*0.117*)**	System H, also has a low frequency and downtime and the best strategy is operate to failure
	**I**	**OTF (*0.117*)**	System I should also be recommended to be operated to failure since it has a lower downtime and frequency

	**J**	**OTF (*0.117*)**	Finally, system J, having the least downtime and frequency should also be operated to failure.

Comparing the two results obtained from the Decision-Making Grid together with the improved fuzzy system, there is a difference in the strategies as shown in Table 7 below, due to the smoothening effect that the fuzzy logic system brings about; which makes it more practical.

Finally, the results can determine the most appropriate strategy to follow from any combination of frequency and downtime. Figure 32 shows the improved surface of the rules.

TABLE 6: A COMPARISON BETWEEN THE TWO RESULTS

ROLLING STOCK SYSTEM	COST/ BENEFIT	STRATEGY (IMPROVED SYETM)	STRATEGY (DMG)
A. Traction	0.875	DOM	DOM
B. Door	0.514	FTM$_5$	FTM$_3$
C. Air Conditioning	0.25	FTM$_1$	FTM$_1$
D. Passenger Information System	0.316	FTM$_2$	OTF
E. Gangway and Car Body	0.126	OTF	OTF
F. Cab	0.117	OTF	OTF
G. Brakes	0.117	OTF	OTF
H. Auxiliary Power Supply	0.117	OTF	OTF
I. Bogie	0.117	OTF	OTF
J. Main Circuit	0.117	OTF	OTF

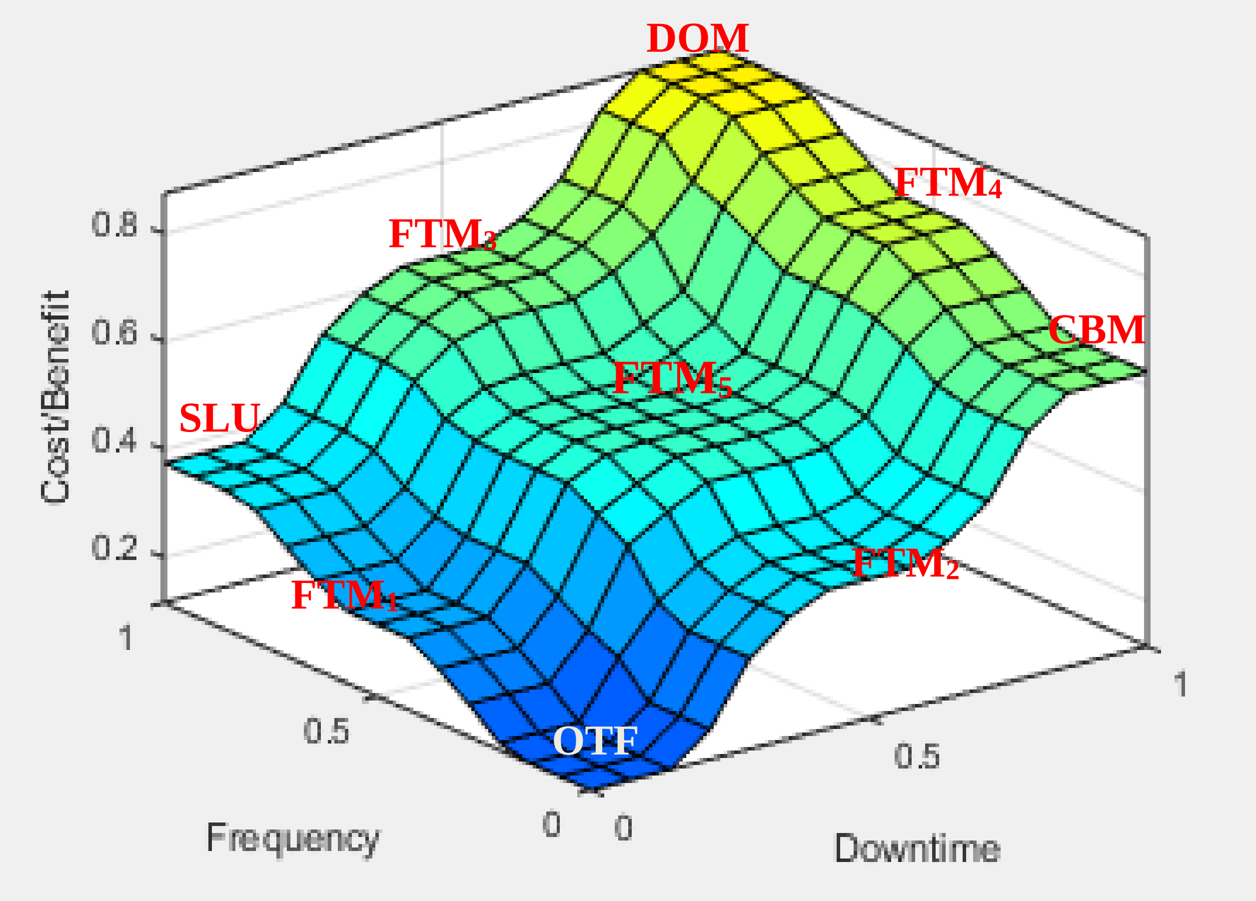


FIGURE 31: IMPROVED THREE-DIMENSIONAL OUTPUT SURFACE

In practice, maintenance strategies are based on the failure rate characteristics, i.e. constant or variable, failure impact and failure rate trend. The DMG takes into account the failure rate, its impact and its trend for recommending and particular maintenance strategy. The failure rate is taken into consideration as the frequency axis.

The failure impact is captured in the downtime axis. It can also be substituted with mean time to repair and the mean time to diagnose (MTTR + MTTD). This value needs to be minimized. Therefore, this is equivalent to downtime in the DMG.

The objective is to implement two factors, which are; Frequency and Downtime, into the decision-making grid (DMG) and then, embedded into the maintenance decision support fuzzy system. The output can determine the most appropriate strategy to follow from any combination of problem factors. Next, the maintenance department can implement this system to support their maintenance decision process.

From the DMG, the easy PM and FTM questions are “Who?”, and “When?” (The efficiency questions). The more difficult ones are “What?” and “How?” (The effectiveness questions), as indicated in the Figure 33.

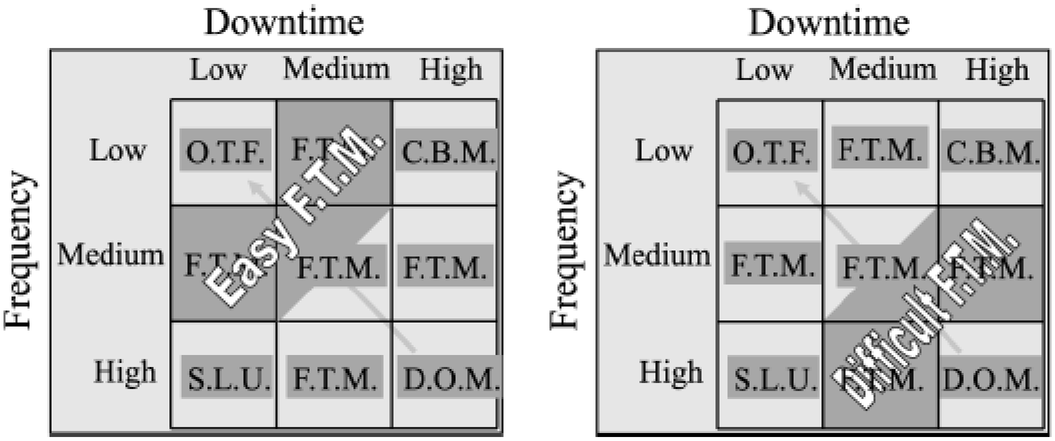


FIGURE 32: REGIONS OF PM SCHEDULES THAT NEED TO BE ADDRESSED IN THE DMG (LABIB 2004)

According to the DMG, SLU of machine tool operators is a fundamental concept of TPM. RCM is applicable for machines exhibiting severe failures (high downtime and low frequency). Also CBM and FMEA will be ideal for such failures and hence an RCM policy will be most applicable. The significance of this approach is that rather than treating RCM and TPM as two competing concepts it unifies them within a single analytical model.

The frequency of failures (i.e. impact on train performance) and the unit downtime due to failures (the number of delay minutes incurred due to each failure – which is a measure of the cost of each failure to the TOC) are some of the most important criteria in terms of system failures on rolling stock. Safety is the most important criterion for any TOC – however it is not used as a measurable in terms of system performance for the purpose of this research.

Application of the DMG at AALRT would also assist engineers in clearly and quickly being able to identify the different approaches that should be taken for systems that perform at the extremes for the two criteria considered (high frequency, low downtime failures and low frequency, high downtime failures) – this too would ensure that resources are deployed more effectively and focused on improving system performance such that the failure modes with the greatest impact are eradicated. Furthermore, using the DMG would reduce the risk of low frequency failures with a high impact on the business from going undetected as both frequency of failure and impact of failure (in terms of delay minutes) are simultaneously used in the application of the DMG.

The DOM strategy is to examine a situation that is currently not fit for purpose and hence a reconfiguration, or re-design strategy should be followed. Either to get rid of the status quo or design a resilience strategy as a fundamental mechanism to prevent occurrence, minimize significance and increase ability to detect and monitor. For this research, the traction system being in the DOM slot in the DMG, expert knowledge is required to determine whether to change the design of some components, changing the maintenance strategy according to what is more practical.

The SLU is one of the activities that should be considered when applying TPM. Therefore, depending on the situation assessed by an expert, TPM as a maintenance strategy can be carried out.

CHAPTER SIX

6. CONCLUSION AND RECOMMENDATION

6.1.CONCLUSION

This research describes a structured maintenance decision support fuzzy system for data analysis at AALRT's maintenance strategy selection. It aims to improve maintenance strategies for the maintenance department using real time maintenance data by extending some theoretical method introduced by Labib (1998b) and Burhanuddin (2009) in DMG model to provide maintenance strategies.

The DMG could be used for practical continuous improvement process because when systems in the top ten have been addressed, they will then, if and only if, appropriate action has been taken, move down the list of top ten worst systems. When they move down the list, other systems show that they need improvement and then resources can be directed towards the new offenders. If this practice is continuously used then eventually all machines will be running optimally.

Training and educational programs should be designed to address the existence of the considerable gap between the skills that are essential to maximize the potential benefits from these advanced systems and technologies in the area of maintenance and asset management and the skills that currently exist in the maintenance sections of most train operating companies.

Maintenance strategies are identified using the DMG model, based on important factors, including the systems' downtimes and their frequency of failures. The systems are categorized into the downtime criterions and frequency of failures, which are high, medium and low using tri-quadrant formulae. The experimental studies are conducted using maintenance dataset given by Fernandez et al. (2003). The proposed models can be used by decision makers to identify appropriate maintenance strategies.

The analysis provides insight by using collative approaches in two-dimensional matrices, and simultaneously investigates three criteria of the downtime and frequency of failures. Tri-quadrant analysis is used to ascertain the model through the incorporation of multiple criterions of the decision-making analysis for AALRT. The result of the analysis provides some decision-making strategies for rolling stock system maintenance.

Finally, the proposed model is presented to provide a decision analysis capability that is often missing in maintenance departments. The effect of such model is to contribute towards the optimization and enhancing decision analysis support to add value to the collected data. The use of AI techniques has also been demonstrated. This enables the maintenance team to carryout maintenance activities on systems depending on the maintenance data rather than depending on the maintenance manuals, which at times may not be practical. Finally, features of next generation maintenance systems have been outlined.

6.2.RECOMMENDATIONS

1. In this documentation, we have investigated the characteristics of Computerized Maintenance Management Systems (CMMSs) and have highlighted. Since the developed DSS depends on the maintenance data, it’s recommended that AALRT should also develop a CMMS such that the maintenance data can be easily accessed for Decision analysis. The basic data requirements are as follows;

   - The ***asset register*** which will identify the different machines and plants,
   - The ***fault counter*** records the frequency of occurrence of faults
   - The ***fault timer*** to record downtime ;

3. As the success of systems implementation are based on two factors, human and systems, it is important to develop and nurture skills as well as to use advanced technologies. Training and educational programs should be designed to address the existence of the considerable gap between the skills that are essential to maximize the potential benefits from these advanced systems and technologies in the area of maintenance and asset management, compared with the skills that currently exist in the maintenance section of AALRT.
4. Adequate staffing is necessary to support the implementation of the recommendations contained in this report. In addition, the most successful agencies have also implemented dedicated staff positions to support the ongoing development of these programs. The position of **DSS** Manager is required – This position would be a full-time resource for the selected DSS. This role would be the resource to direct and assist with the implementation and configuration of the DSS and CMMS, would develop customized reports, provide end user training and

technical support, manage the quality of data and its structure in the CMMS, and make sure that the CMMS and DSS become integrated into the business practices of AALRT.

6.3.FUTURE RESEARCH AND SUGGESTIONS

1. According to Professor Jay Lee, of the National Science Foundation (NSF) Industry/University Cooperative Research Centre on Intelligent Maintenance Systems (IMS) at the University of Cincinnati, unmet needs in responsive maintenance can be categorized as follows:

- ***Machine intelligence*** – intelligent monitoring, prediction, prevention and compensation and reconfiguration for sustainability (self-maintenance);
- ***Operations intelligence*** – prioritization, optimization and responsive maintenance scheduling for reconfiguration needs; and
- ***Synchronization intelligence*** – autonomous information flow from market demand to factory asset utilization.

2. The analysis in this research is carried out on a system level. Therefore, AHP, can be applied to determine which components exactly need the proposed strategy. It’s more practical to deal with the component rather than the whole system.
3. This study focuses on DMG based on few factors respond time, diagnostic time, repair time and frequency of failures. More research on organization procedures and underlying characteristics of the system, such as their model, age, made and price, can lead to a more comprehensive study to aid in decision-making. The external factors such as economic, geographical and social aspects could be incorporated into the models.

It can be concluded that the challenges, and research questions, facing research and development (R&D) concerning next generation maintenance systems are:

1. how to adapt PM schedules to cope dynamically with shop-floor reality;
2. how to feedback information and knowledge gathered in maintenance to the designers;
3. how to link maintenance policies to corporate strategy and objectives, and;
4. how to synchronize maintenance scheduling and planning based on maintenance performance.

CHAPTER SEVEN

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